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Study

Renewable Long-Haul Road Transport Considering Technology Improvements and European Infrastructure

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Summary

In the coming years long-haul road transport must commit to reach Europe's planned reduction targets of greenhouse gases (GHGs) on a medium term (i.e., 2030) as well as on a long term. New technologies, with the potential of making long-haul road transport renewable, are in the process of entering the market. In this study, the most promising are analysed both quantitatively and qualitatively: battery electric vehicles (BEV), hydrogen fuel cell electric vehicles (H_2, FCEV) and vehicles with internal combustion engines (ICE) running on renewable methane (CH_4, biomethane and synthetic methane) and the two renewable liquid fuels E-Diesel and HVO. The analysis uses a Well-to-Wheel (WtW) approach on a European level especially in Germany, Switzerland, France, Italy and Poland.

Even if there are no binding sector specific reduction targets, the "European Green Deal" states an ambition of 90% GHG emissions reduction by 2050 for the transport sector. Legally binding targets that exist, or are in development, are not considering the complete life cycle of long-haul road transport with its heavy-duty vehicles (HDV) but tend to be either Well-to-Tank (WtT) oriented or focus solely on a Tank-to-Wheel (TtW) perspective: The "Renewable Energy Directive" (RED) is a Well-to-Tank (WtT) approach, and the "CO_2 Emission Performance Standard" follows a Tank-to-Wheel (TtW) approach. This can obscure the real actual overall emissions reduction [20]. In this study a Well-to-Wheel (WtW) target for GHG emissions reduction until 2030 of 40% in relation to 2005 is applied. This is less ambitious than the overall European Green Deal target of 55% reduction in relation to 1990, but still very ambitious in relation to the trend of increasing emissions in long-haul road transport since 1990 (Table 4).

For each of the technologies (Table 6) and energy supply paths (Table 8), a theoretical so called "Exclusive Scenario", was developed consisting of a fleet with a share of renewable fuel trucks using one technology and new diesel trucks for the remaining share to comply with the GHG emission reduction targets. This combined fleet is not intended to be regarded as a realistic scenario but serves the academic purpose to make strengths and weaknesses of each technology visible in the results by assuming the extreme case of implementing only one renewable fuel technology option additional to a fleet based on state of the art new diesel vehicles for the year 2030.

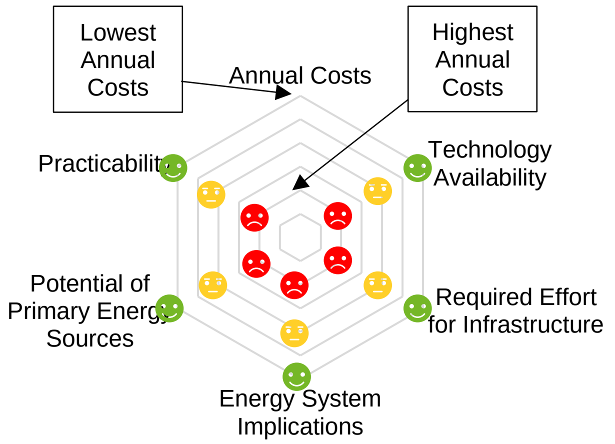
The results show that in all scenarios, at least 37% of the operating fleet needs to be renewable (Table 9), which means that a significant effort is required until 2030 to achieve the defined GHG emissions reduction. However, when using biomethane from manure combined with new diesel, only 15% of the fleet must be renewable assuming that the negative GHG emissions attributed to biomethane from manure used for that purpose are officially credited towards heavy-duty road transport.

In calculating the annual cost in section 4.4 and applying the qualitative assessment in five categories in section 4.5, we have quantified and discussed six different dimensions of each scenario; Annual Costs, Technology Availability, Required Effort for Infrastructure, Energy System Implications (Efficiency, Storability), Potential of Primary Energy Sources and Practicability. The exclusive scenarios show that there are clear strengths and weaknesses connected with all options. As "Battery Electric and new Diesel" and "Hydrogen and New Diesel" in general look competitive from a cost perspective, they have clear drawbacks in the other dimensions of the evaluation such as, Technology Availability, Required Effort for Infrastructure and Practicability. "Battery Electric and New Diesel" also have a drawback in Energy System Implications, where "Hydrogen and New Diesel" is rather regarded as an advantage in that is based on long term storable energy carrier. The overall lowest costs are connected to the exclusive scenario of "HVO and New Diesel", which also reaches high scores on every other evaluation criteria except for Potential of Primary Energy Source. However, if looking at the complete exclusive scenario, it also includes E-Fuels which can compensate for this drawback in the mid- and long term. This is also the case within the "Methane and New Diesel" scenario, where biomethane is a low-cost option that is complemented in the exclusive scenario with synthetic methane and vice versa.

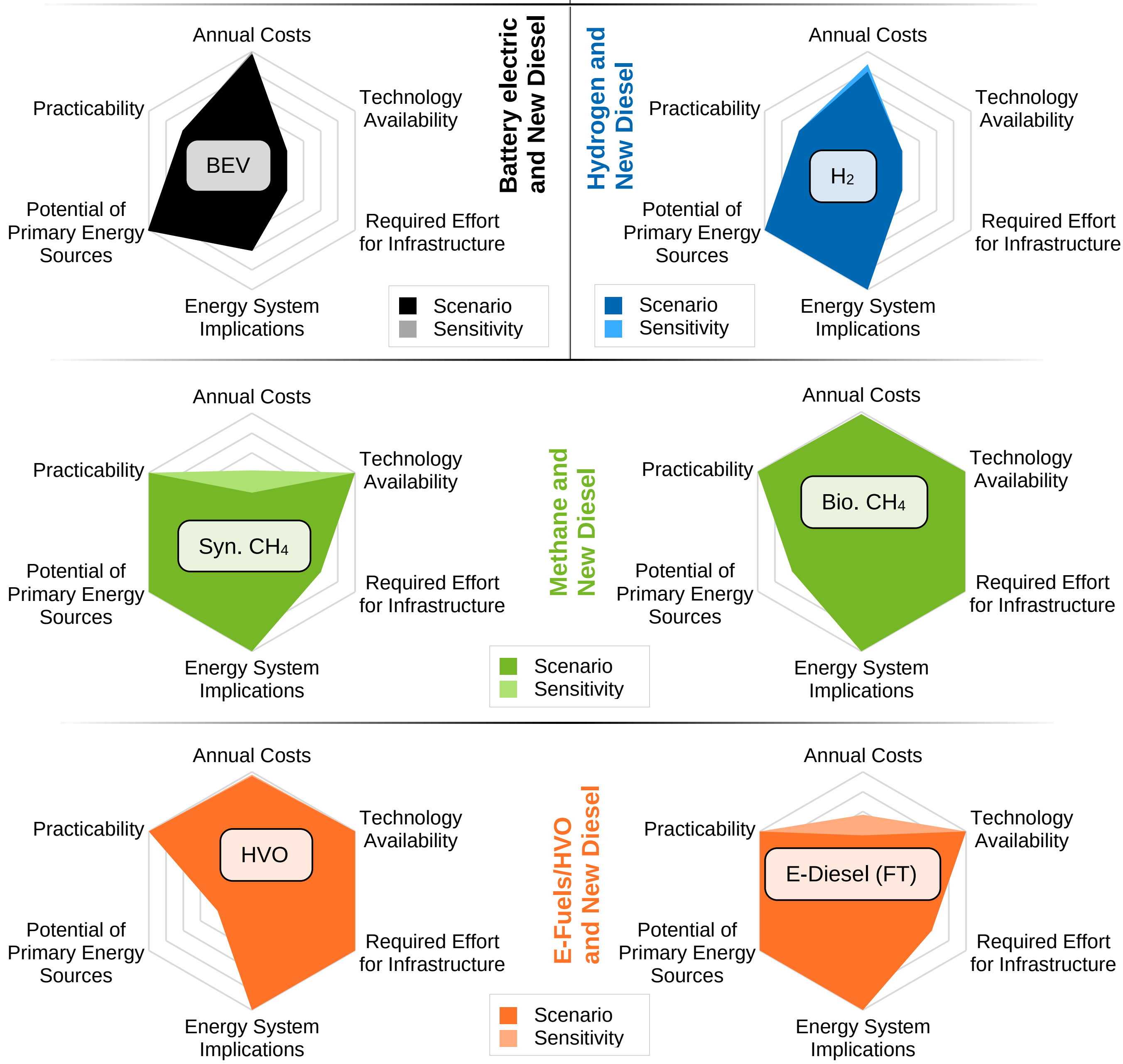
Simplifying and at the same time maintaining the main results was one of the largest efforts in this study. It is also noteworthy that already new diesel vehicles achieve substantial reduction of GHG emissions until 2030 if applied progressively, although not sufficient to meet the set target. Key recommendations are to have strict and fair regulations to allow all renewable technologies to contribute to the GHG targets:

- Give long-term safety for investments into vehicles and infrastructure in defining European rules quickly.
- Set strict rules such that the technologies can compete within fair boundaries. Technology-neutral regulations demanding the same strict goals on GHG emissions from all technologies. Strict rules must make green-washing impossible.
- When setting goals for GHG emissions, at least Well-to-Wheel (WtW) approaches should be followed if considering the entire life cycle (LCA) turns out not to be practically possible.

Figure 26: Spider Diagrams showing qualitative assessment from section 4.5 as well as annual costs from section 4.4 for the exclusive scenarios.



- Every «Exclusive scenario» represents an operating fleet in 2030 fulfilling the EU's goals for GHG emissions and which is composed of one renewable technology and new diesel.
- No Life Cycle Analysis: the emissions from the production of the vehicles are excluded from the GHG emissions targets.
- Annual Costs include costs for electricity, fuel production and transport, refuelling and fleet. Sensitivity: electricity costs reduced to 50%
- Details on qualitative criteria are given in section 4.5.



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Neste

NGVA Europe, Natural and bio Gas Vehicle Association

ÖVGW, Austrian Association for Gas and Water

SVGW, Association for Gas and Heat

Totalenergies

Uniti, Federal Association of Medium-sized Fuel Distributors

VDMA, Mechanical Engineering Industry Association

VSG, Association of the Swiss Natural Gas Industry

Contents

The exact definitions for terms and abbreviations in the context of this study are given in the Appendix on pages 86ff. To make reading of this study easier and at the same time allow relating to other publications, this report always uses the full terminology in the text and gives the abbreviation in parenthesis. Only for the term greenhouse gas in singular, the abbreviation GHG is used throughout and GHGs for the plural form.

1 Introduction

Europe is committed to reducing its emission of greenhouse gases (GHGs) in all sectors, including the long-haul road transport. The latter is an important pillar of the European economy, but it is mainly based on Diesel as energy source used in the internal combustion engines (ICE) of the trucks. The emissions of GHG during fuel production, supply to the fuelling stations and fuelling of the vehicles (Well-to-Tank, WtT) as well as the carbon dioxide CO_2 from the tailpipe (Tank-to-Wheel, TtW) contribute to the emissions of GHGs. In the coming years long-haul road transport must commit to reach Europe's planned reduction targets on a medium term (i.e., 2030) as well as on a long term.

New technologies, with the potential of making long-haul road transport renewable, are in the process of entering the market. They will be commercially available on a larger scale by 2030 and will therefore be available to reduce GHG emissions in 2030. According to the authors of this study, the following technologies are the most promising in terms of reaching market maturity by 2030 in the frame of long-haul road transport: battery electric vehicles (BEV), hydrogen fuel cell electric vehicles (H_2, FCEV) and vehicles with internal combustion engines (ICE) running on renewable methane (CH_4) and the two renewable liquid fuels E-Diesel and HVO (see Table 6). Among these options biomethane has already gained market shares as well as HVO to a smaller degree.

Only renewable energy to power trucks with these technologies was considered (Figure 8). The two low-carbon sources nuclear power and hydrogen from pyrolysis of natural gas were not considered.

The four selected vehicle technologies and their respective fuel supply chains for this study are very different, not only in term of conversion efficiency, but also in term of type of required infrastructure and convenience. Another important aspect of the comparison is related to the associated GHG emissions of each technology option, from the conversion of the primary energy source into energy carrier (i.e., electricity, hydrogen, methane, E-Fuels or HVO) to their subsequent transport and final use. Finally, this study aims at proving an unbiased comparison of the aforementioned technology options to defossilize the long-haul transport sector. To achieve this objective, a well-to-wheel analysis is performed, followed by a cost assessment and a qualitative analysis along five criteria.

1.1 Goals

This study aims at objectively assessing how different vehicle technologies can contribute in reducing the GHG emissions of the European long-haul road transport to reach the targets set by the European Union for 2030. More precisely, the study focusses on the following European countries:

- Germany (DE)
- Switzerland (CH)
- France (FR)
- Italy (IT)
- Poland (PL)

As already previously mentioned, this study considers the technologies that are the most likely to be commercially available on a large scale by 2030, that it can contribute significantly. In contrast to existing studies focusing on GHG emissions of one single generic vehicle[6], this study includes the entire fleet for long-haul road transport as well as the national potentials for supplying the chosen vehicle technologies with renewable energy. The study also shows synergies of the different technologies.

The authors of this study and the funding partners are convinced that objective arguments and analysis are important. They should serve as input for discussions on legal, regulatory and political measures required to reach the targets in reducing GHG emissions. This study and report are intended to be such input and are not intended to be a political statement.

[6] For example LCA: [1] Figure 5.96 page 120, Well-to-Wheel (WtW): [2].

1.2 Governance

As an important prerequisite to achieve the aims set in section 1.1, the authors have committed to the following guidelines:

- Technology neutrality: All technologies are assessed equally with the same methods and based on facts from the most recent version of literature and technical data available.
- Transparency on research partners (see Appendix A.5) and authors (see page 2) as well as funding partners (see acknowledgements page 5).
- Transparency on methods, sources and results.

1.3 Methodology

1.3.1 Proceedings

The objective of defossilizing the long-haul road transport by replacing the fossil-based fuel (i.e., diesel) with renewable energy carriers is very complex to tackle. From a technological point of view there are some new technologies that are about to enter the market, when some others are already used by early adopters in the transport sector today. Moreover, the conditions in long-haul road transport differ from region to region, and depending on the country of interest, the challenges faced may substantially differ. As a result, this might lead to different opportunities to transition towards renewable energies.

Therefore, given the high complexity of the system, in the framework of this study a series of assumptions have been made. However, these assumptions are performed such that the key findings and conclusions remain relevant and valuable. The simplifications also make the proceeding more transparent since it is easier to document and explain in comparison to more complex modelling approaches. Finally, this simplified approach allowed for the completion of the study with the available resources. The main modelling assumptions are listed in Table 1 and are discussed later in the report.

Table 1: Summary of model assumptions and simplifications explained in this section and later in the report.

Model Assumption		Description	Reference
1	Well-to-Wheel (WtW) approach	Only GHG emissions from the supply of the energy to the vehicle, production of the fuel and electricity (in the case of BEV) and the operation of the vehicle are considered. In a WtW approach, battery raw materials, production and recycling are not considered.	Section 1.3.2
2	Geographical Considerations	The five countries Germany (DE), Switzerland (CH), France (FR), Italy (IT) and Poland (PL) are considered.	Section 1.3.3
3	Long-haul Road Transport increases linearly until 2030.	The development of annual tonne-kilometre (tkm) is linearly extrapolated from data based on data from 2010 to 2021.	Section 3.2
4	Four renewable fuel technologies available in 2030 in scales large enough to achieve the emission reduction objectives.	Battery electric vehicles (BEV), hydrogen fuel cell electric vehicles (FCEV) and internal combustion engines (ICE) using renewable methane (CH_4, CNG, LNG), E-Fuels/HVO.	Section 3.3 Table 6
5	For each renewable fuel technology, only renewable energy is used in a total of 36 energy supply paths	Nuclear power and hydrogen from pyrolysis were not considered.	Section 4.1 Table 8
6	One goal	The emission reduction targets are shared equally through all EU member states	Section 2.1
7	Switzerland follows EU	Switzerland, as a country enclosed by EU members and bound to the same Paris agreement will adopt similar GHG reduction targets	
8	Costs for expansion of the necessary infrastructure (i.e., Power grid, gas grid) and for infrastructure for long-term energy storage is neglected	It is considered in the qualitative analysis in the criterion “Required Effort for Infrastructure 2030” section 4.5.2.	Section 4.1
9	Cost model from an economy point of view	No price model, no market effects	Section 4.4
10	Payload reduction through battery weight	Discussed in the qualitative criterion “Practicability”. Regulations allow two extra tons for trucks, if caused by renewable fuel drive train.	Section 4.5.5
11	Times for charging and refuelling	Discussed in the qualitative criterion “Practicability”.	Section 4.5.5
12	Lifetimes of equipment, infrastructure and vehicles	Assumed according to literature data, e.g., vehicle lifetime 8 years with one battery pack during its lifetime in case of battery-electric trucks (BEV).	Appendix A.4

After giving an overview of the aims, assumptions and proceedings in this first section, the report continues with section 2 and focuses on Europe's objectives of reducing GHG emissions until 2030 (section 2.1), Europe's potential for renewable energy sources (section 2.2) and Europe's plans for a future energy system (section 2.3).

Section 3 is dedicated to the current and future (i.e., 2030) situation of Europe's long-haul road transport. Its content is structured as follows: after a brief introduction on the definition of long-haul road transport in section 3.1, section 3.2 reports the historical data on the annual tonne-kilometres $\mathrm{tkm/a}$ driven and the associated GHG emissions; based on these data the situation in 2030 is extrapolated. Furthermore, Europe's targets to reduce GHG emissions are translated to goals for long-haul road transport. The choice of new vehicle technologies considered in this study is described in section 3.3: only technology that are assumed to be available on a large scale in 2030 are taken into consideration. These are battery electric vehicles (BEV), hydrogen fuel cell electric vehicles (FCEV) and trucks with internal combustion engines (ICE) operated with renewable methane (synthetic CH_4 and biological CH_4, stored in compressed form (CNG) and in liquefied form (LNG), as well as the two liquid fuels E-Diesel from a Fischer-Tropsch process (FT) and Hydrotreated Vegetable Oil (HVO) (Table 6). The last section of chapter 3 (Section 3.4) discusses existing and future infrastructure required to accommodate for the new technologies.

Europe's long-haul road transport in 2030 is described in section 4 starting by assigning the respective forms of energy carriers from renewable sources to these four types of vehicles (Table 8). Only the primary energy sources and conversion pathways that will most likely be available at large scale in 2030 are considered both in Europe as well as from regions outside Europe with large solar potential, i.e. the Middle East and North Africa (MENA). The quantitative analysis starts in section 4.2, where the GHG emissions of each technology and energy supply path at the state of the art expected for 2030 is estimated. This analysis is meant as a completion of the data present in the existing literature (i.e.,[2]). From these results "Exclusive Scenarios" for 2030 are developed in section 4.3. Every scenario is an operating fleet performing the predicted annual tonne-kilometres and consisting on the one hand of new diesel trucks, and on the other hand of exclusively one of the four renewable fuel technologies with one of the energy supply paths. The number of vehicles of each type is calculated such that the GHG emissions reduction targets are exactly fulfilled. For every exclusive scenario, a cost estimation is then performed in section 4.4. As already mentioned, this quantitative analysis is based on assumptions that summarized in Table 1, and is finally complemented with the qualitative assessment in using five criteria in section 4.5.

In section 5, the quantitative and the qualitative results are brought together and represented in spider diagrams. The results are analysed and discussed and synergies between the technologies are also shown. To conclude, section 6 includes some recommendations to the stakeholders.

1.3.2 Well-to-Wheel Approach

The authors have chosen a Well-to-Wheel (WtW) approach (model assumption 1, Table 1) and not a full life cycle analysis (LCA) to assess the environmental impact of the four new technologies even if they are well aware of the fact that this approach is limited. It neglects the GHG emissions associated with the production and disposal of the vehicle as well as with the required infrastructure. In fact, it only considers GHG emissions due to the production, the transport (Well-to-Tank, WtT) and the use of the fuels in a vehicle (Tank-to-Wheel, TtW). A tank-to-wheel approach, although often being used in legislation to calculate the emissions of a given vehicle, neglects the emissions associated with the fuel production and therefore leads to an incomplete assessment of the associated environmental impact.

On one hand, the simplification excludes emissions from infrastructure used by all four technologies, so it treats all technologies equally and does not influence the comparison between them. On the other hand, this simplification favours battery electric vehicles (BEV) over the other three technologies since battery production is known to be associated to a considerable environmental impact. The car manufacturing industry has recognised this problem and has declared to work on solutions on several fronts: battery research aiming at reducing energy use in the production process, providing renewable energy for battery production plants and battery recycle schemes. Life cycle analysis

(LCA) considering battery electric vehicles (BEV) and future developments show considerable improvements [3], [4] part of which will be realised in 2030, the year this study is focusing on.

Another reason for using the Well-to-Wheel approach is the fact that international regulations on reducing GHG emissions are based on the GHG emissions within national boundaries. While imports of renewable hydrocarbons can be accounted for [5], no considerations are known that GHG emissions from goods exported from one country and imported into another one are transferred between the two countries. A battery produced outside Europe, for example, does not have a negative impact on Europe's GHG inventory. Nevertheless, the authors hope, that some battery production will be in Europe in 2030 with emissions of GHGs reduced in comparison to the current state of the art. The modelling assumptions of this study are such that the remaining emissions are not considered.

1.3.3 Geographical Considerations

To capture geographical variations across Europe, the analysis is applied to the following five countries:

- Germany (DE)
- France (FR)
- Italy (IT)
- Poland (PL)
- Switzerland (CH)

Germany, France, Italy and Poland, chosen from the European Union EU-27, accounted for 52% of the EU-27's freight transport in 2021 when measured in tonne-kilometres [6].

Since Switzerland was included in the analysis, the term "Europe" is not restricted to the European Union (EU). However, since the Swiss regulatory framework in the transport sector is usually harmonized with the European one, the scenarios of this study are based on European policies and Swiss particularities like the higher availability of hydropower in comparison to the rest of Europe are taken into consideration in the analysis.

The European objective of reducing overall GHG emissions is discussed in section 2.1, where the corresponding reduction target for long-haul road transport is reported. This target is then equally applied to the truck fleets operating in 2030 in the five countries DE, CH, FR, IT and PL. These fleets all need to reach the same level of GHG emissions reduction in a well-to-wheel approach.

1.3.4 Annual Cost Estimations

For the economic evaluation of the considered "Exclusive Scenarios" introduced in section 1.3.1 and fulfilling EU GHG reduction targets (section 2.1), annual cost (C_{annual}) incurred for long-haul road transport were estimated from a macro-economic point of view without including market effects, taxes, penalties, subsidies and incentives. The cost which are associated directly to long-haul road transport were taken into consideration. The costs, which EU27 and Switzerland have to spend for the transition of the energy system (i.e. expansion costs for power grid and gas grid) were not considered in the annual cost calculations in this study due to the fact that they serve the entire economy and are impossible to allocate to long-haul road transport[7]. Only the infrastructure for the transportation of the fuels to the refuelling stations/charging stations are considered in the calculations. Moreover, it is important to mention that the costs in this study are the annual cost estimations for the year 2030. Overall system cost over a certain period of time was not considered. VDI (Verein Deutscher Ingenieure – Association of German Engineers) 6025 was used as basis for the annual cost estimations [7]. Opportunity costs such as waiting times for charging are not considered in the annual costs but in the qualitative criteria "Practicability" in section 4.5.5.

Excluding taxes, penalties, subsidies and incentives means that the estimation of annual costs is not affected by political decisions. Table 2 gives an overview of the parameters included in the costs and their effects on the cost estimations.

[7] These expansion costs are discussed in the qualitative criteria "Required Effort for Infrastructure 2030" in section 4.5.2.

Table 2: Summary of components considered in the estimation of the annual costs.

Parameter	**Included ☑ Excluded ☒**	**Effect on annual cost**
1. Electricity cost, fuel production cost (C_P)	☑	significant
2. Transportation cost (C_T) of the energy carriers to the charging points and respective refuelling stations	☑	significant
3. Electricity prices, fuel prices	☒	significant
4. Market effects	☒	significant
5. Subsidies, penalties, and CO_2 costs	☒	significant
6. Refuelling cost (C_R) (Fast chargers, H_2 refuelling stations, CH_4 refuelling stations)	☑	less significant
7. Expansion of the infrastructure (i.e. power grid, gas grid)	☒	less significant
8. Fleet cost (C_F) (fleet consisting of one renewable fuel technology and the latest diesel trucks)	☑	moderate
9. Remaining $OPEX$, taxes, tolls, subsidies for long-haul trucks	☒	less significant

The calculation of the cost components as listed in Table 2, the annual cost (C_{annual}) include i) fuel production costs (C_P), ii) transportation costs (C_T) iii) refuelling costs (C_R) and iv) fleet costs (C_F) (see Equation 1.1). Selling price and market effects are not included nor are any regulatory taxes, penalties, subsidies or incentives.

$$C_{annual} = C_P + C_T + C_R + C_F \qquad \text{Equation 1.1}$$

C_{annual}	Annual cost
C_P	Fuel production costs
C_T	Transportation costs
C_R	Refuelling costs
C_F	Fleet costs

i) Fuel Production Costs (C_P)

These are the costs related to the fuel production process and power generation for each exclusive scenario and take into account different fuel and/or electricity supply routes. An overview of these pathways is shown in section 4.1.

The electricity costs for every scenario are calculated by using Equation 1.2. In total, four different electricity supply routes are considered: photovoltaic (PV) located in Middle East and Northern Africa (PV-MENA) and Europe (PV-EU) as well as wind turbines located on- and offshore in Europe.

$$\frac{AF \cdot CAPEX_i + OPEX_i}{Cap_i \cdot Full\ load\ hours_i} \qquad \text{Equation 1.2}$$

AF	Annuity Factor
Cap	Capacity of the component
i	Components in the fuel chain

Fuel synthesis plants usually include different production steps. A synthetic methane production plant, for example, consists of an electrolyser (including water treatment), a CO_2 supply (e.g., direct air capture) and a methanation unit. The cost for each component of the process chain is calculated using Equation 1.3.

$$\frac{AF \cdot CAPEX_i \ + \ OPEX_i}{Cap_i}$$ *Equation 1.3*

AF	Annuity Factor
Cap	Capacity of the component
i	Components in the fuel chain

Depending on the plant location, different electricity and CO_2 supply options were considered (see section 4.1 and Table 8 for more details). In case of methane from biogenic origin, production costs are based on literature data [8].

ii) Transportation Costs (C_T)

These include all costs associated with the transport of electricity or fuel to the respective refuelling stations. For example, in the “Battery Electric and New Diesel” scenario, transportation cost consists of the cost for transmission lines and converter (Equation 1.3). The distance for transport of electricity is assumed to be 500 km for onshore power generation and $1{,}000$ km for offshore power generation in each electricity supply route (Appendix A.4 lines 217, 218. For hydrogen in the “Hydrogen and New Diesel” scenario, pipeline transport over a distance of $3{,}000$ km for H_2 production in MENA and 500 km for H_2 production in EU is assumed (Appendix A.4 lines 316, 317). For the transport of methane in the “Methane and New Diesel” scenario, gaseous transport via pipeline (Equation 1.4) with downstream liquefaction for the LNG case is considered. The transport distance for CH_4 by pipeline is assumed to be 3000 km for methanation in MENA and 500 km for methanation in the EU (Appendix A.4 lines 431, 432). The approach to calculate the cost for pipeline transport is shown in Equation 1.4. In the case of LNG, a representative distance between the liquefaction facility and the refuelling station of 200 km covered by truck at a rate of 0.96 €/km is assumed [9] (Appendix A.4 lines 438, 439).

$$C_{T,Pip} = \frac{s}{Cap_{Pip}}\left(\frac{CAPEX_{Comp} \ \cdot \ AF + OPEX_{Comp}}{\Delta s_{Comp}} + CAPEX_{spec,Pip} \ \cdot AF + OPEX_{spec,Pip}\right)$$ *Equation 1.4*

AF	Annuity Factor
$C_{T,Pip}$	Transportation cost of pipeline
Cap_{Pip}	Pipeline capacity
Δs	Distance between compressor stations
s	Total distance of the pipeline
$CAPEX_{Comp}$	$CAPEX$ of Compressor
$OPEX_{Comp}$	$OPEX$ of Compressor
$CAPEX_{spec,Pip}$	Specific $CAPEX$ of pipeline
$OPEX_{spec,Pip}$	Specific $OPEX$ of pipeline

E-Fuel/HVO are assumed to be transported via ship and truck over $2{,}500$ km and 200 km respectively (Appendix A.4 lines 527, 518). The fuel imported by the MENA region is assumed to be transported by ship only. Equation 1.5 and Equation 1.6 show how these transport costs of liquid fuels are determined.

$$C_{T,Ship} = \sum_i \frac{AF\ CAPEX_i + OPEX_i}{Cap_i} + \frac{AF \cdot CAPEX_{Ship} + OPEX_{fix,Ship} + \frac{a}{\frac{2 \cdot s}{v} + t_L} 2 \cdot s \cdot FCo_{Ship}}{\frac{a}{\frac{2 \cdot s}{v} + t_L} \cdot \left(Cap_{Ship} - 2 \cdot BO\right) \cdot t_{av,Ship}}$$

Equation 1.5

AF	Annuity factor
$C_{T,Ship}$	Transportation cost of ship
Cap_i	Capacity of the components
Cap_{Ship}	Capacity of the ship
$CAPEX_{Ship}$	CAPEX of the ship
$OPEX_{fix,Ship}$	Fixed OPEX of the ship
i	Components in the fuel chain
a	Number of days in a year
s	Transportation distance
v	Velocity of the ship
BO	Boil-off rate
t_L	Loading and unloading time of ship
$T_{av,Ship}$	Availability of the ship
FCo_{Ship}	Fuel consumption of ship

$$C_{T,Truck} = \sum_i \frac{AF \cdot CAPEX_i \cdot OPEX_i}{Cap_i} + \frac{AF \cdot CAPEX_{Truck} + OPEX_{fix,Truck} + \frac{a}{\frac{2 \cdot s}{v} + t_L} \cdot 2 \cdot s \cdot FCo_{Truck}}{\frac{a}{\frac{2 \cdot s}{v} + t_L} \cdot (Cap_{Truck} - 2 \cdot BO) \cdot t_{av,Truck}}$$

Equation 1.6

AF	Annuity factor
$C_{T,Truck}$	Transportation cost of truck
Cap_i	Capacity of the components
Cap_{Truck}	Capacity of the truck
i	Components in the fuel chain
a	Number of days in a year
s	Transportation distance
v	Velocity of the truck
BO	Boil-off rate
t_L	Loading and unloading time of truck
$T_{av,Truck}$	Availability of the truck
FCo_{Truck}	Fuel consumption of truck

iii) Refuelling Costs (C_R)

These include only the cost for fast chargers for battery electric (BEV) trucks and refuelling stations for the other technologies. In the case of CH_4, since there already exist a certain number of CNG and LNG refuelling stations, only the costs of additional stations in EU27+CH required by 2030 is considered. For the liquid fuel supply (E-fuels, conventional diesel and HVO), it is assumed that the amount of current refuelling stations is sufficient; therefore, no additional refuelling station cost are considered. The additional investment that might be required to expand the infrastructure (i.e. power grid, gas grid) was not included in this analysis.

iv) Fleet Costs (C_F)

These include the cost for the new technology diesel trucks and for the trucks with alternative drivetrains using renewable electricity. For each scenario and each fuel or electricity supply route (see section 4.1), the share of renewable fuel trucks is calculated by using the results of the well-to-wheel analysis (section 4.2), the total mileage of the trucks (section 3.2) and the EU-27 GHG emission targets (section 2.1). After determining the minimum and maximum share of renewable fuel trucks in the fleet for each scenario (see section 4.3), the fleet cost is calculated by adding up the truck CAPEX. It is important to note that OPEX, taxes or subsidies are excluded from the calculations.

2 European Emissions Reduction Framework and Renewable Energy Potential

2.1 European Plans to Reduce GHG Emissions

In 2015, the “Paris Agreement” was signed by 197 countries. All together, they committed to substantially reduce global Greenhouse gas (GHG) emissions to limit the global temperature increase in this century to 2 °C while pursuing means to limit the increase even further, to 1.5 °C [10]. The European Commission presented “Clean Planet for All” at the end of 2018 [11]. It was the foundation for the “European Green Deal” [12]. Later, each member state was requested to submit their respective national long-term strategy on how to meet their commitments under the Paris Agreement and EU objectives. To reach the targets of the Paris Agreement in the European Union, it was decided, in 2020, to increase the GHG emission reduction targets to 55 % compared with 1990. The new “European Green Deal” set the new 55 % goal as well as carbon neutrality in 2050, and both these targets were then set in the “European Climate Law”, adopted in June 2021. [12,13]

Even if there are no binding sector specific reduction targets, the “European Green Deal” states an ambition of 90% GHG emissions reduction by 2050 for the transport sector. The “Sustainable and Smart Mobility Strategy” [14] sets out a roadmap and identifies policy levers to deliver the 90 % emission reduction. This goal and the ones discussed later in this section are summarised in Table 3.

In December 2020 the EU published the “Sustainable and Smart Mobility Strategy” [14]. It sets out the actions with the ambition to reduce GHG emissions in transport by 90% until 2050 relative to 1990 levels. The strategy suggests a paradigm shift in the approach to decarbonise the mobility sector from incremental to fundamental transformation. It contains 10 flagship areas and an action plan, where road transport has an important role. More details on the flagship areas are given in Appendix A.3 paragraph 1.

In July 2021 “Delivering the European Green Deal” was published, which is also known as the “Fit for 55” package, where 55 refers to the target to reduce GHG emissions by 55% until 2030 relative to 1990 levels. Overall, the package strengthens eight existing pieces of legislation and presents five new initiatives, across a range of policy areas and economic sectors: climate, energy and fuels, transport, buildings, land use and forestry. Eleven pieces of legislation are related to transport. Five are of special significance to impact GHG emissions in heavy-duty long-haul road transport. [15]

In the current “Effort Sharing Legislation” it is defined that 30% GHG emissions reduction with respect to 2005 by 2030 should be reached. “Fit for 55” proposes to increase this target to 40% [16]. This legislation applies for all sectors not regulated in the “European Union Emission Trading System” (EU ETS) nor by regulations on “Land Use, Land Use Change or Forestry” (LULUCF). By today’s situation, this would therefore include the transport sector and thus also apply to long-haul heavy-duty road transport. Only the overall reduction of GHG emissions is regulated. It is not defined, how much each sector contributes and it does not specify that all sectors need to reach equal reductions in GHG emissions.

However, it is also suggested [17] to introduce an “European Union Emissions Trading System” (EU ETS) also for fuel suppliers in one sector called “Road Transport and Buildings”. If this suggestion is implemented the “Effort Sharing Legislation” would no longer be applicable for long-haul road transport and a target is implemented to reduce GHG emission by 43% until 2030 in relation to 2005. It is also suggested to increase the ambitions in the “Energy Efficiency Directive”: instead of reducing final energy consumption by 32.5% in 2030, it should be reduced by 36% by 2030 and primary energy consumption should be reduced by 39% in the same time. [17]

In regard to the revision of the “Renewable Energy Directive” (RED), an overall target share of at least 40%, rather than 32%, of energy from renewable sources in the European Community’s gross final consumption of energy is set. Thereby it is also suggested to replace the 14% target for renewable energy in transport in the current “Renewable Energy Directive II” (RED II) with a 13% GHG emission intensity reduction target in 2030, compared with a liquid fossil fuel baseline GHG emission intensity. [18]

Furthermore, the “Fit for 55” package also proposes a revision of the CO_2 emissions performance standards for heavy-duty vehicles (HDV). It regulates the theoretical GHG emissions potential of the fleet produced by any manufacturer of heavy-duty vehicles (HDV) in a Tank-to-Wheel approach. From 2025 on, manufacturers will have to meet the targets set for the fleet-wide average CO_2 emissions of their new lorries registered in a given calendar year. The targets are expressed as a percentage reduction of emissions compared to EU average in the reference period (July 2019 to June 2020). From 2025 onwards it is a 15% reduction and it increases to 30% from 2030. [19]

More proposals and intended packages consulted for this study without any influence on the targets for GHG emissions used in the subsequent study are discussed in Appendix A.3 paragraph 2. The discussion includes the “Alternative Fuels Infrastructure Regulation” (AFIR), which is also referred to in section 3.4.

To model the exclusive scenarios in this study, a Well-to-Wheel (WtW) target value for the reduction of GHG emissions for the year 2030 is needed, specifically for heavy-duty long-haul road transport. In the review of current regulations and ambitions as presented above, the challenges faced with the overall reduction targets are overarching for multiple sectors or only defined for the transport sector, which in itself needs to be subdivided into several modes of transport and types. Furthermore, some ambitions are defined for the longer perspective of 2050 and not specified further for the year 2030. This means, that although the overall reduction should reach a certain value in 2030, it does not mean that all sectors and modes of transport need to contribute equally to reach that goal. In the same manner, the speed of progress to reach a set target for 2050 could vary. In order not to exceed the total budget of GHG emissions allowed and to stay within the targeted global temperature increase, a faster reduction of the emissions rate is important while still formally complying with the set goal for annual GHG emissions in 2030. A final challenge for stating reduction targets for GHG emissions for long-haul road transport is that the ambitions stated in the “European Green Deal” are not legally binding targets for each member state individually, just an obligation of EU as a whole. Legally binding targets that exist, or are in development, are not considering the complete life cycle of long-haul road transport heavy-duty vehicles (HDV) but tend to be either Well-to-Tank oriented or focus solely on a Tank-to-Wheel (TtW) perspective: The “Renewable Energy Directive” (RED) is a Well-to-Tank (WtT) approach, and the “CO_2 Emission Performance Standard” follows a Tank-to-Wheel (TtW) approach. This can obscure the real actual overall emissions reduction [20]. Furthermore, a recent compilation and evaluation of data by the European Environmental Agency indicates that current legislation is far from sufficient to reach the ambition to reduce GHG emissions by 90% in 2050, even with additional measures current in planning [21].

Table 3: Overview of the stated European ambitions, national legally binding regulations and additional aspects impacting heavy-duty long-haul road transport, stating what target value (GHG emissions, if not stated otherwise) should be reached in which year and which year or other reference that relates to. (New suggestions for both "Renewable Energy Directive" and "CO2 Performance Standard for heavy-duty vehicles" were published in March and February 2023 after concluding this chapter and most of the study. Updated values are included in the last section of this chapter 2.1)*

	2025	2030	2050	Relation
Overall EU Ambition				
– "European Green Deal" in general [12,13]		-55%	-100%	1990
– "European Green Deal" [12,13], specification for the transport sector set out in the "Sustainable and Smart Mobility Strategy" [14]			-90%	1990
Legally Binding Targets				
– "Effort Sharing Legislation" (Fit for 55) [16]		-40%		2005
– "European Union Emissions Trading System" (EU ETS) applied to new sectors: [17] (Fit for 55) – Sector "Power and Industry" – Sector "Road Transport and Buildings"		 -62% -43%		2005
– Well-to-Tank: "Renewable Energy Directive" (RED) (Fit for 55) [18]		-13%*		Baseline with Diesel
– Tank-to-Wheel: "CO_2 Emission Performance Standard for heavy-duty vehicles" (HDV) [19]	-15%	-30%*	*	2019/ 2020
Additional Aspect				
- "Energy Efficiency Directive" (Fit for 55) [17] - Final Energy Consumption - Primary Energy Consumption		13% 8,723TWh 11,400TWh		2020 Reference Scenario

Switzerland is not member of the EU and has set itself and compared to EU goals similar overall goals with a reduction of 50% of its GHG emissions by 2030 and carbon neutrality by 2050. But unlike the EU, Switzerland has not yet translated these targets into a law and the CO_2 act proposition was rejected by a referendum in 2021.

The current situation regarding heavy-duty transport, GHG emissions and reduction goals are similar in the EU and in Switzerland. For this report, it is assumed that the European goals are also valid for Switzerland. In addition, since Switzerland does not have any important heavy vehicle manufacturer and needs to import new vehicles from abroad, mainly from the EU, it is subject to EU standards.

Sometimes, Switzerland is open for creative solutions: Gas suppliers guarantee at least 20% biomethane for fuelling light vehicles up to 3.5 t, which is considered in the fleet emissions calculations of CNG-Vehicles [97]. This rule is planned to be applied for trucks soon. Sometimes, Switzerland has difficulties to find pragmatic solutions: It is still not possible to have imported renewable methane recognised as renewable fuel. And sometimes Switzerland is stricter than the EU: Only fuel produced from bio waste is recognised as renewable. Fuel from agricultural products is treaded and taxed as fossil fuel.

France submitted a national low-carbon strategy published in March 2020 [22]. It has the overall objective to make France carbon neutral by 2050. The strategy states a 28% GHG emissions reduction target by 2030 in relation to 2015 for the transport sector.

Germany published their "Climate Action Plan 2050" in 2016 [23]. It sets out to achieve 80% to 95% reduction of GHG emissions by 2050 and 55% reduction until 2030 compared to 1990. The transport sector represents about 30% of final energy consumption and about 18% share of Germany´s total GHG emissions. The action plan defines that GHG emissions from mobility have to be cut to 95 to 98 $MtCO_{2eq}/a$ by 2030. This would correlate to a 42% to 40% reduction in relation to 1990 GHG emissions from mobility.

Italy submitted the Italian long-term strategy on reducing GHG emissions that was published in 2021 [24]. It states the overall goal of reaching climate neutrality in 2050 and this is translated into a specific GHG emissions reduction target for 2050 of 84% to 87% compared to 1990. There are no intermediate targets or milestones mentioned for 2030, but the strategy is accompanied by modelling projections. Up to 2030 the strategy refers to the "National Integrated Energy and Climate Plan" (NECP) and for 2031 to 2050 the NECP is extended as a "Reference Scenario" and adds a "Decarbonisation Scenario" in order to achieve net-zero emissions. Regarding transport, the "Reference Scenario" reaches nearly 60 $MtCO_{2eq}/a$ by 2050, which would translate into about 40% GHG emissions reduction in relation to 1990 and about 46% in relation to 2005. In the Decarbonisation Scenario no GHG emissions are emitted from the transport sector in 2050. Although no intermediate goals are explicitly mentioned, the NECP indicates around 75 $MtCO_{2eq}/a$ in the transport sector by 2030. Which would correlate to 27% emissions reduction in relation to 1990 and about 42% in relation to 2005.

Poland state their contribution to the realisation of the European Green Deal in their "Energy Policy of Poland" until 2040" [25] published in 2021 by the "Ministry of Climate and Environment". It sets out to implement a low-emission energy transition and initiate a broader modernisation across the economy, while guaranteeing energy security, ensuring fair distribution of costs and protecting the most vulnerable social groups. One key element is the reduction of GHG emissions of about 30% compared to 1990 by 2030.There are no emissions reduction specifications for the transport sector.

Based on this research, this study suggests setting the Well-to-Wheel target for GHG emissions reduction until 2030 to be 40% in relation to 2005 for the purpose of calculating the exclusive scenarios in chapter 4. This can be backed both with the current regulation in the Effort Sharing Legislation (40%) and is also in line with the announced level of a future "European Union Emissions Trading System" (EU ETS) for the transport sector (43%). Applying this to the long-haul heavy-duty transport sector, is more ambitious than current trends, where actual emissions reduction is projected to be within the emissions from cars. It should be mentioned that it is still far from the ambition expressed in the "European Green Deal" of 55% GHG emission reduction until 2030 due to both the difference in percentage value and the difference in referenced year (1990 vs. 2005). This must be kept in mind when evaluating the results regarding progress toward reaching the overall stated ambition of 90% GHG emissions reduction in the transport sector for 2050, which is also referencing 1990 and not 2005.

The context to actual GHG emissions reduction in mobility in general and for long-haul heavy-duty road transport in specific is analysed in section 3.2 and summarized in Table 4 and Table 5.

Since concluding this chapter in 2022, some central regulations have been modified. In February 2023 the EU commission made a new proposal for the CO_2-fleet regulation for heavy-duty vehicles. Instead of reducing fleet emissions by 30% in 2030 in relation to 2019/2020, the new limit is set to a reduction of 45%. This limit is suggested to be lowered substantially in 2035 to meet minus 65% and reach minus 90% already in 2040. It is not suggested to change the scope of the regulation to get closer to a life cycle analysis (LCA) or at least Well-to-Wheel (WtW) approach and thus the regulation remains a pure Tank-to-Wheel (TtW) regulation. [26]

Similar, the suggestion for a new "Renewable Energy Directive" (RED) as presented in "Fit for 55" was amended in trilogue negotiations of the European Parliament, the European Commission and the European Council in March 2023. The target is to have 42.5% of overall energy consumption covered by renewable energy in 2030 with an indicative additional 2.5% allowing for a 45% share goal. In regard to transport, member states can either adopt a 14.5% GHG emissions reduction target through deployment of renewables by 2030 or a share of at least 29% renewable energy in final energy consumption. Sub-targets include that 5.5% of the renewable energy supply to the transport sector should be covered by advanced biofuels and renewable fuels of non-biological origin. There is no amendment to the regulation regarding its scope. It remains a Well-to-Tank (WtW) regulation, although much more technology open and clear in regard to real GHG emissions reductions to be achieved than the “CO_2 performance standard for heavy duty vehicles”. [27]

2.2 Europe’s Renewable Energy Sources (RES)

The public dataset “Energy System Potential for Renewable Energy Sources” (ENSPRESO) [28] contains renewable energy potentials in EU-28 from 2010 until 2050 on national and regional levels. The data is available via the European Commission´s ”Joint Research Centre” (JRC) and covers the renewable potentials from biomass, solar power (both photovoltaic and concentrated solar power plants) as well as wind (onshore and offshore). The dataset had its last update in 2019 and are used in this study as a point of reference for the qualitative assessment in section 4.5 in the criterion “Potential of Primary Energy Sources” in subsection 4.5.4. The real potentials for renewable primary energy, which – most importantly – have to be economically meaningful, is hard to estimate and subject to much debate and research. The objective of this study is not to provide a precise estimation and projections of future build-ups of renewable energy production but rather to establish the orders of magnitude and the potential reach of each renewable source for our exclusive scenarios in section 4.3. The data set is often strictly concentrated on the economic zones of EU-28, resulting in renewable potentials from neighbouring countries not being included. The most distinct gap appears in the offshore wind potential in the North Sea region, when not accounting for the Norwegian potential because Norway is not part of the EU. But it poses an even larger drawback for renewable fuels (H_2, CH_4, E-Diesel and HVO in this study), that can be imported partly by already existing means of energy transport and where the primary energy source is not covered by the database.

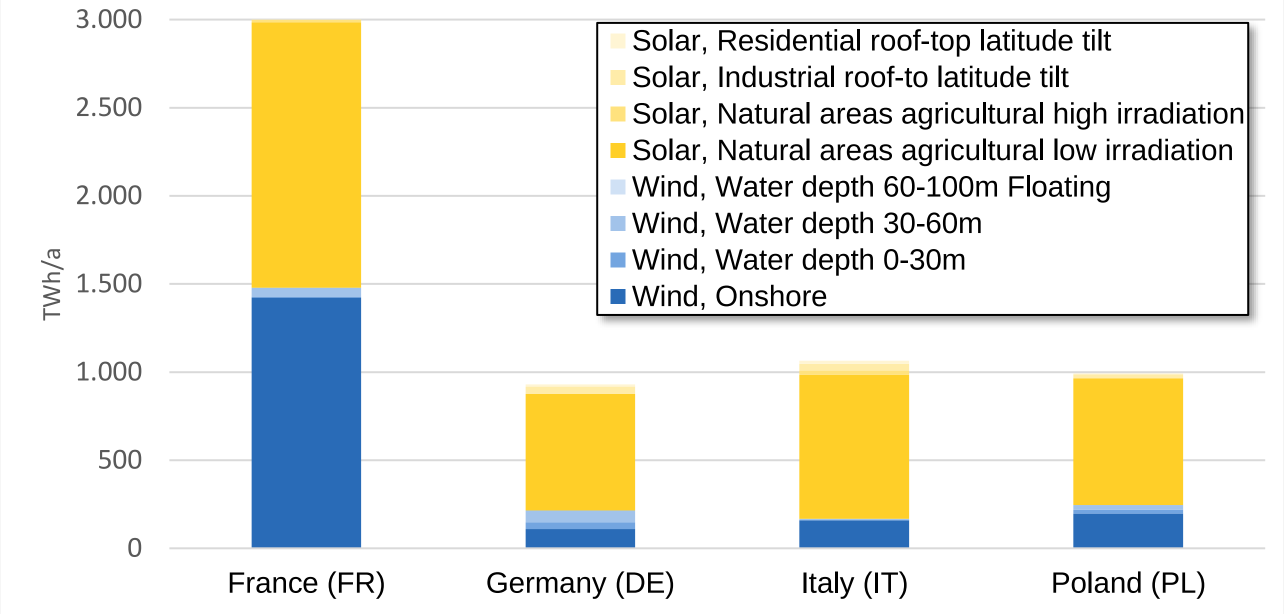
Electricity Potentials from Wind and Solar

Accounting for EU-28, ENSPRESO estimates a $5.7\,\mathrm{PWh/a}$ to $14.1\,\mathrm{PWh/a}$ onshore and $26.5\ \mathrm{PWh/a}$ total offshore potential for electric energy from wind amounting to $32.2\,\mathrm{PWh/a}$ to $40.6\ \mathrm{PWh/a}$ total wind energy potential in EU-28. Other sources, referenced in ENSPRESO, estimate the total wind potential considerably higher for onshore wind to $28\,\mathrm{PWh/a}$ to $34\ \mathrm{PWh/a}$ and offshore wind to $13\,\mathrm{PWh/a}$ to $40\ \mathrm{PWh/a}$, in total $41\,\mathrm{PWh/a}$ to $74\ \mathrm{PWh/a}$ for wind energy in EU-28.

Similarly, the potential estimations for solar power production also vary considerably depending on the restricting assumptions. When considering 3% of the available “non-artificial” areas and assuming a solar electricity production of $170\,\mathrm{MW/km^2}$, it is estimated that $10.7\ \mathrm{PWh/a}$ electric energy can be produced. Industrial and residential roof-tops together with concentrated solar power accounts for $1.4\ \mathrm{PWh/a}$ electric energy in this scenario ($0.38\,\mathrm{PWh/a}$ industrial, $0.29\,\mathrm{PWh/a}$ residential and $0.78\,\mathrm{PWh/a}$ concentrated solar power respectively).

Four of the focus countries of this study; Germany (DE), France (FR), Italy (IT) and Poland (PL) are covered in ENSPRESO and the evaluation for these countries is illustrated in Figure 1. For wind this study considers the scenario “Reference-Large Turbines” but only locations with a capacity factor potential above 25%. The solar potential is based on the assumption of $170\,\mathrm{MW/km^2}$ on 3% of the available non-artificial areas. Furthermore, only electric energy potential from latitude tilt roof-tops and agricultural areas are shown in Figure 1. The four countries clearly have a higher potential in solar energy than in wind energy. Only France has an almost 50/50 ratio between the two types. In wind energy, the largest potential is onshore wind, except in Germany, where there is also an almost equal potential offshore. Within the solar energy potential, agricultural areas with low irradiation are by far the dominating source for total potential.

Figure 1: Wind and solar electric energy potentials per year in the focus countries of France (FR), Germany (DE), Italy (IT) and Poland (PL) according to ENSPRESO. Wind potentials according to the scenario "Reference Large Turbines" and only locations with capacity factor above 25%. Solar potentials based on $170\,\mathrm{MW/km^2}$ and 3% of the available non-artificial areas assumptions and only accounting for latitude tilt roof-tops and agricultural areas. [28]



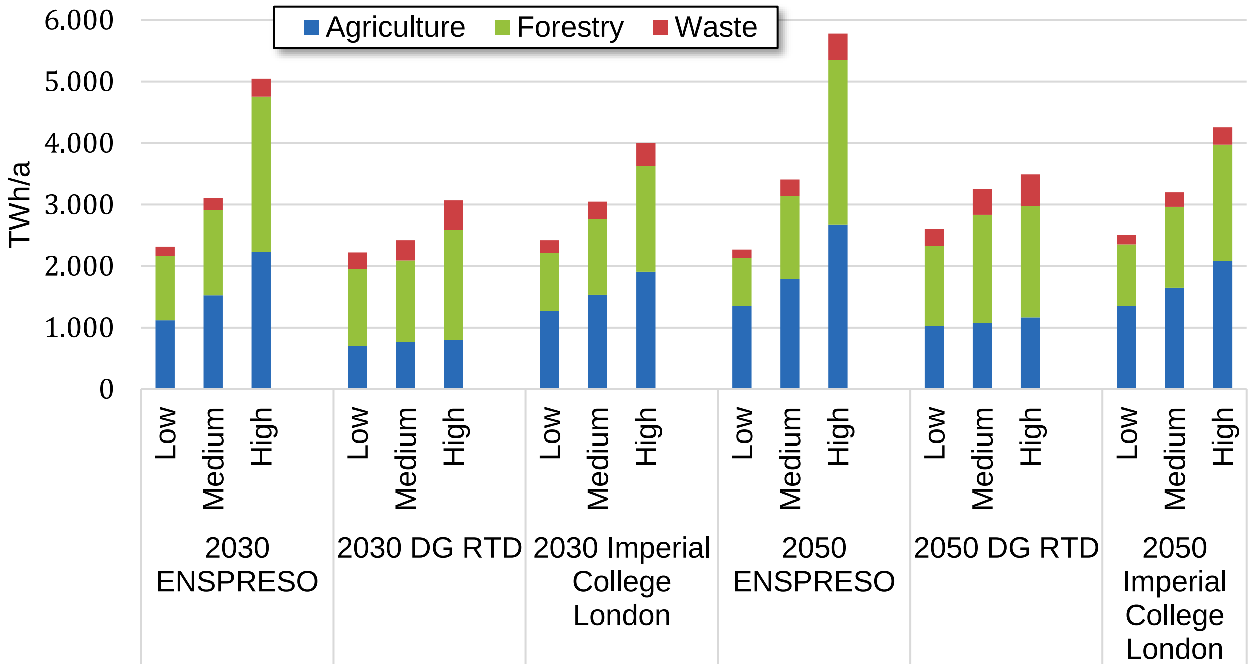
Comparing the European potentials as discussed ($44.3\,\mathrm{PWh/a}$ to $52.7\,\mathrm{PWh/a}$ for wind and solar according to ENSPRESO) with EU-27´s total energy consumption on the one hand of $10.9\,\mathrm{PWh/a}$ [29] and with the total net energy import plus total energy production on the other hand of $17.8\,\mathrm{PWh/a}$ [29], leads to the conclusion, that the primary energy potential is not the limiting factor. This applies regardless of whether the potentials need to cover the direct use of electricity by battery-electric trucks (BEV) or the indirect use in the form of hydrogen (H_2), synthetic methane (Syn. CH_4) or as E-Diesel. The true restrictive factors are rather, time for implementation, technical, financial and systemic issues that need to be considered in relation to social and environmental acceptance.

Energy Potential from Biomass

The overall total potential for renewable gas and fuels from biological origin is much more diverse than for renewable electricity from wind and sun. This is because there is a whole range of different types of feedstock sources, conversion techniques and corresponding energy yields. This study focuses on three main sources, leading to potentials for an Europewide overview according to member state and feedstock. For every individual type of feedstock within the three major categories "Agricultural", "Forestry" and "Waste", three different scenarios are defined: high, medium, and low potential according to limitations in feedstock and land. The potentials are estimated for the years 2030 and 2050. An overview is given in Figure 2.

- ENSPRESO [28] used above for the wind and solar potentials and offers an Europewide overview broken down by member states of EU-28 and different feedstocks.
- A comparable review was published by the "European Commission Directorate-General for Research and Innovation" (DG RTD) in 2017 [30].
- "Conservation of Clean Air and Water in Europe" (CONCAWE), an organisation whose members are oil and gas companies, have recently published an review and outlook on the availability and demand for low-carbon feedstocks, based on an independent analysis of Imperial College London [31].

Figure 2: Comparing the projection of biomass potentials between ENSPRESO [28], DG RTD [30] and Imperial College London [31] for high, low and medium availability scenarios in 2030 and 2050.

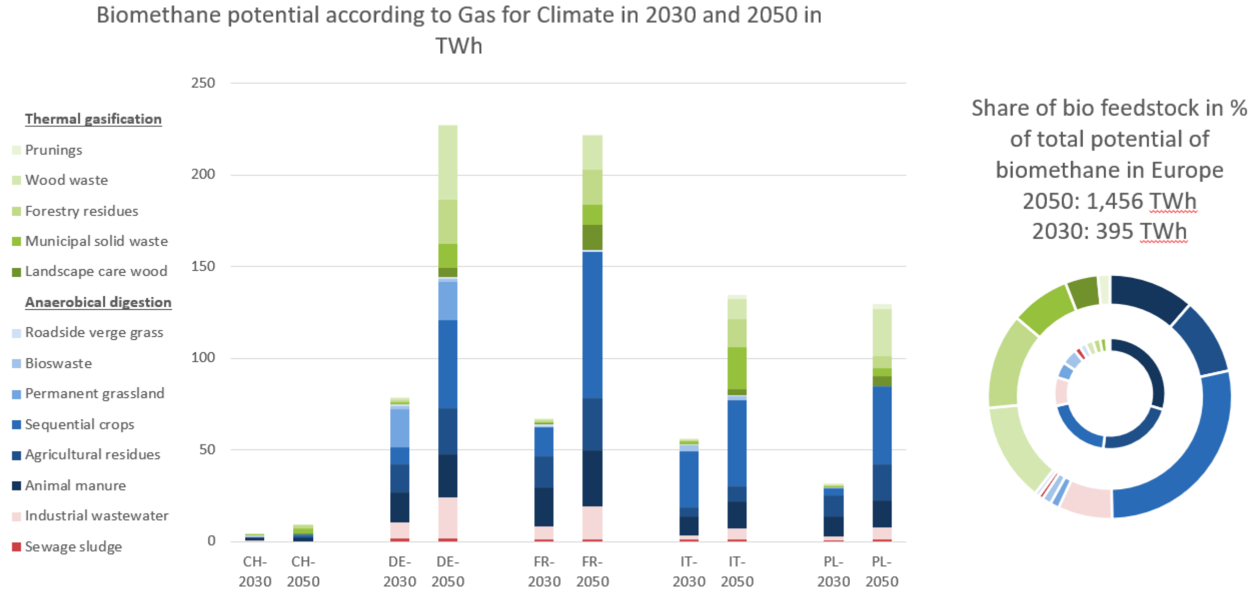


The study of the Imperial College London [31] estimates a potential for biomethane between 15 TWh/a and 18 TWh/a in 2030 and 17 TWh/a and 20 TWh/a in 2050. For Ethanol the same study [31] gives ranges of 308 TWh/a to 487 TWh/a in 2030 and 75 TWh/a to 228 TWh/a in 2050. This potential is lower than in other studies since it is assumed that a large part of agricultural residues (straw-like) is going into a value chain, which by then is more lucrative. It is the Fischer-Tropsch (FT) with catalytic synthesis, which is estimated to have a potential of 532 TWh/a to 943 TWh/a in 2030 and 1,670 TWh/a to 2,616 TWh/a in 2050.

Not included in this are bio-feedstock potentials form algae. It is the most cost intensive bio-feedstock at the moment and is not considered in ENSPRESO [28]. However, DG RTD [30] evaluates this category of biomass and although the current potential is negligible, it has the potential to become the second largest feedstock sector by 2050. The production costs is the limiting factor and in their maximum availability scenario they consider 41 Mt/a dry matter in 2030 and 367 Mt/a in 2050, thereby matching the largest source of bio feedstock forestry which is in a similar range.

Guidehouse and Gas for Climate have recently made study for biomethane production potential in the EU [32] focussing on two pathways for biomethane production: anaerobic digestion and thermal gasification. According to their estimates there are overall biomethane potentials of 395 TWh/a in 2030 and 1,456 TWh/a in 2050 in EU-28, Norway and Switzerland. The focus countries this study is focusing on are all amongst the top five countries with the highest overall biomethane potential, both in 2030 and in 2050, except for Switzerland (see Figure 3)

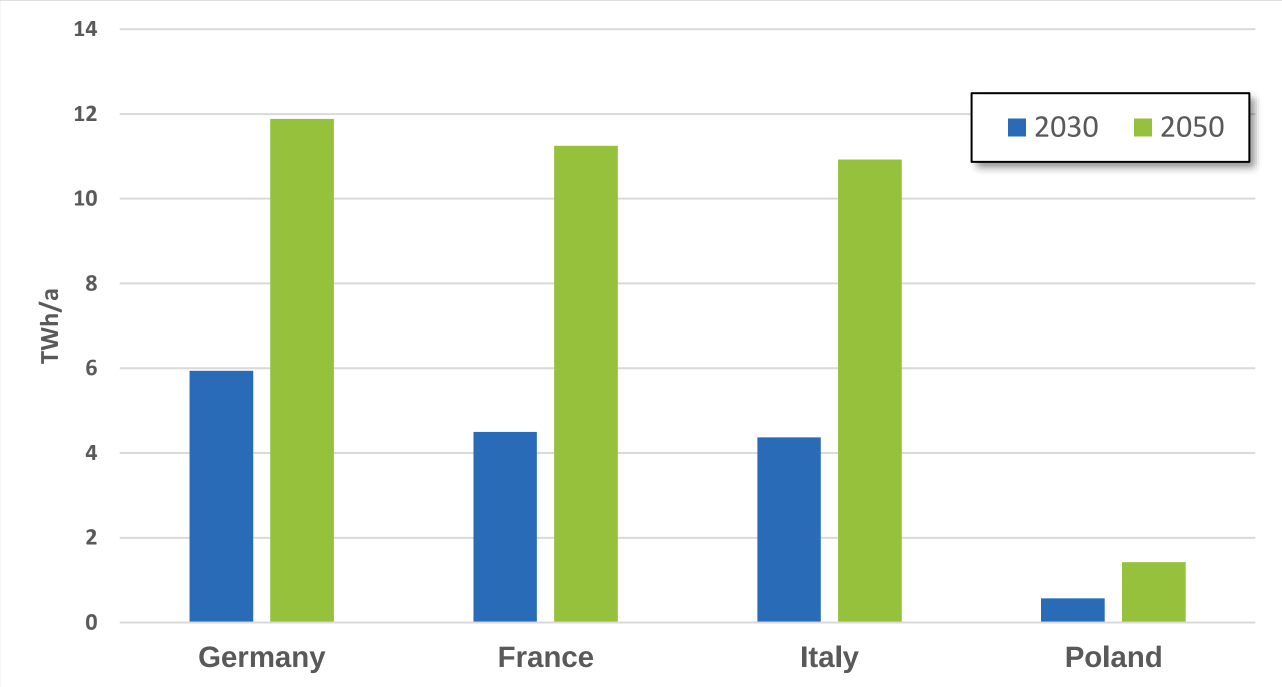
Figure 3: Total biomethane potential in Europe in TWh/a *and it´s division of feedstock as well as biomethane potential in Switzerland, Germany, France, Italy and Poland. [32]*



Energy Potential from Used Cooking Oil (UCO)

For hydrogenated vegetable oil (HVO), the related feedstocks are animal fats and used cooking oil (UCO). The projected increase in HVO potential in the study by Imperial College London [31] between 2030 and 2050 stems solely from the increase in used cooking oil (UCO). This feedstock is not considered in ENSPRESO [28]. In DG RTD [30], used cooking oil (UCO) is considered, revealing a very small potential with below 5 Mt/a dry matter in the "improved supply" scenario in 2050). The Imperial Collage London study [31] stated a more precise estimation of used cooking oil (UCO). It shows that between 2011 and 2016, the utilisation of used cooking oil (UCO) increased from 0.68 Mt/a to 2.44 Mt/a. There is also a substantial trade in used cooking oil (UCO) with source countries such as China, Indonesia and Malaysia. In EU-28 in 2016 a total potential of 1.7 Mt/a (0.9 Mt/a in household and 0.8 Mt/a in industry sector) are estimated of which 0.7 Mt/a were collected [31]. Current recovery rates are appreciated to 5.6% in private households and 86% in industry. The study assumes an increase in the recovery rate to 90% for industry in 2030 remaining on this level also in 2050 and a substantial increase in the recovery rate from households reaching 15% in 2030 and 45% in 2050. This adds up to 3.3 Mt/a of used cooking oil (UCO) in 2030 and 2.2 Mt/a of animal fats leading to 52 TWh/a potential hydrogenated vegetable oil (HVO) in 2030 and almost twice that amount in 2050 [31]. An increase in used cooking oil (UCO) potential up to 7.7 Mt/a in 2050 leads to 97.7 TWh/a hydrogenated vegetable oil (HVO) potential in total. When looking at the focus countries (see Figure 4), Germany (DE), France (FR) and Italy (IT) are amongst the countries in EU with the highest potentials both for 2030 and 2050. Poland (PL) is below average and there is no estimation for Switzerland included.

Figure 4: The potential feedstock of used cooking oil (UCO) in Germany, France, Italy and Poland in 2030 and 2050 in thousands tonnes according to Imperial College London, own illustration based on [31] and calculated with $37\ \mathrm{MJ/kg}$ *LHV.*

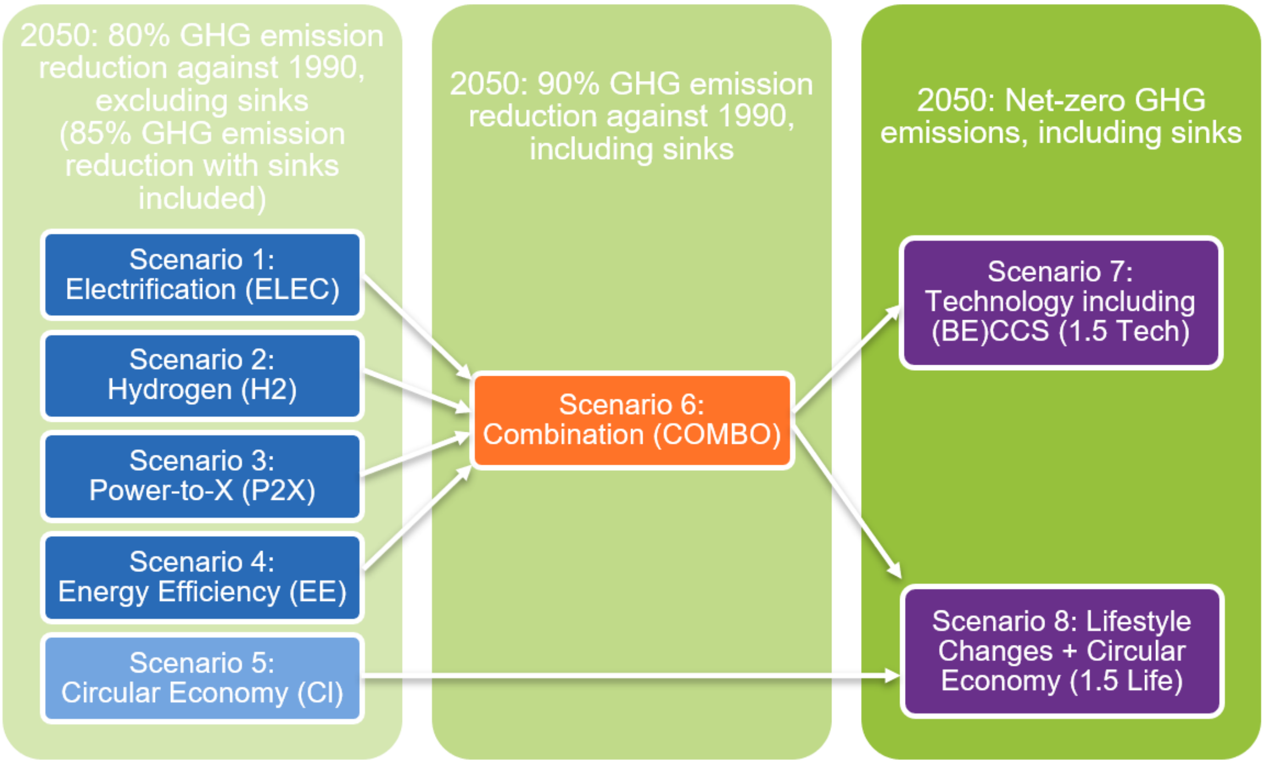


A recent study of CE Delft [33] is a bit more conservative and estimates $1.7\ \mathrm{Mt/a}$ availability in 2030 for EU-28, but also considers imports and estimates total supply to be in the same range 3.1-$3.3\ \mathrm{Mt/a}$ in 2030.

2.3 European Plans for a Future Energy System

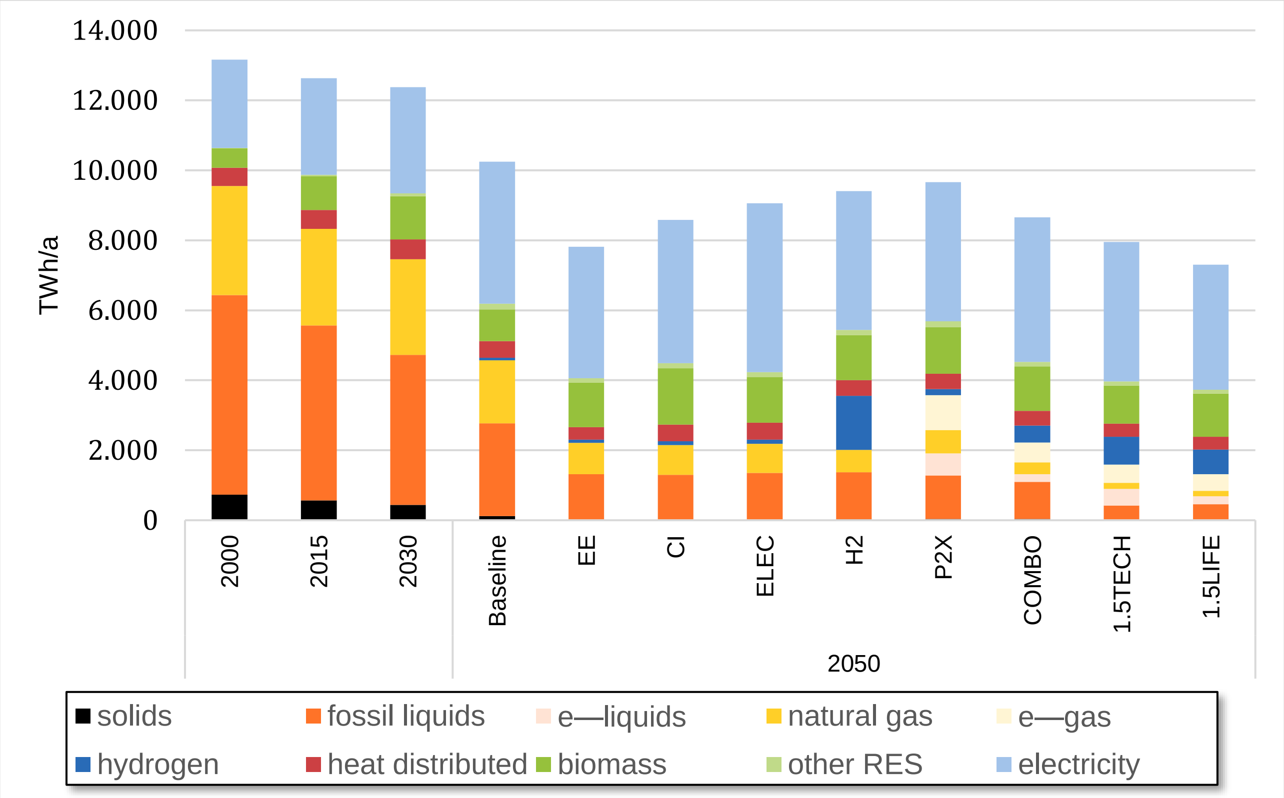
This section summarises the European Commission's communication in depth analysis supporting the "Clean Planet for All" [34] and the "European Grean Deal" indicating the future European energy system to comply with the European commitment to the "Paris Agreement" [10]. The communication presents eight long term strategy options in the form of scenarios reaching different levels of ambitious GHG reduction targets (see Figure 5). Scenarios 1 to 5 follow an ambition to limit global warming "well below $2\ ^\circ\mathrm{C}$" and reach a reduction of 80% in GHG emissions in 2050 (reduction of 85% when including sinks). Scenarios 1 to 5 foresee a total decarbonisation of the electric power sector. Scenarios 1 to 4 are combined in the scenario 6 "Combination (COMBO)", reaching 90% GHG emission reduction in 2050 (including sinks). The two most ambitious scenarios number 7 and 8 are even in line with limiting global warming at $1.5\ ^\circ\mathrm{C}$ and have a reduction of GHG emission of 100% in 2050 (including sinks). They are based on the "Combination (COMBO)" scenario 6 including lager shares of negative emissions in the "1.5 Tech"-Scenario and adding elements from scenario 5 "Circular Economy (CI)" in scenario 8 "1.5 Life". Since the goal in the European Green Deal is set to net carbon neutral in 2050, only scenario "1.5 Tech" and "1.5 Life" complies with this completely.

Figure 5: Overview of the scenarios in the in depth analytic of the "Clean Planet for all" publication [34] sorted by GHG emissions impact relation to each other.



All scenarios are referenced on the Baseline scenario, building extensively on the EU Reference Scenario 2016. This includes considerations on the recent legislations and the achievement of the energy and climate 2030 targets, as adopted by EU leaders on October 2014, further refined on May 2018 with the agreement on the "Effort Sharing Regulation" and enhanced on June 2018 with the agreement on the recast of "Renewable Energy Directive" (RED, [18]) and the revised Energy Efficiency Directive. Due to the fact that current legislations have a large impact on the short-term perspective, the report states that all scenarios lead to comparable results until 2030. The differences are noticeable in the longer time frame (e.g. 2050)

Figure 6: Final energy consumption in the EU in TWh/a *according to scenarios in the detailed analysis of the Clean Planet for all communication and it´s division between energy carriers [34].*



In comparison of the final energy consumption in the different scenarios, every scenario would imply energy consumption reduction in comparison with the baseline and today's values. However, electricity consumption increases dramatically and reaches 3,000 TWh/a in 2030. The total electricity consumption increases further in all the scenarios until 2050 and in the two scenarios in line with the "Green Deal" ambition of net carbon neutrality in 2050. In scenario 7 "1.5 Tech" and scenario 8 "1.5 Life", the electricity consumption ranges between 3,600 TWh/a and almost 4,000 TWh/a. The highest demand is in scenario 1 "Electrification" with 4,830 TWh/a consumption. Considering the electricity generation needed in the different scenarios, all the scenarios from scenario 2 "Hydrogen", scenario 3 "Power-to-X", scenario 6 "Combination" and both 1.5-scenarios 7 and 8 require higher generation of electricity than scenario 1 "Electrification" resulting in approximately 100-150% higher generation in 2050 compared to 2015. Whereas scenario 1 "Electrification" requires about 75% increase.

3 European Long-Haul Road Transport

Long-haul road transport contributes significantly to the European economy; currently, 6.2 million trucks transports goods and freight across Europe [35]. Like other important sectors, the transport sector will undergo significant changes over the next years, and among the many challenges that it will face there is the need of new infrastructures to support the change towards zero emissions by 2050.

3.1 Definition

Available reports show different definitions and assumptions of what is considered as long-haul road transport, heavy-duty vehicles (HDV), long distance road transport and other related names. To perform the quantitative analysis and compare it with the existing literature, the following aspects are defined:

1. Distances: For the technical and techno-economic comparison, we assume that distances of more than $150\ \mathrm{km}$ must be possible with the vehicles without interim charging/fuelling. This limit is the same as in the Eurostat databases that have been used as source of data for this report.
2. Total weight and payload: The study considers a 40-ton truck (total weight) as representative vehicle for a long-haul road transport fleet, which corresponds to a type 5 vehicle "tractor semi-trailer combination for long-haul" [2,36]. An average representative payload of $10\ \mathrm{tons}$ is assumed since the average load carried is assumed to be between 35% and 50% of the maximum capacity.
3. Type of travel: We assume that there are no delivery stops within $150\ \mathrm{km}$ and that the truck mainly travels on highways.
4. Consumption: For all technologies investigated, we assumed an average fuel/electricity consumptions per km or tkm. This value depends on the previous three assumptions and are listed in Appendix A.4 (Table 22 lines 605, 608, 610 and 612). Specific consumption profiles due to varying routes and/or topologies of regions/countries are not analysed.

3.2 Road Freight Distances and GHG Emissions in 2020 and in 2030

The total road freight transport of EU-27 currently corresponds to $1{,}900$ billion tonne-kilometres travelled per year [6] ($\mathrm{Gtkm/a}$) by $1{,}600{,}000$ trucks type 5 [37], and $52\ \%$ of these tonne-kilometres are allocated in the five countries selected as case study of this analysis (namely, Germany: $300\ \mathrm{Gtkm/a}$, France: $170\ \mathrm{Gtkm/a}$, Italy: $130\ \mathrm{Gtkm/a}$ Poland: $350\ \mathrm{Gtkm/a}$ and Switzerland: $10\ \mathrm{Gtkm/a}$ [6]). Figure *7* shows the historical trends from 2010 to 2021, and via a linear extrapolation the data for 2030 are computed. According to this estimation, the number of type 5 vehicles should increase to $2{,}400{,}000$ by 2030, and they would perform a total of about $2{,}150\ \mathrm{Gtkm/a}$ in the EU-27 and Switzerland. In Table 5 this figure is split between heavy-duty vehicles (HDV) and light-duty vehicles (LDV), and the transport capabilities of heavy-duty vehicles (HDV) are attributed to long-haul (the type of transport investigated in this study) and regional.

Figure 7: Amount of road freight transport in billion tonne-kilometres per year ($\mathrm{Gtkm/a}$) in the EU-27, Germany, France, Italy, Poland and Switzerland [6]. The data displayed cover the carriage of goods by vehicles registered in the reporting countries.

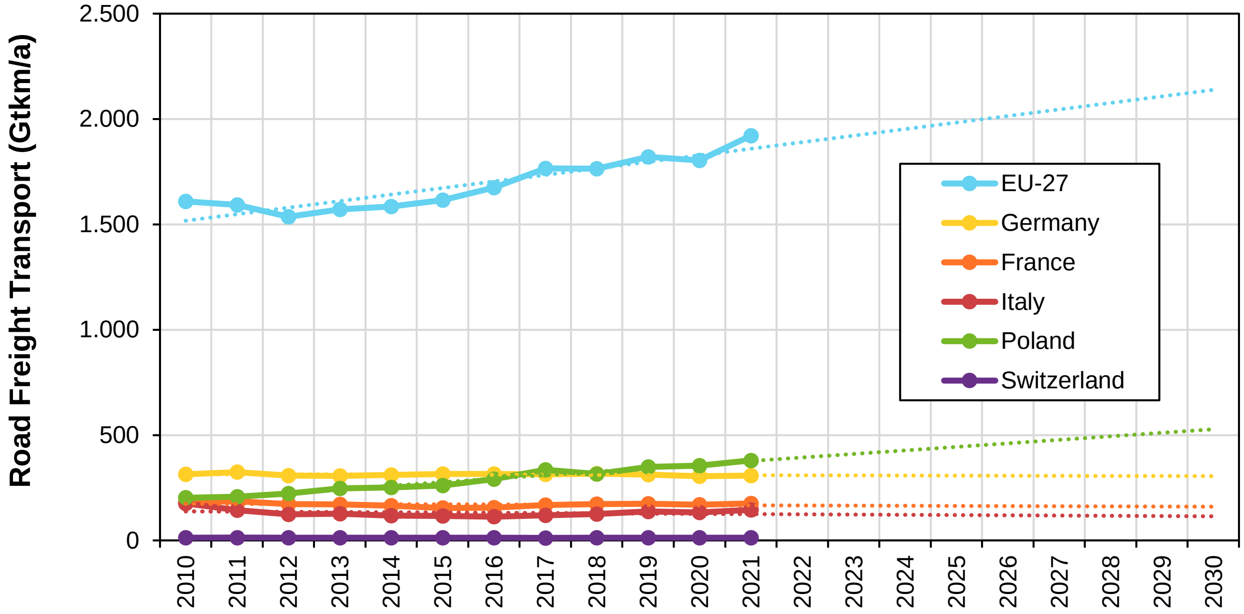


Figure 7 also shows that road freight transport is generally increasing in EU-27. However, although the annual transport demand is projected to increase in Poland, no significant variation is expected in Germany, France and Switzerland between now and 2030. In Italy the trend is even decreasing. Consequently, if customized emissions reduction targets are applied to the individual countries, it would mean that countries like DE, FR, IT and CH could reach their target by simply reducing the tkm performed per year while keeping their diesel trucks fleet. For countries like Poland, where the tkm are expected to increase by 2030, the entire fleet would need to be renewable by 2030 to reach the emissions reduction targets. The authors therefore decided to set a single emissions reduction target for all EU-27 countries, Switzerland included.

Table 4 shows data of GHG emissions from heavy-duty road transport for 1990, 2005, 2019 and 2020. The two targets defined in section 2.1 and summarized below, translate into a maximum amount of GHG emissions that can be emitted within the heavy-duty transport sector.

1. "Effort Sharing" reducing GHG emissions by 40% with respect to 2005 means that heavy-duty road transport is allowed to emit $130\,\mathrm{MtCO_{2eq}/a}$ in 2030.
2. "Green Deal for all" reducing GHG emissions by 55% with respect to 1990 means a maximum GHG emissions of $74\,\mathrm{MtCO_{2eq}/a}$ for heavy-duty road transport.

These target numbers now need to be broken down to long-haul and regional.

Table 4: Annual emissions of GHG from heavy-duty road transport, data for years 1990, 2005, 2019 and 2020 and targets [38]. Numbers rounded to three significant digits.

Data				Target for 2030	
1990	**2005**	**2019**	**2020**	**Effort Sharing**: -40% with respect to 2005	**Green Deal for all**: -55% with respect to 1990
$165\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$	$216\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$	$212\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$	$195\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$	$130\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$	$74.3\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$
				$-86.4\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$	
					$-90.8\,\frac{\mathrm{MtCO_{2eq}}}{\mathrm{a}}$

The numbers discussed here are summarised in Table 5. In 2020 the total road freight transport of the EU-27 performed $1{,}800\ \mathrm{Gtkm/a}$ and was responsible for about 270 million tons of carbon dioxide equivalent emissions per year ($\mathrm{MtCO_{2eq}/a}$) [38]. Although heavy-duty vehicles (HDV, > 3.5 t) are performing over 95% of the current road freight transport ($1'750\ \mathrm{Gtkm/a}$) [6], their share of GHG emissions in the total road freight transport is only slightly more than 70% ($195\ \mathrm{MtCO_{2eq}/a}$, [38] compare Table 4). The remaining share is caused by light-duty vehicles (LDV, < 3.5 t). Within the HDV-category type 5-vehicles (long-haul)[8] and type 4-vehicles (regional)[9] can be differentiated: The former category is currently responsible for approximately 80% of the freight transport ($1'400\ \mathrm{Gtkm/a}$) and for roughly 50% of the emissions ($97\ \mathrm{MtCO_{2eq}/a}$) [2,6,39].

It is assumed that the share in the amount of freight transport (tkm) and GHG emissions between heavy-duty vehicles (HDV) and light-duty vehicles (LDV) as well as within the heavy-duty vehicles (HDV) between Type 5 (long-haul) and Type 4 (regional) remains the same in 2030 as it was in 2020. With this assumption, the HDV type 5 will perform $1'660\ \mathrm{Gtkm/a}$ in 2030 with allowable GHG emissions of $64\ \mathrm{MtCO_{2eq}/a}$ for Effort Sharing targets and of $37\ \mathrm{MtCO_{2eq}/a}$ for Green Deal for all respectively. The current average emissions of HDV type 5 of $69\ \mathrm{gCO_{2eq}/tkm}$ must decrease to $39\ \mathrm{gCO_{2eq}/tkm}$ or $22\ \mathrm{gCO_{2eq}/tkm}$ respectively.

Table 5: Tonne-kilometres (tkm) and GHG emissions of the road freight transport in EU-27 in 2020 and 2030 [2,6,39] in round numbers. Long-haul road transport is highlighted. Targets for 2030 from section 2.1. Share in tkm and share in GHG emissions in 2030 are assumed to be the same as in 2020. See main text for more details on data sources.

Category	Data 2020	Transport Capacity in 2030 Targets for 2030	
		Effort Sharing: -40% with respect to 2005	**Green Deal for all**: -55% with respect to 1990
Road freight transport	$1'800\ \mathrm{Gtkm/a}$	$2'140\ \mathrm{Gtkm/a}$	
	$270\ \mathrm{MtCO_{2eq}/a}$	x	x
	$150\ \mathrm{gCO_{2eq}/tkm}$	x	x
Heavy-duty vehicles (HDV) (> 3.5 t)	$1'750\ \mathrm{Gtkm/a}$	$2'080\ \mathrm{Gtkm/a}$	
	$195\ \mathrm{MtCO_{2eq}/a}$	$130\ \mathrm{MtCO_{2eq}/a}$ [10]	$74\ \mathrm{MtCO_{2eq}/a}$[10]
	$110\ \mathrm{gCO_{2eq}/tkm}$	$63\ \mathrm{gCO_{2eq}/tkm}$	$36\ \mathrm{gCO_{2eq}/tkm}$
HDV: Type 5 / long-haul	$1'400\ \mathrm{Gtkm/a}$	$1'660\ \mathrm{Gtkm/a}$	
	$97\ \mathrm{MtCO_{2eq}/a}$	$64\ \mathrm{MtCO_{2eq}/a}$	$37\ \mathrm{MtCO_{2eq}/a}$
	$69\ \mathrm{gCO_{2eq}/tkm}$	$39\ \mathrm{gCO_{2eq}/tkm}$	$22\ \mathrm{gCO_{2eq}/tkm}$
HDV: Type 4 / regional	$350\ \mathrm{Gtkm/a}$	$415\ \mathrm{Gtkm/a}$	
	$98\ \mathrm{MtCO_{2eq}/a}$	$66\ \mathrm{MtCO_{2eq}/a}$	$37\ \mathrm{MtCO_{2eq}/a}$
	$280\ \mathrm{gCO_{2eq}/tkm}$	$160\ \mathrm{gCO_{2eq}/tkm}$	$90\ \mathrm{gCO_{2eq}/tkm}$
Light-duty vehicles (LDV) (< 3.5 t)	$52\ \mathrm{Gtkm/a}$	$62\ \mathrm{Gtkm/a}$	
	$76\ \mathrm{MtCO_{2eq}/a}$	x	x
	$1'500\ \mathrm{gCO_{2eq}/tkm}$	x	x

[8] "tractor semitrailer combination for long-haul" [2].
[9] "rigid trucks used in regional delivery mission" [2].

3.3 Renewable Fuel Technologies Available in 2030

Nowadays, long-haul road transport almost exclusively uses fossil Diesel as energy source. More efficient drive trains, other vehicle technologies (e.g. reduced rolling resistance and aerodynamic measures) or the admixing of renewable fuels can reduce the resulting GHG emissions of Diesel drive trains [40][11], but they cannot operate fully carbon neutral. Consequently, the long-haul road transport sector will face a change in technology in the coming years.

Out of several renewable fuel technologies, the authors have chosen four, which are listed in Table 6. These technologies are about to become market-ready, they will roll out in the coming years, and their respective vehicles and supply chain elements are considered to be available at large scale in 2030. These technologies are: Battery electric vehicles (BEV), Hydrogen fuel cell electric vehicles (H_2, FCEV) and vehicles with internal combustion engines (ICE) operated with renewable methane (CH_4), liquid biofuels or liquid E-Fuels. Both synthetic methane (Syn. CH_4) and methane of biological origin (Bio CH_4) are considered. Among liquid biofuels and liquid E-Fuels (E-Fuels/HVO), E-Diesel from Fischer-Tropsch processes (FT) and hydrogenated vegetable oil (HVO) produced from used cooking oil (UCO) and rapeseed oil are included.

Table 6: Renewable fuel technologies for long-haul road transport considered in this study.

Propulsion	Abbreviation	Vehicles	Renewable Energy Carrier	Required Infrastructure	
				Existing	New
Electric vehicles (EV)	BEV	Battery electric vehicles (BEV)	Renewable electricity	Electricity grid	Charging stations suitable for trucks, strong grid reinforcements (independent of long-haul road transport)
	H_2	Fuel cell electric vehicles (FCEV)	Green hydrogen		Generation of green hydrogen, hydrogen distribution and refuelling stations
Vehicles with internal combustion engines (ICE)	CH_4: Bio CH_4 Syn. CH_4	Vehicles using methane (CNG or LNG)	Biomethane or renewable synthetic methane	Gas infrastructure for distribution	More CNG and LNG refuelling stations suitable for trucks
	E-Fuels / HVO: FT HVO	Vehicles using liquid fuels	E-Diesel (Fischer-Tropsch, FT) Hydrogenated Vegetable Oil (HVO)	Distribution of liquid fuels, fuelling stations	Fuel synthesis in Power-to-X processes

The state of technology in 2030 expressed in energy use per tonne-kilometre (tonne payload) for all vehicle technologies are taken from [2]. Some of the selections are further specified and explained in the following text.

Fuel Cell Electric Vehicles (FCEV, H_2): This study considers hydrogen stored in compressed form only. While a pressure of $700\ \mathrm{bar}$ is the standard for passenger cars, trucks rely on $350\ \mathrm{bar}$ storage, with some manufacturers announcing going towards $700\ \mathrm{bar}$ for trucks as well. In case hydrogen-fuelled trucks with internal combustion engines (ICE) hit the market by 2030, they are included in this study under the assumption to have similar efficiencies and costs as fuel cell electric vehicles

[11] Appendix B page 78/123 Table 29

(FCEV). The study does not consider trucks fuelled with liquefied hydrogen nor with hydrogen from liquid organic hydrogen carriers (LOHC) since both technologies are not market ready today and are considered not to be available in large scale in 2030.

Renewable methane includes synthetic methane (Syn. CH_4) and biomethane (Bio CH_4) both used compressed (CNG) and liquefied (LNG) and used in internal combustion engines. For information, a comprehensive analysis of a real LNG application is available in [41]

The liquid renewable fuels considered in this study are E-Diesel and hydrogenated vegetable oil (HVO). While the main energy source of E-Diesel is renewable electricity, the production of hydrogenated vegetable oil (HVO) relies both on chemical energy in used cooking oil (UCO) and electricity required to produce hydrogen. This study does not consider methanol and dimethyl ether (DME) as fuels, which are sometimes considered as a potential future fuel for road vehicles. Methanol is a liquid under normal conditions and dimethyl ether (DME) can be kept in its liquid form at pressures above $12\ \mathrm{bara}$ (at temperatures up to $52\ °\mathrm{C}$). Both fuels are not considered in this study since there are very few commercialisation activities, and they are not expected be available in large scale in 2030. Liquified petroleum gas (LPG) is not included in this study because it is not renewable.

There are hybrid technologies, some already commercially available, which are not looked at separately in this study. Diesel-electric drivetrains are included in the latest Diesel technology available in 2030 (“New Diesel”) and might be a contribution to the improved efficiency. There are drivetrains making use of combined fuels, sometimes also referred to as hybrid solutions: A certain share of hydrogen can be used in methane drivetrains. Trucks using both fuels diesel and methane are available which both can be renewable. All hybrid technologies can be regarded as either being included in the renewable fuel technologies or as being combinations of them.

3.4 Infrastructure for Renewable Fuel Technologies

The overarching steering instrument of the EU to develop the transport infrastructure across Europe is the “EU´s trans-European transport network policy (Ten-T policy). It includes all modes of transport for both personal mobility and transport. It aims to create a seamless transport system across border, to close gaps, dissolve bottlenecks and at the same time reduce the environmental impact and increase safety and resilience. The plans consist of nine corridors across Europe.

1. Atlantic Corridor
2. Baltic - Adriatic Corridor
3. Mediterranean Corridor
4. North Sea - Baltic Corridor
5. North Sea – Mediterranean Corridor
6. Orient – East Mediterranean Corridor
7. Rhine – Alpine Corridor
8. Rhine – Danube Corridor
9. Scandinavian – Mediterranean Corridor

Looking at the focus countries of the study, Germany has the most corridors crossing or entering its territory (1, 4, 5, 6, 7, 8 and 9). France is directly connected to; 1, 3, 5 and 8. Italy are part of; 2, 3, 7 and 9. Poland is the starting/ending point of the Baltic – Adriatic corridor (2) and also connected to the North Sea – Baltic corridor (4). Finally, Switzerland is included in the Rhine – Alpine Corridor (7). One aspect of Ten-T is the establishment of infrastructure for alternative fuels. With in the “Fit for 55” package of the European Green Deal, there was a proposal for alternative fuels infrastructure from 2014 in the form of a directive (AFID) . After the authors of this study concluded chapter 3, an agreement between the EU Parliament and the council to replace the directive with a legally binding regulation i.e., the Alternative Fuels Infrastructure Regulation (AFIR) was met in March 2023. The full details are still to be published but regarding long-haul heavy-duty road transport some information is available regarding recharging stations (see section 3.4.1) and hydrogen refuelling stations (see section 3.4.2).

3.4.1 Electric Infrastructure

Existing Electric Infrastructure

Public charging stations for passenger cars are in the process of being built and form a growing network with increasing density; in fact, their number almost tripled between the beginning of 2020 and the end of 2022 [42,43]. However, public charging stations with enough space and power to accommodate heavy-duty vehicles are essentially inexistant in Europe [44]. And even if it is technically possible to charge battery-electric trucks on charging points designed for passenger cars, this would take several hours due to the low power output in comparison to a truck battery size. Additionally, in most cases, it would be also difficult to find the space required to park the truck next to the charging point, which makes it therefore impossible for operators of truck fleets to rely solely on the existing public charging stations. For these reasons, the few battery-electric trucks (BEV) on the roads today are charged overnight at the fleet operator's premisses. But this method is suitable for regional transport only as long-haul transport requires the driver to be able to recharge during breaks or at night, on the way. Therefore, publicly accessible charging stations for trucks are necessary.

From a distribution infrastructure point of view, an effective electric distribution network exists and will be able to partially withstand the increasing number of battery electric vehicles.

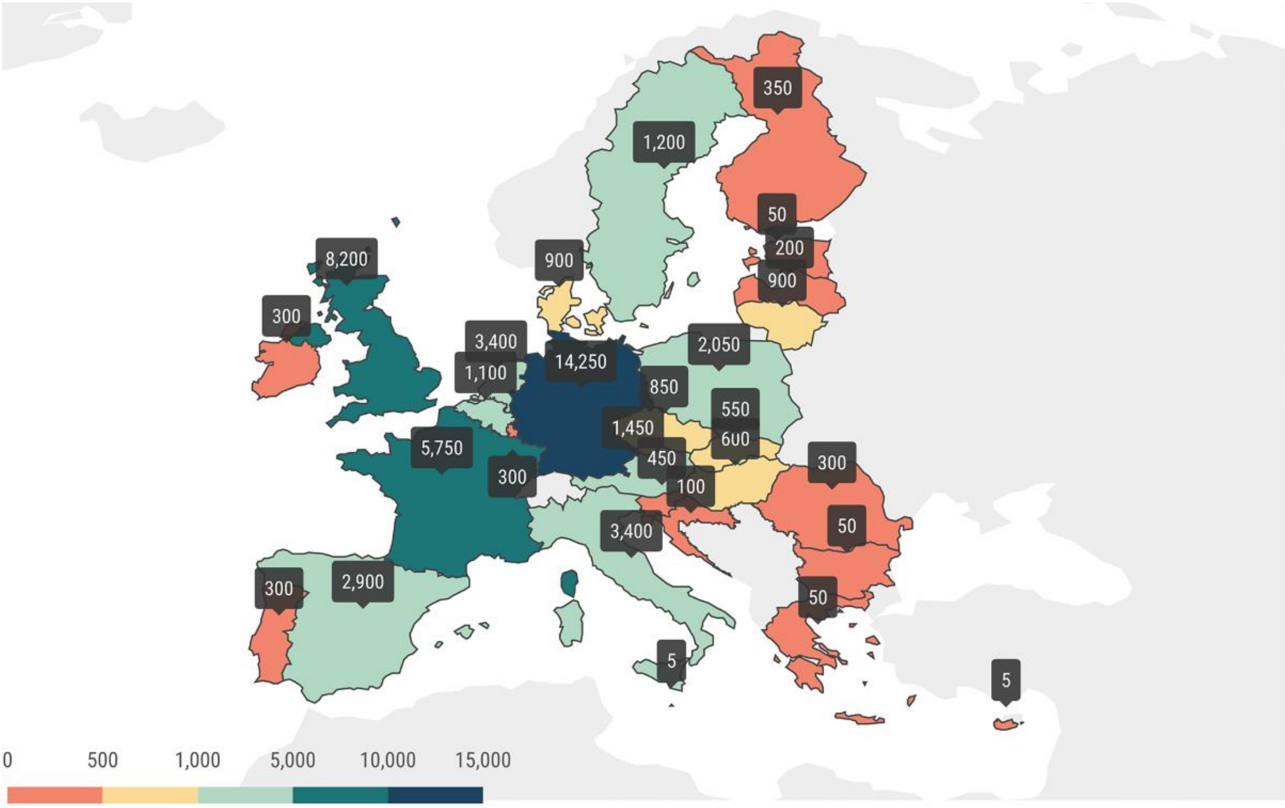
Plans for Future Electric Infrastructure

According to ACEA [45], a total of $15{,}000$ charging points for HDV will be required in Europe by 2025 and $50{,}000$ by 2030. Their repartition according to the share of new registered vehicles of a given country as well as its GDP and average mileage is represented in Figure 8. Still according to ACEA [45], at least $30{,}000$ of these charging points should support fast charging and thus should be part of the Megawatt Charging System (MCS) as soon as it is available. As its name suggest, this standard allows vehicles to be charged with direct current and an electrical power from a $1\ \mathrm{MW}$ up to $3.75\ \mathrm{MW}$ [46,47]. This allows to fully charge a truck in less than one hour and possibly even in a few minutes. No explicit number of charging points is calculated in this study. Instead, their costs are computed with the total amount of required electricity and the specific cost of a charger (see annex A.4)

As a matter of fact, it is expected that charging stations for trucks will be mainly installed along motorways. They will most probably offer multiple charging points to allow long-haul drivers to charge during their mandatory breaks. In October 2022, the Transport and Tourism Committee of the European Parliament adopted a draft negotiating mandate on the deployment of alternative fuels infrastructure [48]. It states that for electric vehicles, suitable charging stations should be installed every $60\ \mathrm{km}$ along the main transport corridors (TEN-T [49]) by 2026, also for heavy-duty vehicles. Since motorways and their areas are outside existing settlements, additional power lines would most probably need to be built to supply these charging points. Furthermore, as trucks carry heavy and powerful batteries, high-power chargers will be required for most of these charging stations and the power grid would also need to be upgraded to support the additional load. However, as mentioned in section 1.3 Table 1 line 8, the expansion of the power grid was not considered in the estimation of annual costs, but in the qualitative criteria of "Required Effort for Infrastructure" in section 4.5.2.

The new Alternative Fuels Infrastructure Regulation (AFIR) foresees recharging stations dedicated to heavy-duty vehicles with a minimum output of $350\ \mathrm{kW}$ deployed every $60\ \mathrm{km}$ along the TEN-T core network, and every $100\ \mathrm{km}$ on the larger TEN-T comprehensive network from 2025 onwards. The complete network coverage should be achieved by 2030. In addition, recharging stations must be installed at safe and secure parking areas for overnight recharging as well as in urban nodes for delivery vehicles.

Figure 8: Repartition of required heavy-duty vehicles (HDV) charging points by 2030 according to ACEA [45]



Renewable electricity production

In 2022, Wind energy generation in EU-28 reached $489\ \mathrm{TWh/a}$, the share of electricity consumption from wind onshore reached 14.1% and the share from wind offshore reached 3.2%. A total of $255\ \mathrm{GW}$ of wind power capacity is now installed in Europe, of which 88% ($225\ \mathrm{GW}$) are onshore and 12% ($30\ \mathrm{GW}$) are offshore. [50]

For the EU to reach a $45\ \%$ renewable energy target by 2030, wind energy installations need to average $31\ \mathrm{GW}$ per year between 2023 and 2030. This is based on an installed wind power capacity target of $440\ \mathrm{GW}$. It is expected to be $19.4\ \mathrm{GW}$ of new capacity installations in 2023 in Europe. Over the five years to 2027, installations in Europe are expected to fall $16\ \mathrm{GW}$ short of the required ramp-up rates set out in the 2030 Targets Scenario. [50]

The EU's solar power generation capacity increased by 25% to $208.9\ \mathrm{GW}$, from $167.5\ \mathrm{GW}$ in 2021. In four years, capacities increased from $100\ \mathrm{GW}$ in 2018 to reach the double capacity and produce 7.3% ($203\ \mathrm{TWh/a}$) of EU electricity in 2022. Assuming a 29% annual growth rate for 2023 the increase in capacity will be above $50\ \mathrm{GW}$. In a "Medium Scenario", growth rates are assumed to be 19% in 2025 and 15% in 2026. This would imply $74.1\ \mathrm{GW}$ in 2025 and $85.2\ \mathrm{GW}$ in 2026 annual solar deployment volumes. [51]

3.4.2 Hydrogen Infrastructure

Existing Hydrogen Infrastructure

In the year 2022, Clean Hydrogen Monitor revealed that 504 active sites for hydrogen production exist within Europe. These facilities collectively possess an annual production capacity of $11.5\ \mathrm{million\ t/a}$. Based on the estimated hydrogen consumption in 2020, the average capacity utilization rate in the same year was approximately 76%. Notably, Germany, Netherlands, Poland, Italy, and France possess the most significant hydrogen production capacity. Together, these nations account for 55% of the EU, EFTA, and the UK's total hydrogen production capacity [52].

Regarding heavy-duty hydrogen fuel cell electric vehicles (FCEV) only a few are right now in operation in Europe. The manufacturer of the only current mass produced hydrogen truck, Hyundai Motors, has delivered 47 lorries in Switzerland and is opening the market to Germany as of mid-2022 [53]. Others such as Daimler Trucks, MAN, Scania and Volvo, are expected to release hydrogen trucks in a near future, but they are currently all in the prototype phase.

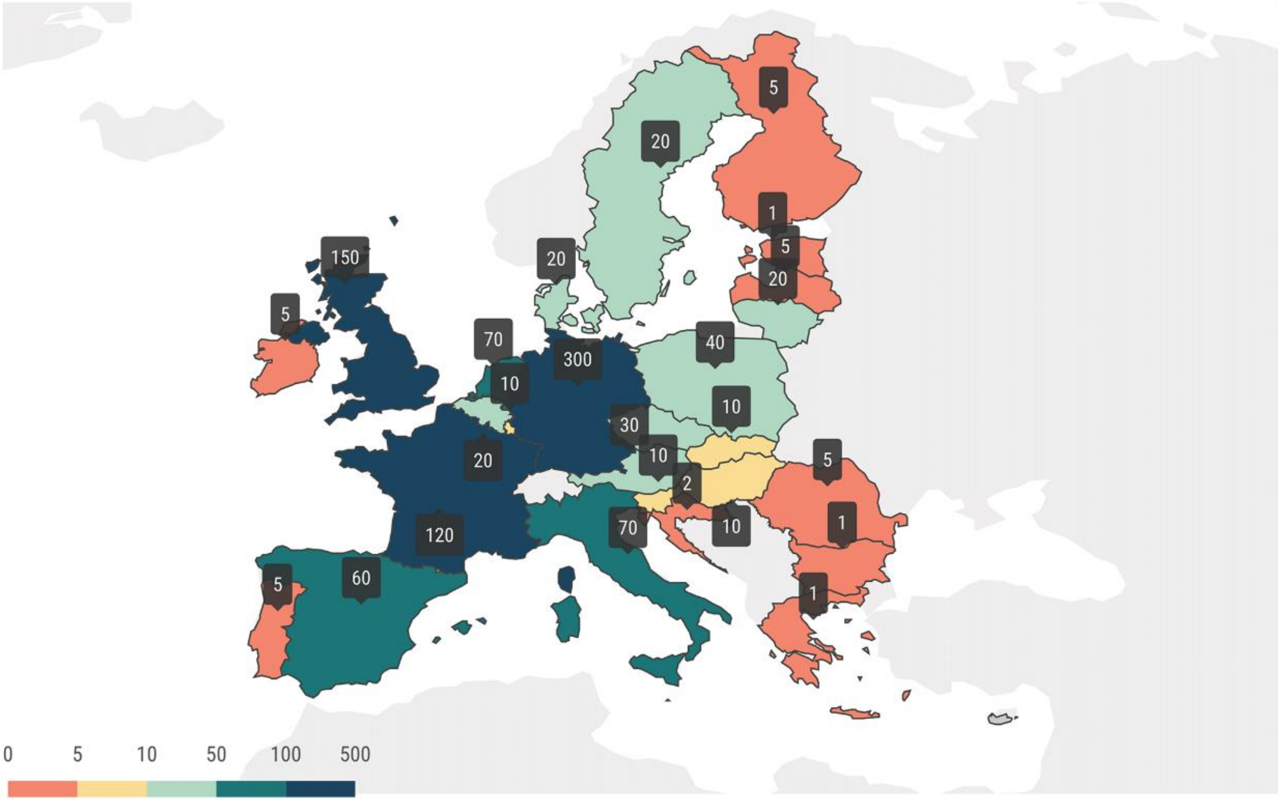
To refuel these vehicles, around 150 stations were operating in the European Union in 2021 [54], of which 89 (65 %) in Germany, 19 in France, 1 in Italy and none in Poland. Switzerland was, until mid-2022, the only country in Europe with hydrogen trucks in commercial operation [53] and is therefore one of the country with the highest density of hydrogen refuelling stations per capita with 12 stations [55] in operation. Most of these stations offer a pressure up to 700 bar to fill heavy-duty vehicles as well as passenger cars.

Currently, hydrogen is mainly transported throughout Europe by road with specific trailers for compressed hydrogen, and because of the limited amount of hydrogen transportable in a single trailer (typically 600 kg compressed, 7,000 kg liquid), the transport cost is significant. Pipelines allow a more cost-effective transport of large quantities of hydrogen, but investment costs are much higher, and no significant distribution grid currently exists in Europe. Nowadays, about 1,500 km of hydrogen pipelines are installed in Europe, mostly around the most industrial areas of the EU: the Netherlands, Belgium, Norther France and Northern Germany. About 300 km of hydrogen pipelines exist in France, 400 km in Germany and less than 10 km in Switzerland and Italy [56].

Plans for Future Hydrogen Infrastructure

According to Hydrogen Europe's central scenario, the demand for hydrogen is expected to reach 492 TWh by 2030 and rapidly increase by 2050 as the EU's transition to a decarbonized energy system takes place. The Clean Hydrogen Monitor central scenario forecasts a demand of 1,010 TWh by 2050, representing approximately 11% of the EU's total energy demand. It also indicates that industry ambitions, based on announced projects, already amount to 138 GW for 2030 [52]. Many additional hydrogen refuelling stations are in the planning phase and expected to enter service in the next years. Most of them might be fitted with 700 bar for refuelling hydrogen passenger cars or future heavy-duty vehicles, but it is expected that some will focus on current heavy-duty vehicles only, limiting themselves to 350 bar. The mandate of the Transport and Tourism Committee of the European Parliament mentioned in the previous section [48] also suggests building hydrogen refuelling stations every 100 km for trucks and buses along the main roads of the Trans-European Network (TEN-T) [49] by 2028. According to ACEA [45], at least 1,000 hydrogen refuelling stations are required in Europe (EU27+UK) by 2023: 300 in Germany, 120 in France, 70 in Italy and 40 in Poland. In the map displayed in Figure 9, these refuelling stations are distributed according to the countries' proportion of newly registered lorries, average mileage and GDP. Additionally, Roses and Neumann [57] modelled the German highway network and predicted the need of 137 hydrogen refuelling stations on highways for domestic transport. In comparison, there are currently around 360 conventional fossil fuel filling stations on German highways [58]. In Switzerland for example, 13 refuelling stations are currently in service and 6 are in the planning phase, suggesting an increase of 50 % in their number in the next years [55]. All Swiss hydrogen refuelling stations support a pressure of up to 700 bar. Similarly to the electric chargers, the number of required hydrogen refuelling stations is not explicitly calculated in this study. Their price is estimated directly from the quantity of hydrogen needed and the specific cost of a refuelling station (see also annex A.4).

Figure 9: Repartition of required heavy-duty vehicles (HDV) hydrogen refuelling stations by 2030 according to ACEA [45]



In the future, more cost-effective capabilities for hydrogen transport and distribution are required in Europe. The largest project in this regard is the European Hydrogen Backbone Initiative [59]. It is supported by 31 European energy infrastructure operators from 28 European countries and aims at the construction and extension of the hydrogen pipeline network by building new pipelines and re-purposing natural gas pipelines. The current plans for 2030 and even more so the 2040 plans are to be carefully considered as most of the extensions are subject to potential modifications. As summarized by Bucheli, the HIPS-NET network (Hydrogen in Pipeline Systems) is currently working on the concrete issues to bring the project to life [60]. As shown in the report [59], the highest density of network is expected to be installed in the industrial area between Northern Germany and the Netherlands, where a small hydrogen network already exists. Additionally, based on this network prediction, the role of the pipelines in peripheric countries appears to be crucial to bring hydrogen from high import and production potential areas such as the North Sea, the Baltic, Spain or Italy, to the industrial regions of central Europe, Germany or the Netherland for example. In this study it is assumed that part of the European Hydrogen Backbone is already in place by 2030 allowing the import of hydrogen from the MENA region, mainly over Italy. The assumed transport distance is $500\ \mathrm{km}$ for the hydrogen produced in Europe and $3'000\ \mathrm{km}$ for the one produced in the MENA region (see annex A.4).

The EU Parliament and the council concerning the Alternative Fuels Infrastructure Regulation (AFIR) have agreed in March 2023 that hydrogen refuelling infrastructure must be deployed from 2030 onwards in all urban nodes and every $200\ \mathrm{km}$ along the TEN-T core network, to serve both cars and lorries and to allow hydrogen vehicles to travel across the EU.

3.4.3 Methane Infrastructure

Existing Methane Infrastructure

Natural gas of fossil origin is a mixture of methane (at least 90%) and other gases (i.e., CO_2, C_xH_y), and is as such chemically very similar to synthetic methane (Syn. CH_4) and biomethane (Bio CH_4). All of them can therefore be distributed in the same infrastructure, used in the same vehicles, and are all available in compressed form (compressed natural gas, CNG, compressed biomethane, CBG) or liquefied form (liquefied natural gas, LNG, liquefied biogas, LBG). The handling of both states, gaseous and liquid, is well established, and they are interconnected trough liquefaction and regasification plants. For the sake of simplicity, only liquefaction but no regasification is considered in this study (see Figure 13).

Natural gas refuelling stations have been operating in Europe for many years, and their number is increasing steadily even though their distribution between countries is uneven. This uneven distribution reflects an uneven market share, which has its reason in tax benefits acknowledging reduced GHG emissions by renewable methane only in some of the countries. Within Europe[12], 3'380 refuelling stations were in service in January 2018, 3,900 in January 2021 and 4,160 in January 2023 [61,62], hence the number of units increases between 3% and 5% every year. CNG is used in both heavy-duty vehicles (HDV) and passenger cars but only a fraction of the refuelling stations are suitable for trucks in terms of methane flow rate and amount of methane refillable per day. On the other hand, liquified natural gas (LNG) targets mainly heavy-duty trucks and so all refuelling stations can be used by trucks. Table 7 shows the number of refuelling stations of each type available within the five countries of interest and in whole Europe. Based on direct information from gas associations, we assume that 10% of the CNG refuelling stations are suitable for heavy-duty vehicles (HDV). Some of the listed refuelling stations are private (e.g. Switzerland's three LNG stations) and thus not openly accessible.

Table 7: Number of CNG and LNG refuelling stations in 2022, Sources: [62,63],

	Compressed natural gas (CNG) refuelling stations	CNG refuelling stations suited for heavy-duty vehicles (HDV) assumed to be 10% of all CNG refuelling stations	Liquefied natural gas (LNG) refuelling stations
Germany (DE)	770	77	160
France (FR)	210	21	70
Italy (IT)	1,500	150	130
Poland (PL)	22	2	24
Switzerland (CH)	150	15	4
Total Europe[12]	4,160	416	632

A wide network of pipelines, compressors and pressure reduction stations is already operating in Europe for the transport and distribution of natural gas. This network has been built decades ago and connects most of the households and industries in the majority of European countries. It is available as a convenient base to supply new refuelling stations for long-haul road transport as it follows the main communication axes. Most of the time, the methane is available at a low pressure (50 mbarg or 5 barg) from the grid and it is compressed at the refuelling station to allow a pressure of 200 bar in the vehicle.

If not by pipeline, methane is mostly transported from centralised liquefaction facilities to the refuelling stations in its liquid state (LNG) in cryogenic transport trailers at a temperature of -160 °C. If the destination is an LNG refuelling station, the methane is directly fed into the vehicle. Otherwise, it is regasified in a dedicated facility before being delivered to the CNG refuelling station.

It is also possible to transport the centrally compressed gas by truck before being simply stored in the refuelling station and fuelled to the vehicles. Due to the lower density and thus the larger volume, this solution tends to increase the cost of transport but at the same time it allows to decrease the investment costs for the refuelling stations itself.

As for oversea transport, methane can be transported in compressed or liquified state. Both CNG and LNG carriers are matured means of transportation, the first type being used for short and medium distances while the second type is used for longer distances. After being transported overseas,

[12] EU-27 + Bosnia and Herzegovina, North Macedonia, Norway, Serbia, Switzerland, Turkey and the United Kingdom

LNG can be regasified before being further transported in pipelines. This is a classic transportation path for natural gas and the infrastructure is already in place.

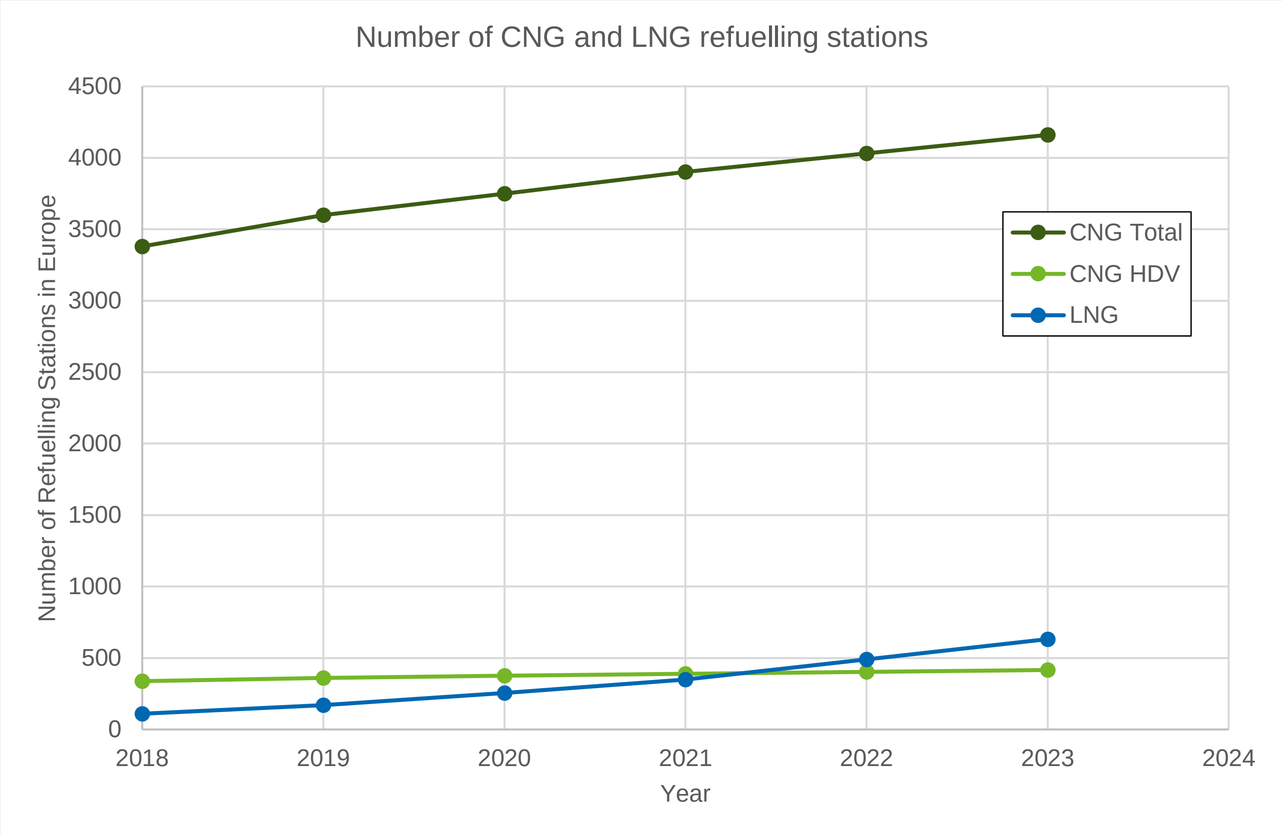
Plans for Future Methane Infrastructure

In its communication from November 2017 [64], the European Commission asserts its intention for the European Union to become *a world leader on decarbonisation* and provides guidance to the member states to reach the low emission mobility goals. Looking at compressed and liquified methane, the goal in 2017 was to add around 2’600 CNG refuelling stations as well as 250 to 450 LNG stations by 2025. If the number of refuelling stations continues to increase linearly, over 5’000 refuelling stations for compressed methane (CNG) will be operational in 2030. Their construction is hence under way, even if the target mentioned above for CNG refuelling stations will not be totally achieved.

The number of LNG stations is also increasing linearly with a slight acceleration [61]. If this trend continues, between 1,300 and 1,600 LNG stations will be in operation by 2030. The study of ACEA [45] suggests that 1,500 stations should be installed by then, which is in line with the current pace. Moreover, according to Heckler [65], Germany should have built 200 LNG refuelling stations by 2025. That translates into an increase of 35% from today, which can be outreached if the current pace of construction is kept constant.

But even if these figures are promising, one must keep in mind that the number of vehicles fuelled with compressed methane (CNG) – and in a lesser extend with liquefied methane (LNG) – are rather on a downward slope in Europe. Because the EU fleet emission regulation does not consider them CO_2-neutral, even when powered by biomethane or synthetic methane, the manufacturers are increasingly reluctant to offer new models. As a consequence, the number of customers also decreases and so might the number of methane-powered vehicles on the roads in a short-term future. For the operators of refuelling stations, this means fewer customers, less revenues and therefore less investment in the infrastructure in the absence of subsidies. It is therefore far from obvious that the number of CNG and LNG refuelling stations will indeed continue to increase in the future and that the above-mentioned targets will be reached. For this study, it was assumed that 10 % of all CNG refuelling stations are suitable for heavy-duty vehicles (HDV) (see Figure 10), and that these will stay in operation in the future.

Figure 10: Number of CNG and LNG refuelling Stations in Europe [54,61–63,65], CNG for heavy-duty vehicles (HDV) are estimated to be 10% of total CNG refuelling stations.



The natural gas transport infrastructure is well developed in Europe; hence an extension is not required to supply methane for long-haul transport. However, the European Hydrogen Backbone mentioned in section 3.4.2 also foresees using existing natural gas pipelines for hydrogen which would then no longer be available for methane. The pipelines cannot carry both natural gas and hydrogen separately, and a mixture of them would make the separation at the fuelling station difficult and expensive. Indeed, while CNG and LNG vehicles are approved for a maximum hydrogen content of 2%, regulations are about to be changed such that more hydrogen is allowed in the gas infrastructure. It is therefore important to keep this aspect in mind when planning the future distribution network of natural gas and hydrogen. In this study, a transport distance of $500\ \mathrm{km}$ is assumed for the methane produced in the EU and $3'000\ \mathrm{km}$ for the methane produced in the MENA region (see annex A.4 Table 22 lines 431 and 432).

In case the use of LNG substantially increases, it could be convenient to build a liquification facility closer to the fuelling stations. As a result, methane could be transported via pipeline up to the liquefaction facility and LNG can be stored locally, close to the refuelling station.

Renewable gas production

The bulk of European renewable gas production today is in raw biogas. Only a smaller portion is processed further into biomethane. While the total raw biogas production has stagnated over the past decade, biomethane production is still growing. In 2021 the combined raw biogas and biomethane production in Europe was about $196\ \mathrm{TWh/a}$, with an increase in biomethane production corresponding to 20% and $37\ \mathrm{TWh/a}$. Since REPowerEU there is a clear target to reach $35 \cdot 10^9\ \mathrm{Nm}^3$ ($\sim 337\ \mathrm{TWh/a}$) biomethane production in 2030. [66]

58% of the biomethane in Europe are connected to the distribution grid and 19% to the transport grid. 9% of European biomethane plants do not have a grid connection and for the remaining 14% of Europe's plants no information is available. There were 15 active Bio-LNG producing plants in Europe by the end of 2021, and this number is expected to increase sharply in the years 2022 (+ 19 plants), 2023 (+ 43 plants) and 2024 (+ 21 plants). Two extra plants are already planned to start operation in 2025. The combined Bio-LNG production capacity by 2025, considering only confirmed plants, adds up to $12.4\,\mathrm{TWh/a}$. 133 plants are known to compress biomethane on-site to produce Bio-CNG. [66]

3.4.4 E-Fuels/HVO Infrastructure

Existing E-Fuels/HVO Infrastructure

There is currently little infrastructure worldwide to produce E-Fuels. The first plant was “George Olah Renewable Methanol Plant” in Iceland in operation between 2012 and 2019 with a capacity of $4{,}000\,\mathrm{t/a}$ [67]. Plants currently in operating are “Haru Oni” in Chile opened in December 2022 [68], “Next GATE” in Hamburg, Germany [69], CAC Synfuel Plant in Freiberg, Germany [70], “Atmosfair Fairfuel” in Werlte, Germany [71] and “CRI Shunli Project” operated in Anyang, China [67].

Worldwide production capacity of hydrogenated vegetable oil (HVO) in 2021 was $6{,}520{,}000\,\mathrm{t/a}$ half of it in Europe [72]. HVO is produced at nine sites in Europe, with the first one being in operation since 2007 [31]. The total European production in 2021 was $3{,}295{,}000\,\mathrm{t/a}$ [72]. The last facility that went into production is located in Gothenburg, Sweden with a production capacity of $210{,}000\,\mathrm{t/a}$ [31].

The transport of diesel is also a well-established process, and the current main path is the following: crude oil is transported by oil tankers to the main ports of Europe and then brought by pipelines to the refineries. Once the fuel is refined, the products are transported by truck to storage tanks and final customers (industry or refuelling stations). Every step of this process is state-of-the-art and well in place. E-Diesel from Fischer-Tropsch (FT) and hydrogenated vegetable oil (HVO) are comparable to fossil diesel and therefore the same transport and refuelling infrastructure as well as type of vehicle can be used. $140{,}000$ conventional diesel fuelling stations spread over all countries operate in the EU-27 [73].

Plans for Future E-Fuels/HVO Infrastructure

The E-Fuel Alliance website shows a map with a selection of announced or already existing production sites [74]. In addition to the methanol site closed in 2019 and the four currently operating plants mentioned above, the website shows 12 more projects in the planning phase. Company websites [67,75] list four more planned production sites. [76] mentions 35 announced future plants. Production capacity of hydrogenated vegetable oil (HVO) was increasing constantly in recent years [72,77] and is expected to continue to do so. One new European plant in Sweden is planned to start production in 2024 with a capacity of $750{,}000\,\mathrm{t/a}$ for example. Another one, in Rotterdam, is expected to see its production almost double by 2026, from 1.3 to $2.7\,\mathrm{mio}\,\mathrm{t/a}$ [78].

E-Diesel/HVO can be transported in the current infrastructure and can be fuelled in the current traditional refuelling station with little to no modification required. Therefore, future plans on this existing infrastructure does not need to be discussed. A transport distance of 200 km by pipeline is assumed for the E-Fuels/HVO produced in Europe and 2’500 km by ship for the fuel produced in the MENA region (see annex A.4).

4 European Long-Haul Road Transport in 2030

4.1 Energy Supplies for Renewable Fuel Vehicle Technologies

This section focuses on the supply chain of the four main energy carriers considered as input fuel for the four renewable fuel powertrains described in section 3.3, Table 6. As described in section 1.3.1, this study considers two locations where energy carriers are produced: Europe and the region consisting of Middle East and Northern Africa (MENA). Different assumptions are made depending on the geographic location of the fuel production. These assumptions are summarized in Table 8, which gives an overview of the energy supply paths. Figure 11 to Figure 15 and Table 22 in Appendix A.4 show the path-specific parameters assumed in this study.

In the case of battery electric vehicles (BEV), the electricity is assumed to be entirely produced in Europe from PV, wind onshore and wind offshore facilities (see section 2.2 for the assumptions on the potential of renewable energy production). Indeed, it is assumed that in 2030 no infrastructure is available to import electricity from Middle East and Northern Africa (MENA) to Europe. This would have been the idea of the Desertec Initiative [79] founded in 2003, but the project has been abandoned, and only renewable electricity produced in Europe is therefore considered in this study.

In the case of hydrogen-fuelled vehicles, only hydrogen produced by electrolysers commercially available today is considered in this study. Novel electrolyser concepts with higher efficiencies (e.g., high temperature electrolysers and capillary electrolyser [80,81]) are assumed not to be available on a large scale in 2030 and are therefore not included here. Regarding the geographical location of the production facilities, it is assumed that hydrogen is produced by converting renewable electricity either in Europe or in the region Middle East and Northern Africa (MENA). In the latter case, it is imported to Europe through the European Hydrogen Backbone (see section 3.4.2).

In the frame of this study both synthetic methane (Syn. CH_4) and biomethane (Bio CH_4) are considered. Hydrogen and CO_2 are required to produce synthetic methane (Syn. CH_4). The same production at the same locations is assumed. The hydrogen from the Middle East and Northern Africa (MENA) is not transported but converted to methane in the same location. CO_2 is provided by means of carbon capture technologies selected based on the geographic location of the methane production plant. If synthetic methane is produced in Europe, CO_2 is assumed to be captured from point sources, such as flue gases of industrial processes or biogas facilities. If the production is in the Middle East and Northern Africa (MENA), CO_2 is provided by direct air capture (DAC). This technology is selected despite its higher energy consumption per unit of CO_2 captured because only few CO_2 point sources are assumed to be available in the Middle East and Northern Africa (MENA) at the same location with ample renewable electricity for economic hydrogen production. In other words, the amount CO_2 from industry, biogas plants or wastewater treatment are not enough to provide the necessary amount synthetic methane. The synthetic methane produced is assumed to be imported through the existing natural gas pipelines connecting the Middle East and Northern Africa (MENA) with Southern Europe. Regarding biomethane, given the biomass scarcity in the MENA region, no import of biomethane is assumed. All biomethane production is located in Europe. Depending on the type of biogenic waste processed in the biogas plant, the composition of the raw biogas can vary. In this study a volumetric composition of 60% CH_4 and 40% CO_2 is assumed. By applying a CO_2 separation unit, biomethane is separated from CO_2. This production path is reported as “Bio. CH_4” in Table 8. Additionally, the biogenic CO_2 can be combined with hydrogen to generate CH_4. Here the same hydrogen production pathways as described above are considered. This option is named “CC from Biogas” and is included in Table 8.

The same assumptions made for synthetic methane are applied to E-Diesel produced in Fischer-Tropsch processes (FT). The E-Diesel produced in Middle East and Northern Africa (MENA) is imported to Europe by ship while using the same infrastructure used for fossil diesel todays. Finally, hydrogenated vegetable oil (HVO) from both used cooking oil (UCO) and rapeseed oil are considered and assumed to be available both in Europe and in the Middle East and Northern Africa (MENA).

Between the options listed in Table 8 some energy supply paths use agricultural products: The "Biogas (Corn)" path, where corn is the main energy input, and the three path for hydrogenated vegetable oil (HVO), where rapeseed oil is used as the main source of energy. Since these agricultural products (i.e., corn and rapeseed oil) compete with food production on limited cultivable land, a "food vs fuel" debate arises. Europe's "Renewable Energy Directive II" (REDII) therefore limits the use of these fuels in the EU, and Switzerland does not recognise them as sustainable and applies the same tax as for fossil fuels.

The study focuses on renewable energy supply paths only. Some technologies with low GHG emissions do not fall into the category of the renewables and were not considered: Nuclear power for battery electric trucks (BEV) and for production of hydrogen (H_2), synthetic methane (Syn. CH_4), E-Fuels and hydrogenated vegetable oil (HVO). Pyrolysis, where fossil natural gas or biogas is split into hydrogen (H_2) and solid carbon easily storable.

Table 8: Supply paths of renewable energy for the four renewable fuel technologies from Table 6.

Energy used in Vehicle	Europe / abroad	Well-to-Tank Paths	Abbreviation
Electricity (Figure 11)	Produced in Europe	PV Europe	BEV-PV
		Wind onshore Europe	BEV-Wind Onshore
		Wind offshore Europe	BEV-Wind-Offshore
Hydrogen (Figure 12)	Imported to Europe	PV and power-to-H_2 in MENA, import through European Hydrogen Backbone	H2-PV-MENA
	Produced in Europe	PV and power-to-H_2 in Europe	H2-PV-EU
		Wind onshore, power-to-H_2 in Europe	H2-Wind Onshore
		Wind offshore, power-to-H_2 in Europe	H2-Wind Offshore
Methane, both synthetic (Syn. CH_4) and biogenic (Bio. CH_4) (Figure 13)	Imported to Europe	PV, atmospheric CO_2 (DAC), power-to-CH_4 plant, all in MENA, import as CNG and LNG through existing infrastructure today used for natural gas.	CH4-PV-MENA CH4 Gas DAC CH4-PV-MENA CH4 Liq DAC
	Produced in Europe	PV, CO_2 from concentrated sources (for Syn. CH_4 from flue gases of industrial processes, whereas for Bio. CH_4 from biogas plants), power-to-CH_4 plant in Europe, CNG and LNG.	CH4-PV-EU CH4 Gas CC from Ind. CH4-PV-EU CH4 Liq CC from Ind. CH4-PV-EU CH4 Gas CC from Biogas CH4-PV-EU CH4 Liq CC from Biogas
		Wind onshore, CO_2 from concentrated source (flue gas or biogas plants), power-to-CH_4 plant in Europe, CNG and LNG.	CH4-Wind On. CH4 Gas CC from Ind. CH4-Wind On. CH4 Liq CC from Ind. CH4-Wind On. CH4 Gas CC from Biogas CH4-Wind On. CH4 Liq CC from Biogas
		Wind offshore, CO_2 from concentrated source (flue gas or biogas plants), power-to-CH_4 plant in Europe, CNG and LNG.	CH4-Wind Off. CH4 Gas CC from Ind. CH4-Wind Off. CH4 Liq CC from Ind. CH4-Wind Off. CH4 Gas CC from Biogas CH4-Wind Off. CH4 Liq CC from Biogas
		European biomethane from three different feedstocks: Manure, Corn, Biowaste, CNG only	CH4-Biogas (Manure) CH4-Biogas (Corn) CH4-Biogas (Biowaste)

Energy used in Vehicle	**Europe / abroad**	**Well-to-Tank Paths**	**Abbreviation**
E-Diesel from Fischer-Tropsch process (FT) (Figure 14)	Imported to Europe	E-Diesel from PV, atmospheric CO_2 (DAC), power-to-liquid plant (FT), all in MENA, import through same infrastructure used for fossil fuels	FT-PV-MENA (DAC)
	Produced in Europe	E-Diesel from PV, CO_2 from concentrated industrial source, power-to-liquid plant (FT), all in Europe	FT-PV-EU (CC from Ind.)
		E-Diesel from Wind onshore, CO_2 from concentrated industrial source, power-to-liquid plant (FT), all in Europe	FT-Wind On. (CC from Ind.)
		E-Diesel from Wind offshore, CO_2 from concentrated industrial source, power-to-liquid plant (FT), all in Europe	FT-Wind Off. (CC from Ind.)
Hydrogenated Vegetable Oil (HVO) (Figure 15)	Imported to Europe	HVO from rapeseed or used cooking oil (UCO), electricity from PV, all in MENA, import through same infrastructure used for fossil fuels	HVO-PV-MENA (Rapeseed oil) HVO-PV-MENA (Used oil)
	Produced in Europe	HVO from rapeseed or used oil, electricity from PV, production in Europe	HVO-PV-EU (Rapeseed oil) HVO-PV-EU (Used oil)
		HVO from rapeseed or used oil, electricity from wind onshore, production in Europe	HVO-Wind On. (Rapeseed oil) HVO-Wind On. (Used oil)
		HVO from rapeseed or used oil, electricity from wind offshore, production in Europe	HVO-Wind Off. (Rapeseed oil) HVO-Wind Off. (Used oil)

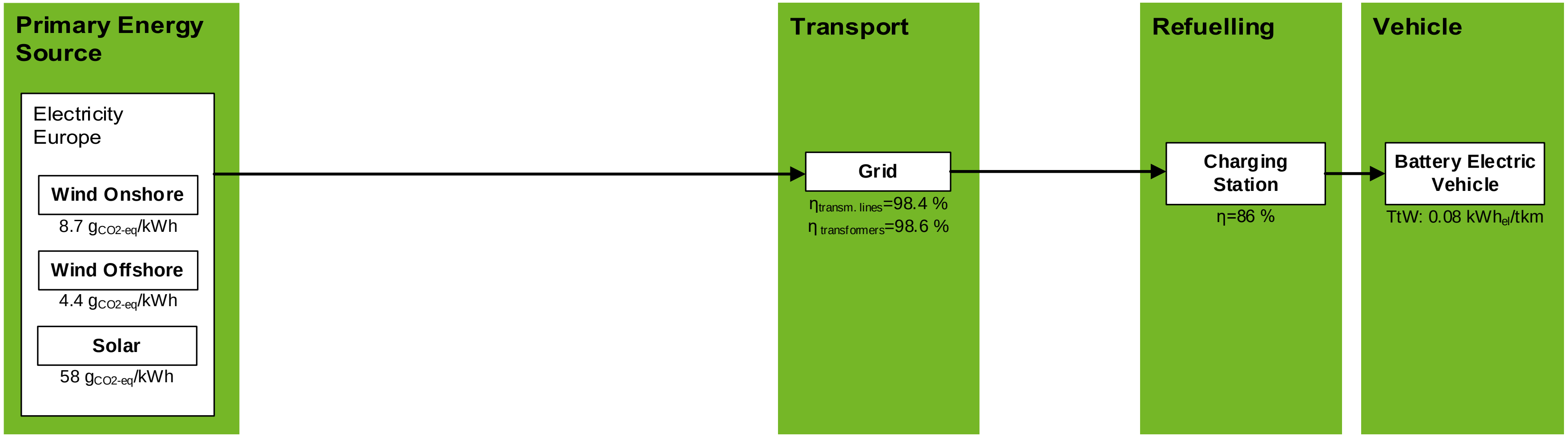


Figure 11: Supply of renewable energy for battery electric vehicles (BEV).

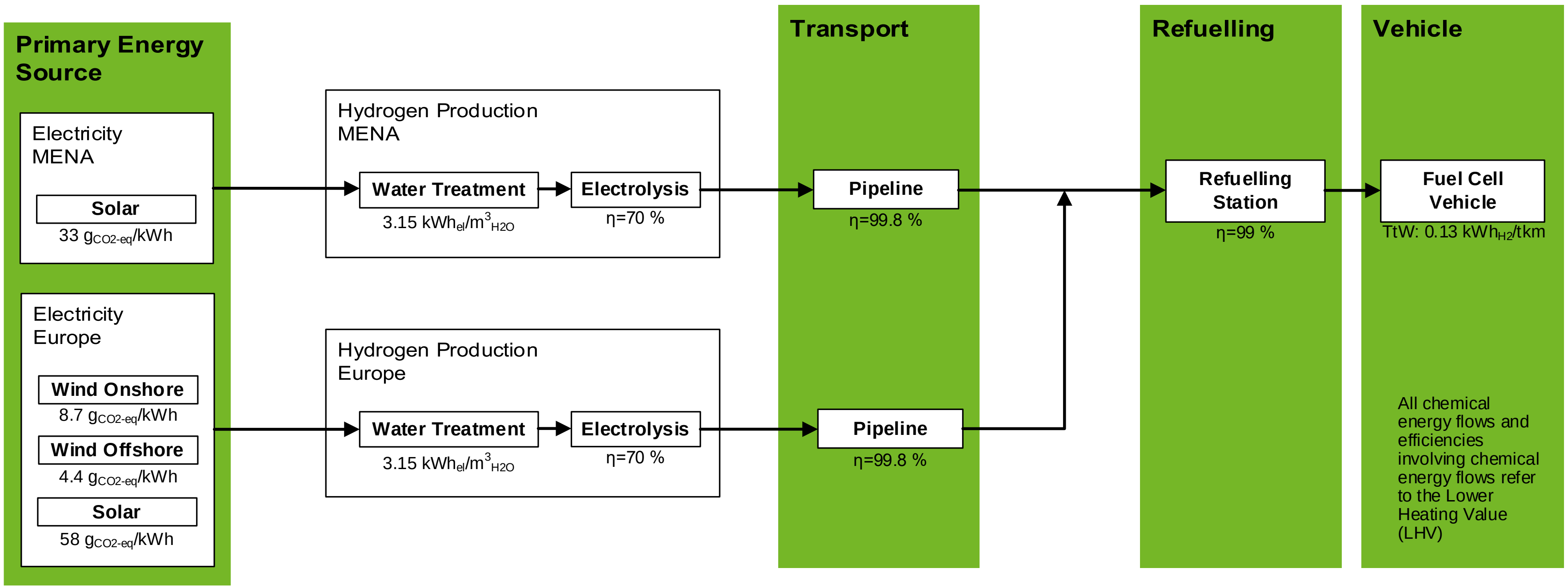


Figure 12: Supply of renewable energy in the form of hydrogen (H_2) fuel cell electric vehicles (FCEV).

Figure 13: Renewable energy for vehicles with internal combustion engines (ICE) using renewable methane (CH_4).

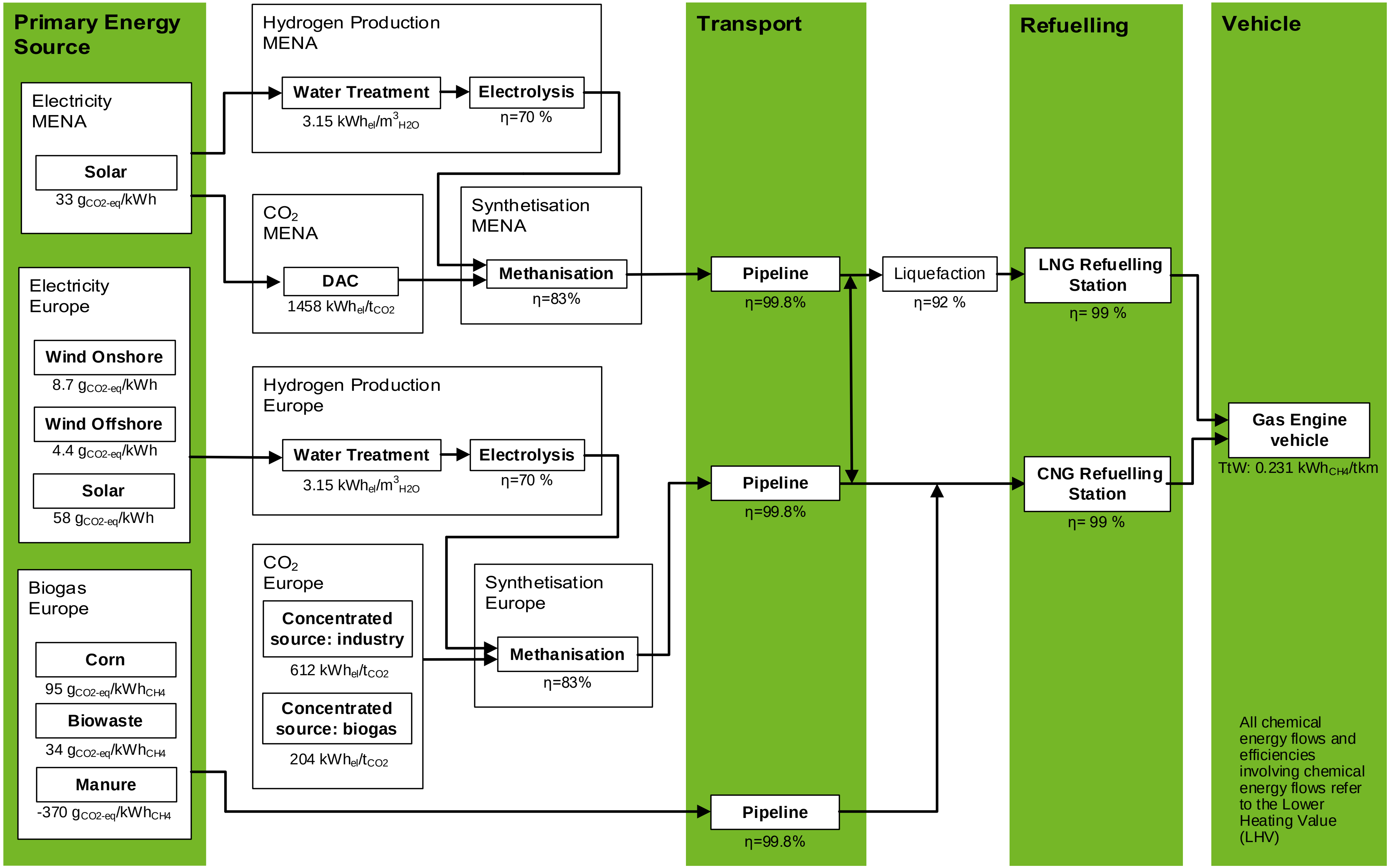


Figure 14: Energy supply paths for vehicles with internal combustion engines (ICE) using E-Diesel.

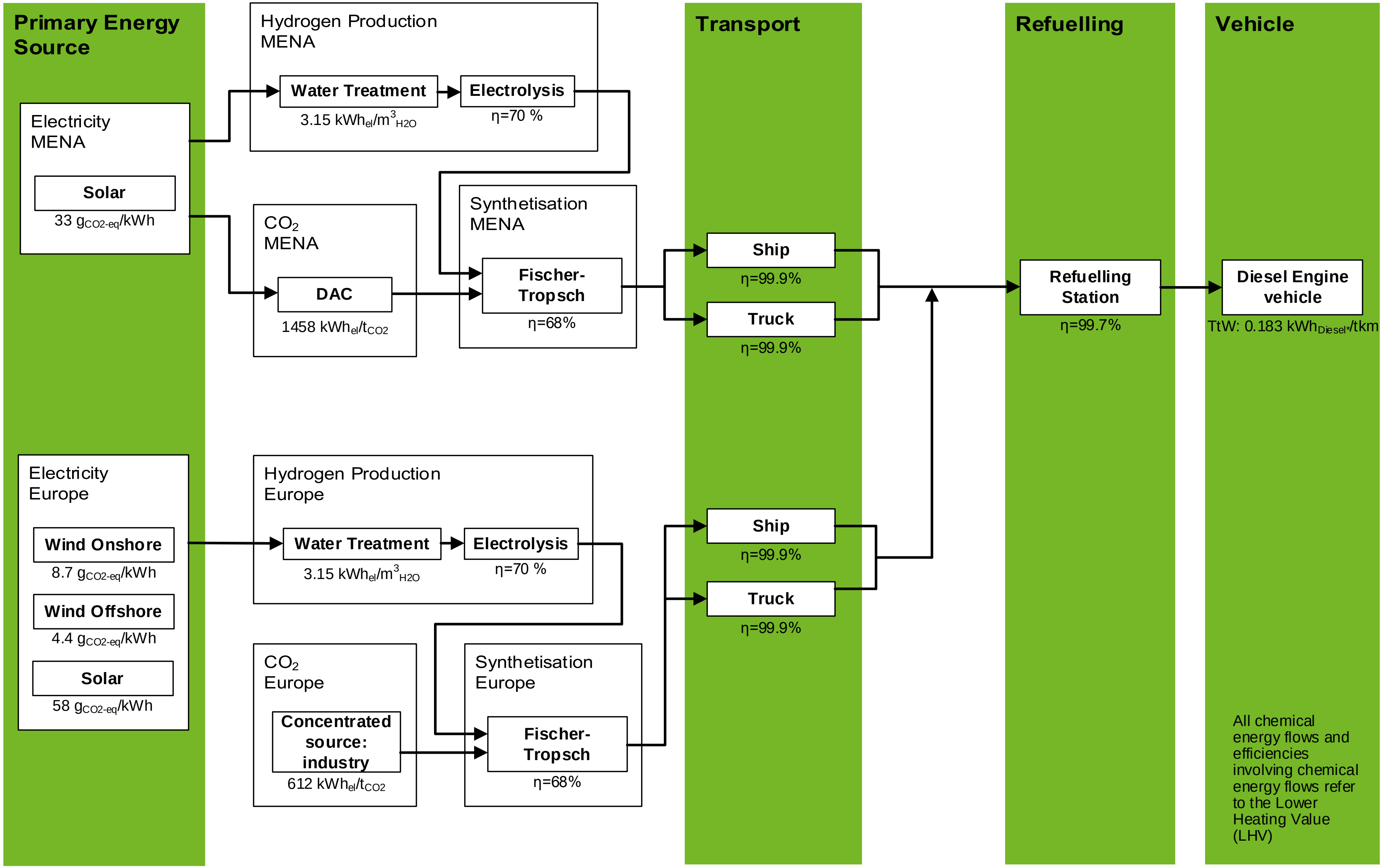
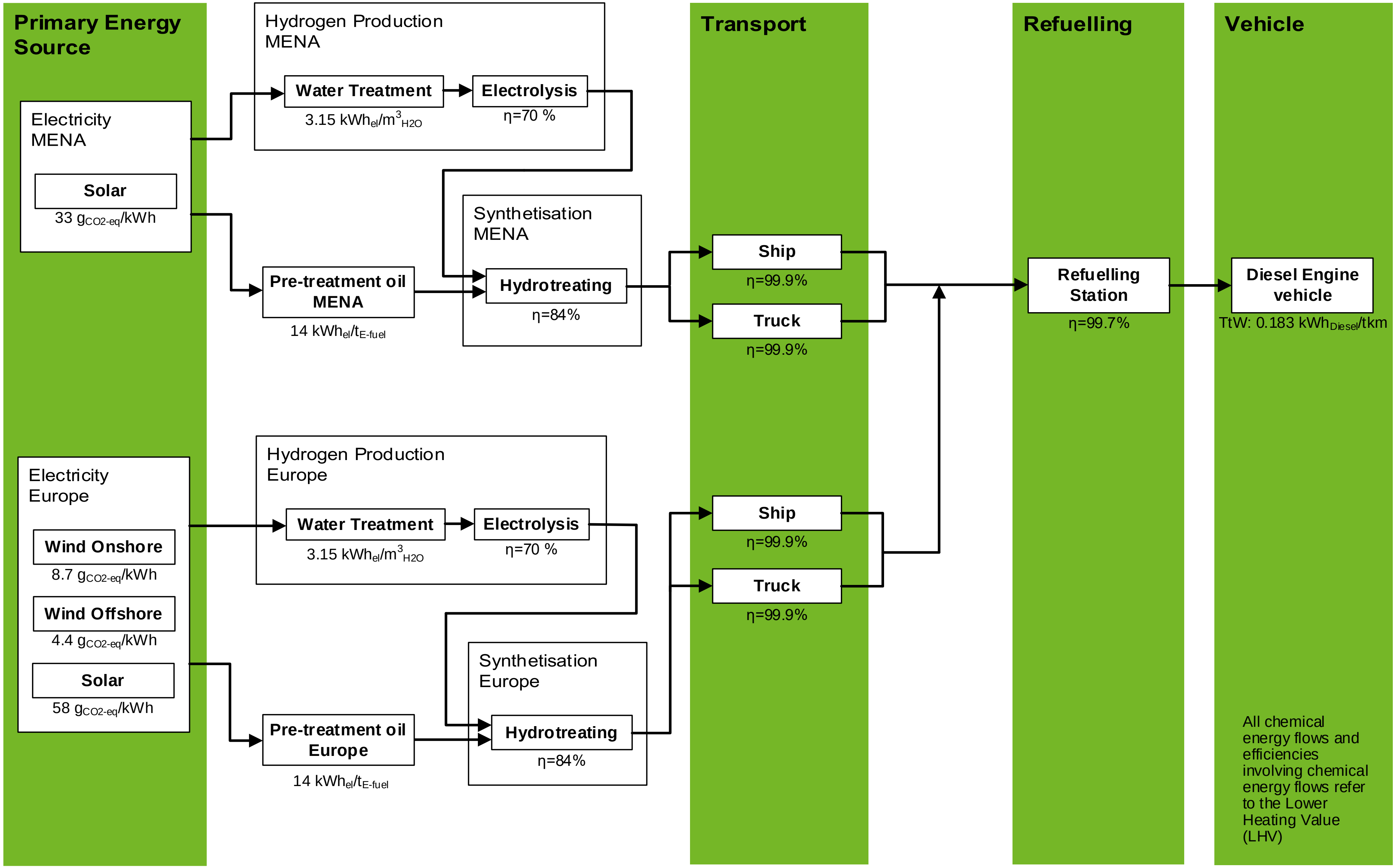


Figure 15: Energy supply paths for vehicles with internal combustion engine using hydrogenated vegetable Oil (HVO).

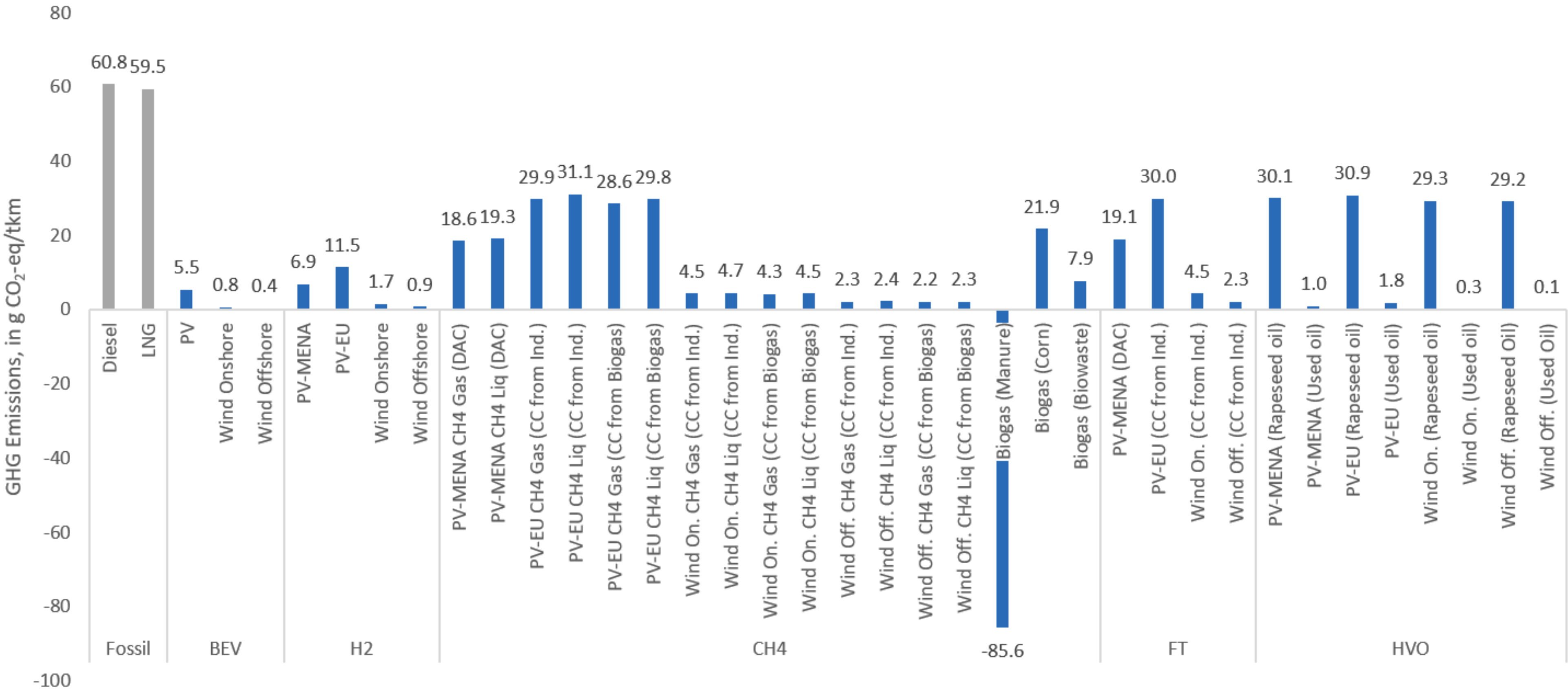


4.2 GHG Emissions of Renewable Fuel Vehicle Technologies

The GHG emissions (Well-to-Wheel, WtW) of the four renewable fuel technologies listed in Table 6 supplied with renewable energy through the paths shown in Table 8 are displayed in Figure . And for comparison, the GHG emissions of 2030 state-of-the-art diesel trucks and trucks running on liquefied fossil natural gas (LNG) are presented as well. The following observations can be made:

- Comparing the $61\,\mathrm{g\,CO_{2eq}/tkm}$ of new Diesel trucks from Figure with the $69\,\mathrm{g\,CO_{2eq}/tkm}$ in 2020 from Table 5 shows that Diesel technology will improve and be able to reduce GHG emissions per functional unit by almost 12%.
- The fact that among the electricity sources considered, electricity from PV has the highest GHG emissions ($33\ \mathrm{g\,CO_{2eq}/kWh}$) followed by wind onshore ($8.7\,\mathrm{g\,CO_{2eq}/kWh}$) and wind offshore ($4.4\,\mathrm{g\,CO_{2eq}/kWh}$) manifests itself in the final GHG emissions per tonne-kilometre of each individual technology. The energy supply paths for battery-electric vehicles (BEV) have the same order of magnitude in GHG emissions. The same is true for the four energy supply paths for fuel cell electric vehicles (H_2), the many energy supply paths for synthetic methane (CH_4) and E-Diesel (FT).
- The negative GHG emissions attributed to biomethane from manure (CH_4-Biogas (Manure) in Table 8) of $-85.6\,\mathrm{g\,CO_{2eq}/tkm}$ stands out. The reason for the negative value is that if manure is not used for biomethane production, it remains on the farm and emits GHGs also in the form of methane, which has a much higher impact on global warming than CO_2. Producing biomethane avoids these emissions and therefore leads to negative emissions.
- The GHG emissions using renewable methane are almost the same for compressed methane (CNG) and liquefied methane (LNG) with a slight advantage for compressed methane (CNG) due to the higher effort for liquefaction in comparison to compression.
- The figures for synthetic methane and E-Diesel show that using CO_2 diluted in the atmosphere by direct air capture (DAC) gives a small disadvantage compared to using CO_2 from concentrated sources.
- The energy supply paths using agricultural products (Table 8, “Biogas (Corn)” and the paths of hydrogenated vegetable oil (HVO) using rapeseed oil) have considerably higher GHG emissions than when the energy carrier is based on waste products. Hydrogenated vegetable oil (HVO) from used oil is among the best performing energy supply paths considered.

Figure 16: GHG emissions per tkm from a Well-to-Wheel analysis for the expected state of the art in 2030 of the technologies from Table 6 and the energy supply paths from Table 8.



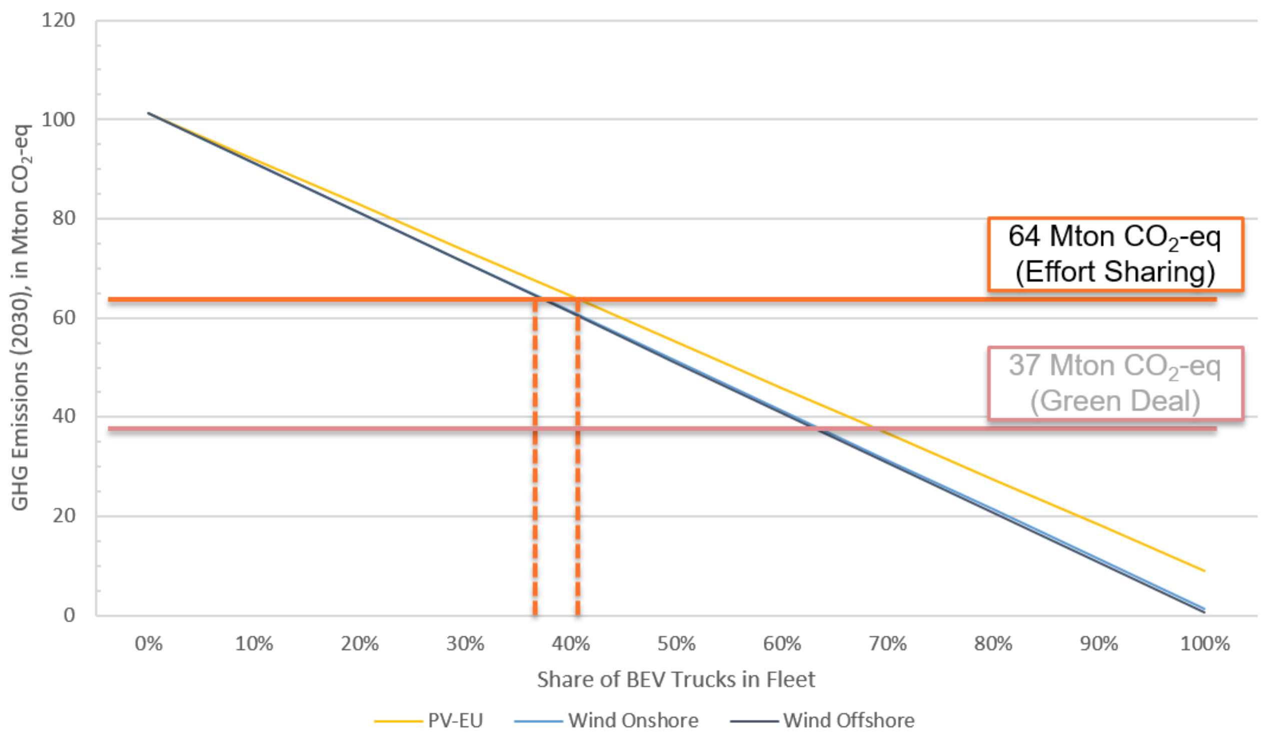
4.3 Exclusive Scenarios

If in 2030 the European long-haul road transport is addressed by a fleet of only new diesel trucks, the GHG emissions of long-haul road transport would reach $101\,\mathrm{MtCO_{2eq}/a}$ (see Figure 17). Table 5 shows that despite a predicted increase in transport capacity by 18%, from $1{,}400$ Gtkm/a in 2020 to $1'660\,\mathrm{Gtkm/a}$ in 2030, GHG emissions would increase by 4% only, from $97\,\mathrm{MtCO_{2eq}/a}$ to $101\,\mathrm{MtCO_{2eq}/a}$, thanks to the new diesel power trains. However, this value is way above the two targets mentioned in section 3.2. of $64\,\mathrm{MtCO_{2eq}/a}$ according to the "Effort Sharing" approach and $37\,\mathrm{MtCO_{2eq}/a}$ according to "Green deal for all".

In the framework of this study four exclusive scenarios are defined. The aim of this exclusive scenarios is to reach the targets of GHG emissions by combining one new powertrain technology from Table 6 with new diesel trucks. The current diesel truck fleet is assumed to be replaced with 2030-state-of-the-art diesel truck, here referred to as "New Diesel". Table 8 summarizes the GHG emissions per tonne-kilometre of the renewable energy supply paths considered. In each exclusive scenario, the fleet will perform $1{,}660\,\mathrm{Gtkm/a}$.

Figure 17 shows the Well-to-Wheel GHG emissions of the trucks fleet in the frame of the exclusive scenario "Battery Electric and New Diesel" as a function of the share of BEV vehicles introduced. With 0% share of battery-electric vehicles, the GHG emissions would be $101\,\mathrm{MtCO_{2eq}/a}$ as discussed above. To reach the effort sharing target of $64\,\mathrm{MtCO_{2eq}/a}$, a share of 37% up to 40% (depending on the origin of the renewable electricity) is required. To reach the green deal target of $37\,\mathrm{MtCO_{2eq}/a}$, a share of BEV vehicles between 64% and 70% would be required.

Figure 17: Exclusive Scenario "Battery Electric and New Diesel": Well-to-Wheel (WtW) GHG emissions of Europe's long-haul truck fleet consisting of new diesel trucks and a share of battery-electric vehicles (BEV).



Similar analysis can be conducted for the exclusive scenarios "Hydrogen and New Diesel", "Methane and New Diesel" and "E-Fuels and New Diesel". The results are shown in Figure 18, Figure 19 and Figure 20 respectively. The results are then summarised in Table 9.

Figure 18: Exclusive Scenario "Hydrogen (H2) and New Diesel": Well-to-Wheel (WtW) GHG emissions of Europe's long-haul truck fleet consisting of new diesel trucks and a share of hydrogen fuel cell electric vehicles (FCEV).

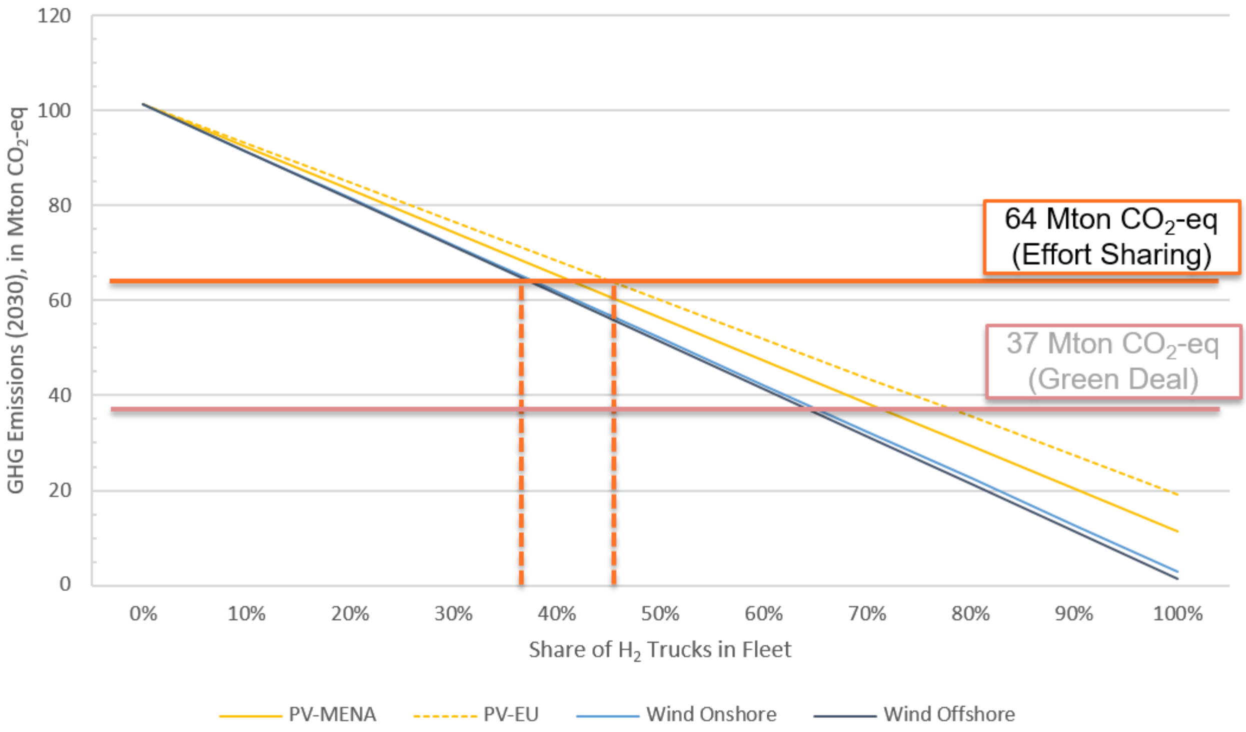


Figure 19: Exclusive Scenario "Methane (CH_4) and New Diesel": Well-to-Wheel GHG emissions of Europe's long-haul truck fleet consisting of new diesel trucks and a share of trucks with internal combustion engines running on renewable methane (CH_4).

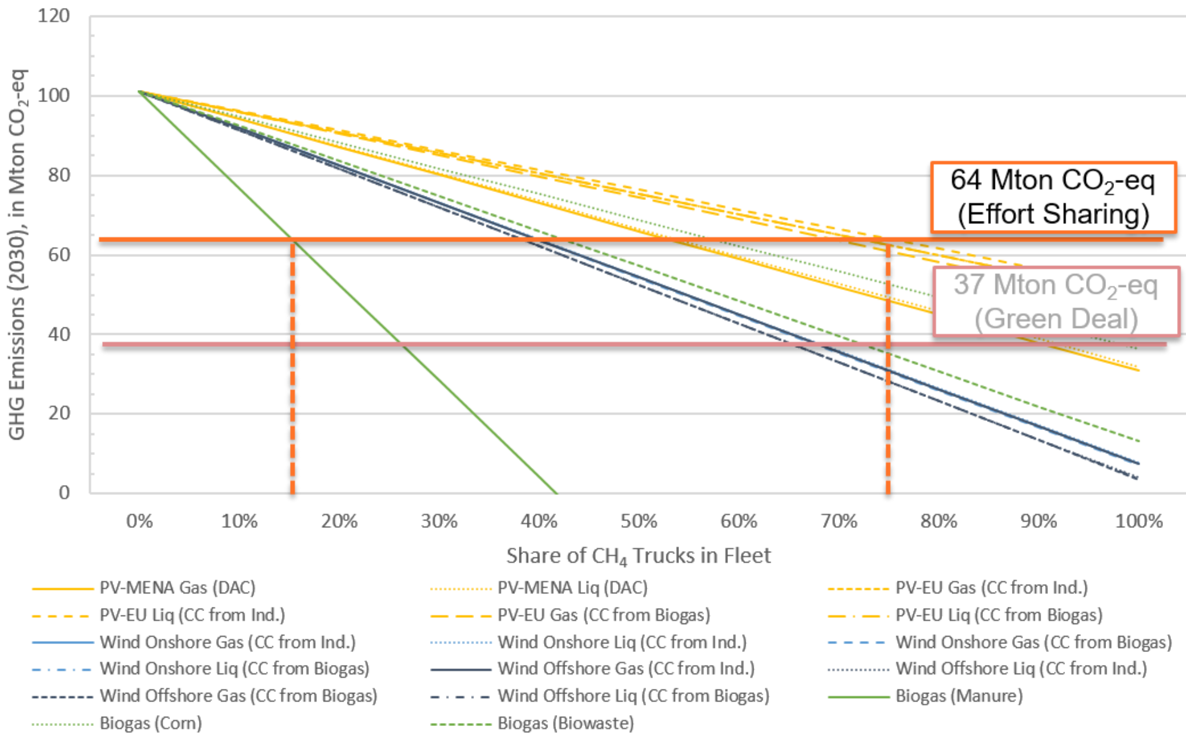


Figure 20: Exclusive Scenario "E-Fuels and New Diesel": Well-to-Wheel GHG emissions of Europe's long-haul truck fleet consisting of new diesel trucks and a share of trucks with internal combustion engines running on E-Fuels.

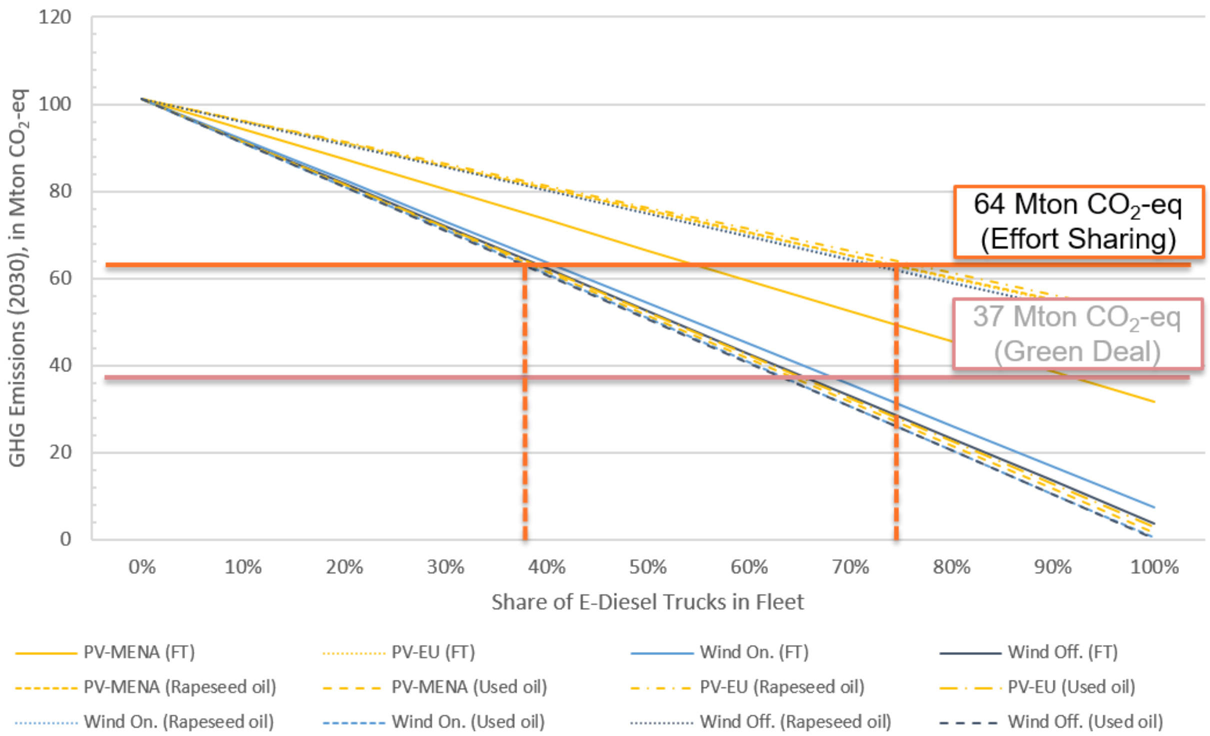


Table 9: Exclusive Scenarios as well as the minimum and maximum shares of the renewable fuel technology in the operating fleet. The energy supply paths from Table 8 determining the minimum share and the maximum share are also given.

Exclusive Scenarios	**Composition of operating fleet in 2030 to fulfil target of GHG emission following the "Effort Sharing" approach:** $1'660\ \mathrm{Gtkm/a}$ with allowable GHG emissions of $64\ \mathrm{MtCO_{2eq}/a}$	
	Minimum share	Maximum share
Battery Electric and New Diesel	37% BEV "Wind Onshore & Offshore"	40% BEV "PV-EU"
Hydrogen and New Diesel	37% FCEV "Wind Offshore"	45% FCEV "PV-EU"
Methane and New Diesel	38% CH_4 "Wind Offshore"	75% CH_4 "PV-EU"
	15% CH_4 "Biogas (Manure)"	57% CH_4 "Biogas (Biowaste)"
E-Fuels and New Diesel	38% E-Fuel "Wind Offshore"	72% E-Fuel "PV-EU"
	37% E-Fuel "All Used Oil paths"	75% E-Fuel "PV-EU (Rapeseed oil)"

4.4 Estimated Annual Cost of Exclusive Scenarios

For each "Exclusive Scenario" and energy supply chain from Table 8, the annual cost is estimated for the year 2030. As detailed in section 1.3.4 Equation 1.1, the annual cost consists of (i) fuel production cost C_P, (ii) transportation cost C_T, (iii) refuelling cost C_R and (iv) fleet cost C_F. The parameters used for calculating the annual cost are discussed in the following subsections and listed in Appendix A.4. The parameters are average parameters from the references, which is important to keep in mind especially for parameters with large fluctuations. These are the solar potential not only increasing towards the south but also varying with altitude and wind potentials, which can deviate from the average considerably.

4.4.1 Vehicles

The quantitative data used in the annual cost calculation is given in Appendix A.4 Table 22. As an example of data used and because it might be interesting to many readers, the capital expenditures (CAPEX) for trucks anticipated for 2030 are shown in Table 10. The data shows that battery-electric trucks (BEV) are considered 35% more expensive than new diesel trucks in 2030, fuel cell electric trucks (FCEV) 26% and trucks for methane 10%.

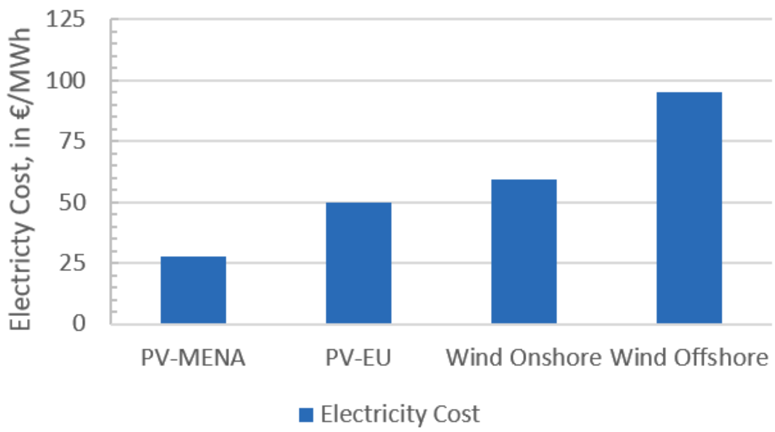
Table 10: CAPEX of heavy-duty vehicle type 5 in 2030. Sources: [82], Lines refer to Table 22 in Appendix A.4

	CAPEX	Line
New diesel trucks	115,252 €/truck	612
Battery-electric truck (BEV)	155,200 €/truck	604
Fuel cell electric truck (FCEV) with hydrogen (H_2)	144,800 €/truck	607
Truck with internal combustion engine (ICE) for Methane (CH_4)	126,777 €/truck	609
Truck with internal combustion engine (ICE) for E-Fuels/HVO	115,252 €/truck	612

4.4.2 Electricity Production

Electricity is the primary energy source in many of the energy supply paths investigated (see Table 8). And since electricity costs turn out to have a high impact on production costs of energy carriers and on the overall costs of every "Exclusive Scenario", electricity production costs are shown here separately. For all four electricity sources considered, the production costs are shown in Figure 21.

Figure 21: Electricity Production Cost from MENA Region and EU in 2030, Full load hours: PV-MENA: 1,800 h/a, PV-EU: 1,000 h/a, Wind Onshore EU: 2,200 h/a, Wind Offshore EU: 3,800 h/a.



4.4.3 Exclusive Scenario "Battery Electric and New Diesel"

As described in section 4.1 (Table 8), no electricity import from Middle East and Northern Africa (MENA) is considered due to the lack of current and future import infrastructure. Therefore, out of the four electricity sources from the previous section 4.4.2, only three are relevant in the Exclusive Scenario "Battery Electric and New Diesel". The final cost of the fuel supplied to the vehicle (in this case electricity) is displayed in Figure 22. The results show that power generation costs are the main contributor to specific electricity cost. Depending on the location, the share of power generation on total electricity supply cost ranges between 72% (PV) and 78% (Wind Offshore). The most cost-effective option to provide electricity for the battery-electric trucks is power generation via photovoltaic in Europe (69 €/MWh), followed by onshore wind turbines (81 €/MWh) and offshore wind turbines (121 €/MWh).

The annual fleet costs as well as the corresponding number of new diesel trucks and renewable fuel trucks per fleet can be seen in Table 11. According to the fleet calculation results (see section 4.3) for the Exclusive Scenario “Battery Electric and New Diesel” the total fleet cost (battery-electric and new diesel trucks) range between 49.8 billion €/a and 50.2 billion €/a.

Figure 22: Specific cost of electricity produced in EU in 2030, Transport distance for the electricity was taken as 500 km for PV and Wind Onshore, 1,000 km for Wind Offshore. See Table 22 Appendix A.4 lines 217 and 2018

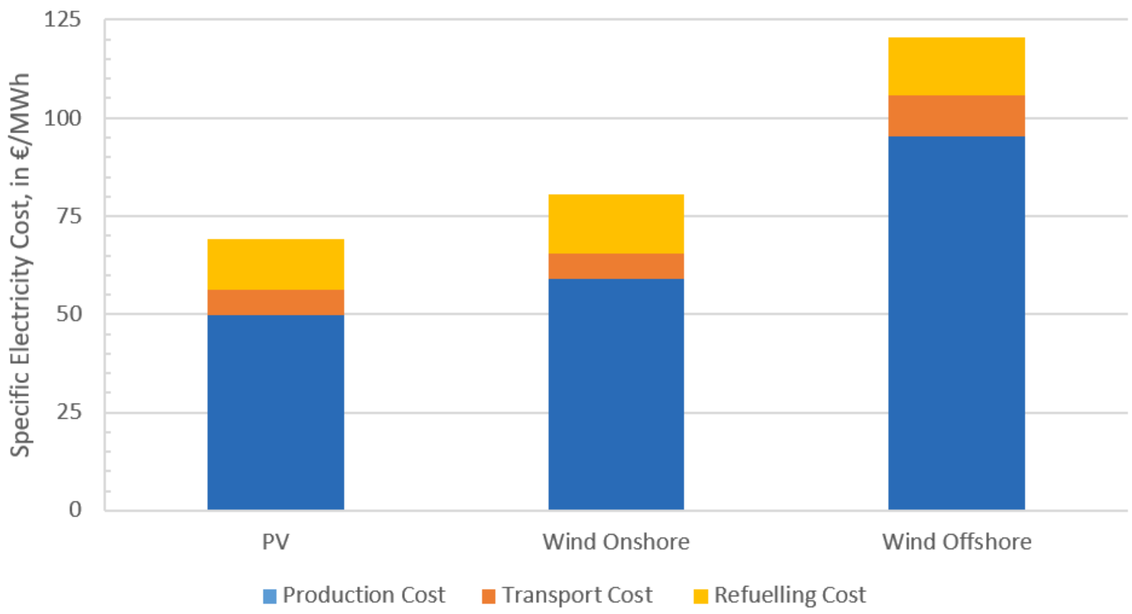


Table 11: Fleet cost, number of trucks and share of trucks in the fleet for Exclusive Scenario “Battery Electric and New Diesel” in 2030

Fleet “Battery Electric and New Diesel”	Cost (billion €/a)	Number of trucks	Share of trucks
Battery electric trucks (BEV)	22.0 – 23.7	755,000 – 816,000	37% – 40%
New Diesel Trucks	26.4 – 27.8	1,224,000 – 1,285,000	60% – 63%
Total	**49.8 – 50.2**	**2,040,000**	100%

4.4.4 Exclusive Scenario “Hydrogen and New Diesel”

Figure 23 shows the specific fuel cost in 2030 for the Exclusive Scenario “Hydrogen and New Diesel” for the considered hydrogen supply routes Table 8. The lowest hydrogen production cost is achieved with a production in the MENA region, which offers a low electricity cost. The cost benefits are, however, cancelled by higher transportation costs due to the transport by pipeline from MENA to Europe (distance assumed: 3,000 km, Table 22 Appendix A.4 line 316). Therefore, the total specific cost of hydrogen from MENA region (6.2 €/kg H_2) is actually higher than the one of hydrogen production in Europe using electricity from PV (5.8 €/kg H_2) but lower than if using onshore wind turbines (6.3 €/kg H_2). The highest specific fuel cost for hydrogen is reached when using electricity from offshore wind turbines in Europe (8.1 €/kg H_2).

Table shows the fleet cost, number of trucks and the share of trucks of each type in the fleet. As it can be observed in Table 12, the overall fleet cost (Fuel cell electric trucks (FCEV) and new diesel trucks) ranges between $48.3 \text{ billion } €/a$ and $49.2 \text{ billion } €/a$.

Figure 23: Specific fuel cost of Hydrogen for different supply chain paths in 2030

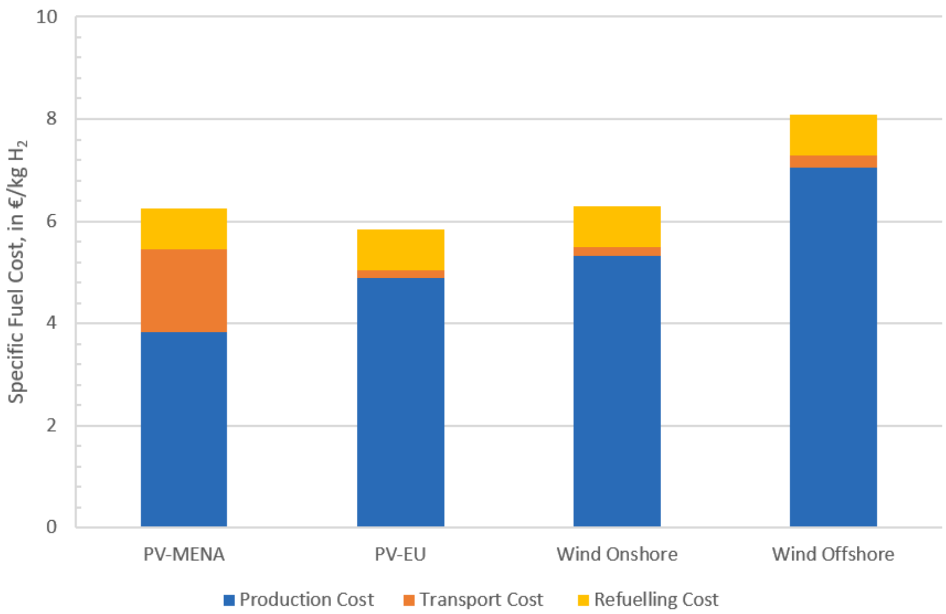


Table 12: Fleet cost, number of trucks and share of trucks per fleet for "Hydrogen and New Diesel" Scenario in 2030

Fleet "Hydrogen and New Diesel"	Cost (billion €/a)	Number of trucks	Share of trucks
Fuel cell electric trucks (FCEV, H_2)	20.5 – 24.9	755,000 – 920,000	37% – 45%
New Diesel Trucks	24.2 – 27.8	1,120,000 – 1,285,000	55% – 63%
Total	**48.3 – 49.2**	**2,040,000**	100%

4.4.5 Exclusive Scenario "Methane and New Diesel"

The specific fuel cost in 2030 for the Exclusive Scenario "Methane and New Diesel" and the considered methane supply routes can be seen in Figure 24. As mentioned in section 4.1 the Exclusive Scenario "Methane and New Diesel" considers liquefied and gaseous synthetic methane as well as gaseous biomethane.

Similarly, to the Exclusive Scenario "Hydrogen and New Diesel", the lowest production cost for synthetic methane is associated with the MENA region. However, due to the higher transportation costs compared to the other fuel supply routes, specific fuel cost of synthetic methane from MENA region are higher ($3.29 \text{ €/kg } CH_4 - 3.54 \text{ €/kg } CH_4$) than the methane production in Europe using electricity from PV ($3.13 \text{ €/kg } CH_4 - 3.53 \text{ €/kg } CH_4$). Producing synthetic methane using electricity from PV in EU is the most cost-effective supply option for synthetic methane, followed by methanation using electricity from PV in MENA and from onshore wind turbines in EU ($3.41 \text{ €/kg } CH_4 - 3.66 \text{ €/kg } CH_4$). Due to high electricity cost and therefore high methane production cost, the total specific cost is the highest when using electricity from offshore wind turbines ($4.49 \text{ €/kg } CH_4 - 4.78 \text{ €/kg } CH_4$). And because of the additional liquefaction step, the costs for liquefied methane are slightly higher compared to gaseous methane supply. Methane as fuel can also be produced from energy crops (e.g., corn), agricultural residues or manure. In this case, the production cost and therefore the annual fuel cost are significantly lower ($0.61 \text{ €/kg } CH_4$ and $0.97 \text{ €/kg } CH_4$ for biomethane from manure and from corn respectively).

Total fleet cost, number of trucks and the share of trucks per fleet can be seen in Table 13. The annual cost of the fleet (CH_4 trucks and new diesel trucks) for synthetic methane and biomethane range between $45.7\text{ billion }€/\text{a} - 47.4\text{ billion }€/\text{a}$ and $44.7\text{ billion }€/\text{a} - 46.6\text{ billion }€/\text{a}$ respectively.

Figure 24: Specific fuel costs for renewable methane in 2030 (both in gas and liquid form) for different supply chain paths

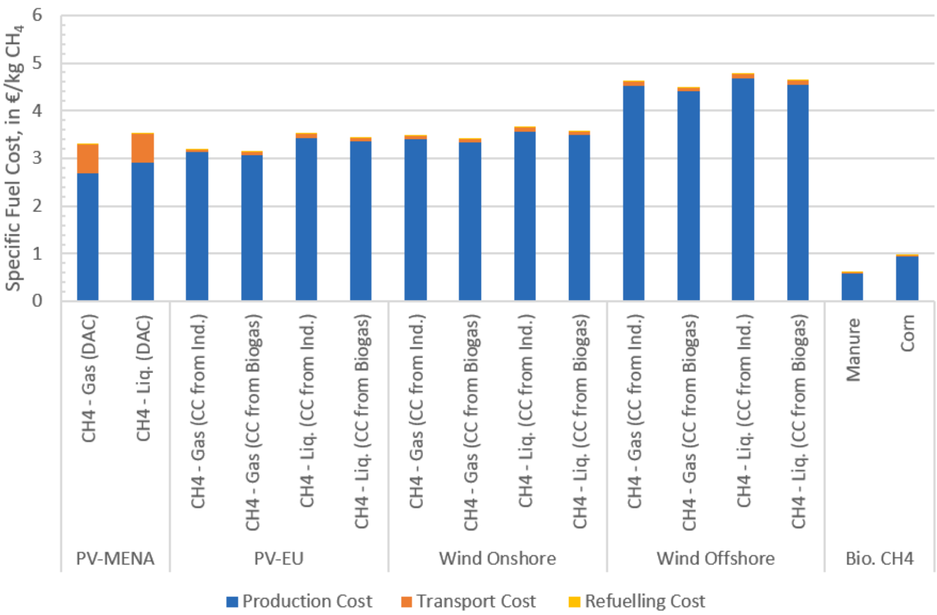


Table 13: Fleet cost, number of trucks and share of trucks in the fleet for Exclusive Scenario "Methane and New Diesel" in 2030

Fleet "Methane and New Diesel":		Cost (billion €/a)	Number of trucks	Share of trucks
Syn. CH_4	CH_4 Trucks	18.4 – 36.4	775,000 – 1,500,000	38% – 75%
	New Diesel Trucks	11.0 – 27.3	540,000 – 1,265,000	25% – 62%
	Total	**45.7 – 47.4**	**2,040,000**	100%
Bio. CH_4	CH_4 Trucks	7.3 – 27.6	306,000 – 1,163,000	15% – 57%
	New Diesel Trucks	19.0 – 37.5	877,000 – 1,734,000	43% – 85%
	Total	**44.7 – 46.6**	**2,040,000**	100%

4.4.6 Exclusive Scenario "E-Fuels/HVO and New Diesel"

Figure 25 shows the specific fuel cost results for E-Diesel from a Fischer-Tropsch process (FT) and hydrogenated vegetable oil (HVO). Due to the high investment cost and the high electricity demand of the Fischer-Tropsch synthesis, the specific cost for E-Diesel, compared to HVO, are significantly higher ranging between $3.08\ €/\text{kg}$ (PV-MENA) and $4.98\ €/\text{kg}$ (Wind Offshore). Other studies [83,84] estimate the specific fuel cost between 1.2 - 3.3 €/kg. The reason for this could be the difference between some assumptions (choice of location, fullload hours, etc.) Hydrogenated vegetable oil (HVO) based on used cooking oil (UCO) and electricity supply by photovoltaic in MENA (PV-MENA) are the most cost-effective liquid renewable fuels $0.79\ €/\text{kg}$) thanks to its lower electricity consumption and lower investment cost for the synthesis plant.

Since the same trucks are used for both the E-Fuel fleet and the new diesel fleet, the annual cost of the fleet stays the same for different paths and is calculated to be $44.1\text{ billion }€/\text{a}$. The share of how many of the $2{,}040{,}000$ long-haul trucks need to be operated with E-Diesel or HVO respectively in order to fulfil EU's targets for GHG emissions is shown in Table 14.

Figure 25: Specific fuel costs for E-Fuels/HVO: E-Diesel from Fischer-Tropsch processes (FT) and hydrogenated vegetable oil (HVO) in 2030 for different supply chain paths. According to Appendix A.4 Table 22 the full load hours are: electricity PV MENA: 1,800 h/a, electricity PV EU: 1,000 h/a, electricity Wind Onshore EU: 2,2000 h/a, Wind Offshore EU: 3,800 h/a, electrolyser: 2,475 h/a, Fischer-Tropsch reactor: 6,000 h/a. CO_2 sources used see Table 8 e.g., direct air capture (DAC) for E-Diesel produced from PV in the MENA region.

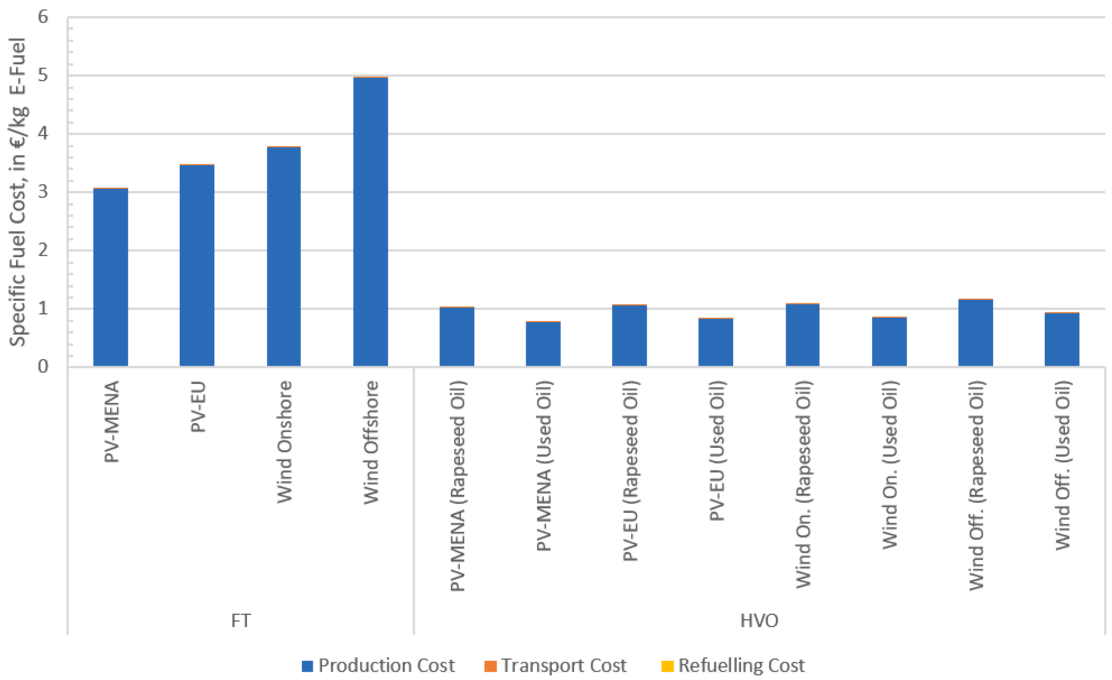


Table 14: Fleet cost, number of trucks and share of trucks in the fleet for Exclusive Scenario “E-Fuels/HVO and New Diesel” in 2030

Fleet “E-Fuels/HVO and New Diesel”		Cost (billion €/a)	Number of trucks	Share of trucks
E-Diesel, Fischer-Tropsch (FT)	E-Diesel Trucks	17.6 – 31.7	775,000 – 1,500,000	38 % – 72 %
	New Diesel Trucks	12.4 – 26.5	540,000 – 1,265,000	28 % – 62 %
	Total	**44.1**	**2,040,000**	100%
Hydrogenated Vegetable Oil (HVO)	HVO Trucks	16.3 – 31.3	755,000 – 1,530,000	37 % – 75 %
	New Diesel Trucks	12.8 – 27.8	510,000 – 1,285,000	25 % – 63 %
	Total	**44.1**	**2,040,000**	100%

4.4.7 Results for all Exclusive Scenarios

Table 15 shows the cost breakdown of the four “Exclusive Scenarios”; battery electric trucks, hydrogen fuel cell electric trucks (FCEV), renewable methane separated into synthetic methane (Syn. CH_4) and biomethane (Bio CH_4) as well as E-Fuels with the two options E-Diesel from Fischer-Tropsch (FT) and hydrogenated vegetable oil (HVO). The minimum and maximum cost of each technology are given by the corresponding energy supply paths with lowest and highest electricity or fuel supply cost (see sections 4.4.3 to 4.4.6).

Table 15: Annual costs breakdown for fleet, fuel production, fuel transport, and refuelling stations for long-haul heavy-duty road transport in EU27 and CH in 2030. Each case includes a different carbon neutral technology in combination with the most recent diesel technology and fulfils the EU's GHG emissions reduction goals. Min and Max are given by the energy supply paths from Table 8 with the highest and the lowest annual costs respectively.

in billion €/a			Share of fleet using renewable fuel technology				Share of fleet with latest diesel power trains using fossil diesel				Sum
			Fuel Production Cost	Fuel Transport Cost	Refuelling Cost	Fleet Cost	Fuel Production Cost	Fuel Transport Cost	Refuelling Cost	Fleet Cost	
Battery Electric and New Diesel		**Min.**	3.2	0.4	0.8	23.7	8.6	0.1	0.0	26.4	**63.3**
		Max.	5.6	0.6	0.9	22.0	9.0	0.1	0.0	27.8	**66.0**
Hydrogen and New Diesel		**Min.**	13.2	0.4	2.0	21.0	8.8	0.1	0.0	27.3	**73.0**
		Max.	17.1	0.6	1.9	20.5	9.0	0.1	0.0	27.8	**76.9**
Methane and New Diesel	**Syn. CH_4**	**Min.**	37.2	0.7	0.1	19.4	8.6	0.1	0.0	26.4	**92.5**
		Max.	78.0	1.6	0.6	36.4	3.6	0.1	0.0	11.0	**131.1**
	Bio. CH_4	**Min.**	2.4	0.1	0.0	7.3	12.1	0.2	0.0	37.5	**59.6**
		Max.	15.0	0.3	0.1	27.6	6.1	0.1	0.0	19.0	**68.3**
E-Fuels/ HVO and New Diesel	**FT**	**Min.**	38.7	0.1	0.0	17.6	8.6	0.1	0.0	26.5	**91.5**
		Max.	63.9	0.2	0.0	31.7	4.0	0.1	0.0	12.4	**112.2**
	HVO	**Min.**	7.5	0.1	0.0	16.3	9.0	0.1	0.0	27.8	**60.7**
		Max.	21.1	0.1	0.0	31.3	4.1	0.1	0.0	12.8	**69.6**

As it can be observed in Table 15, in all scenarios, the fleet costs contribute with a high share to the annual cost (36% to 79%). Thanks to the high GHG reduction potential of manure (see Figure 16), the Exclusive Scenario "Methane and New Diesel" with the energy supply path biomethane from manure ("CH_4-Biogas (Manure)" from Table 8) has the lowest share of renewable fuel trucks in the fleet and therefore the lowest renewable fleet cost. In total, biomethane based on manure and HVO based on used cooking oil (UCO) are the most cost-efficient options ($59.6\,\text{billion}\,€/\text{a}$ and $60.7\,\text{billion}\,€/\text{a}$, respectively) thanks to their low electricity need and therefore low fuel production cost combined with high GHG reduction potentials. Additionally, these options are not subject to the discussion tank versus plate. Battery-electric trucks (BEV) benefit from high Well-to-Wheel (WtW) efficiencies (drivetrain and electricity supply) and thus also show relatively low annual cost ($63.3\,\text{billion}\,€/\text{a}$ to $66.0\,\text{billion}\,€/\text{a}$). E-Diesel from Fischer-Tropsch (FT) and synthetic methane (Syn. CH_4) have the lowest Well-to-Wheel (WtW) efficiency resulting in the highest fuel production cost and therefore the highest annual cost ($92.5\,\text{billion}\,€/\text{a}$ to $131.1\,\text{billion}\,€/\text{a}$ and $91.5\,\text{billion}\,€/\text{a}$ to $112.2\,\text{billion}\,€/\text{a}$ respectively).

As mentioned in the methodology section 1.3.4 Table 2 line 7, the expansion of the infrastructure cost was not included in the calculations. Fuel transport cost only include the necessary primary infrastructure needed in order to transport the necessary amount of fuel or electricity to the refuelling stations/chargers (Table 2 line 2). Moreover, this cost is only around 1% of the annual cost. It is important to note that this brings an imbalance in the evaluation of the alternative drive options; in other words, "BEV and New Diesel" scenario would need higher investment cost in the infrastructure than "E-Fuels and New Diesel" scenario since the infrastructure already existing can be used for the latter scenario. However, when using electricity, the costs for setting up the grid infrastructure, in particular for providing high charging capacities for trucks, are not taken into account. This is a problem also in the other studies and used methodologies available in the literature, since the power grid infrastructure cannot be specifically assigned to the transport or truck sector. Renewable electricity is increasingly being used in all energy-consuming sectors and electricity infrastructures need to be expanded in general. A scientific analysis is currently not available and would require an in-depth analysis of breakdown of costs to the level of individual charging stations respectively chargers. For a rough estimate, data from the ACEA study [85] shows that the additional investment needed on the power grid for the charging stations due to the increase electrification of transportation is around $5\,\text{billion}\,€$. Nevertheless, this cost is not the annual costs. In order to compare it with the approach in this study, this has to be broken down into annual values, which would then be some $100\,\text{million}\,€/\text{a}$. This shows that it does not significantly increase the electricity supply costs given the annual cost of around $60\,\text{billion}\,€/\text{a}$.

4.4.8 Sensitivity Analysis of Electricity Cost

One of the most important factors in the annual cost estimation is the cost of electricity. As it was explained in detail in the methodology part (Section 1.3.4), the electricity cost was calculated separately for 4 different renewable energy sources with their respective full load hours per year: PV in the MENA region with $1{,}800\,\text{h/a}$, PV in Europe with $1{,}000\,\text{h/a}$, Wind Onshore in Europe with $2{,}200\,\text{h/a}$ and Wind Offshore in Europe with $3{,}800\,\text{h/a}$. Furthermore, annual full load hours for electrolysers of $2{,}475\,\text{h/a}$, for methanation plants of $6{,}000\,\text{h/a}$ and for Fischer-Tropsch plants also of $6{,}000\,\text{h/a}$ were taken (compare Appendix A.4 Table 22). Instead of providing electricity from wind turbines or solar systems separately, combining the two technologies at suitable locations with good wind and solar conditions (for example Chile) would yield to a higher utilization of electrolyers and thus to a reduction of the hydrogen production cost. The costs of hydrogen production are especially important in the overall production costs of synthetic methane and of E-Fuels. Therefore, an increase in full load hours of the electrolysis (in the range of $4{,}000$ to $5{,}000\,\text{h/a}$) would lead to a reduction of the energy cost and would bring down the annual cost of these technologies. According to the Agora Study [83], the electricity production cost from combined systems (PV and Wind) range between 3 to $6\,€/\text{MWh}$ by 2030. Furthermore, they also show a decrease around 50% between the years of 2020 – 2050.

To show the effect of electricity cost on our model, a sensitivity analysis was carried out. A reduction of 50% of the electricity cost was assumed and its effects on the annual cost studied. Results are shown inTable 16. The impact of electricity cost is the highest on synthetic methane (Syn. CH_4) and E-Diesel from Fischer-Tropsch (FT), and the gap between high- and low electricity consuming processes is reduced. The reason for this is that the methanation (Syn. CH_4) and Fischer-Tropsch (FT) paths consume more electricity and more hydrogen to produce the respective fuels. For the exclusive scenario “Synthetic methane (Syn. CH_4) and New Diesel” the annual cost decrease by $10\,\text{billion}\,€/\text{a}$ to $18\,\text{billion}\,€/\text{a}$ and for the FT fuels the annual cost reduction is around $10\,\text{billion}\,€/\text{a}$ to $15\,\text{billion}\,€/\text{a}$. Since biomethane and hydrogenated vegetable oil (HVO) require only small amounts of hydrogen and thus electricity, they are hardly influenced by the decrease in electricity cost. The analysis underlines the high sensitivity of synthetic fuels, especially E-Fuels, to electricity cost. If E-Fuels can be produced under optimal conditions and imports of such fuels in larger quantities can be realized, this group of fuels will gain competitiveness against the other alternative drive options.

Table 16: Sensitivity analysis of annual costs breakdown: a 50 % reduction in electricity cost is assumed.

in billion €			**Annual Cost**	
			Min.	**Max.**
Battery Electric Vehicles (BEV) and New Diesel		**Original**	63.3	66.0
		Sensitivity	61.7	63.2
Hydrogen (H_2) and New Diesel		**Original**	73.0	76.9
		Sensitivity	69.4	71.2
Methane (CH_4) and New Diesel	**Syn. CH_4**	**Original**	92.5	131.1
		Sensitivity	82.6	113.4
	Bio. CH_4	**Original**	59.6	68.3
		Sensitivity	59.6	68.2
E-Fuels and New Diesel	**FT**	**Original**	91.5	112.2
		Sensitivity	81.4	96.8
	HVO	**Original**	60.7	69.6
		Sensitivity	60.5	67.8

4.5 Qualitative Assessment of Exclusive Scenarios

This section complements this study’s quantitative analysis with qualitative assessments. The author’s experiences from various projects show, that other criteria are equally important when deciding which technology and which energy supply path to choose. The qualitative arguments have been grouped into the following four criteria, which are discussed in the subsections:

1. Technology Availability in section 4.5.1:
2. Required Effort for Infrastructure 2030 in section 4.5.2
3. Energy System Implications, Efficiency, Storability in section 4.5.3
4. Potential of Primary Energy Sources in section 4.5.4
5. Practicability in section 4.5.5

Each of the technologies and energy supply paths has advantages and disadvantages in some of the qualitative criteria. The discussions and the assessments are summarised in assigning a smiling face , neutral face or a sad face to the technologies for each criteria indicating advantages and disadvantages of one technology over the other technologies. So, it is a relative assessment. All “Exclusive Scenarios” are challenging to implement compared to the current situation based on fossil diesel. Because the latter does not fulfil the GHG reduction targets, it is not included in the comparison. Using only three faces is a rough granularity, which is owed to the fact that these criteria were not quantified but only assessed qualitatively.

4.5.1 Technology Availability

The availability of a technology between today and 2030 influences how difficult it is to implement a scenario relying on this technology. In addition to looking at the maturity of the technologies today expressed in "technology readiness level" (TRL), we have also included the availability of commercial products and announcements for future product releases for Europe. The "technology readiness level" (TRL) range from TRL1 for a basic principle observed to TRL9 for a system proven in a real environment ready to be commercialized. Since only technologies available commercially and in large scale in 2030 are considered in this study, they all have a high technology readiness level (i.e., at least TRL 7 to 8 now) and are likely to reach TRL9 in the coming years. A recent evaluation of technology readiness levels is available in [86]. A high TRL does not automatically mean that the respective technology is commercially available, let alone on a large scale.

In this section, we discuss the availability along the energy supply paths: technologies for production of the energy carriers from primary energy sources, transport technologies, refuelling/charging stations and finally the vehicles.

Production

The production technologies for renewable electricity are available on the market and are/will be implemented in spite of the current challenges in global supply chains. Biomethane production (Bio CH_4) and the production of hydrogenated vegetable oil (HVO) are well established. The industrial production of synthetic methane (Syn. CH_4) started in Germany in 2013 [87], and two industrial power-to-methane plants are currently in operation: The first plant was built on behalf of Audi in Werlte in Germany, now owned and operated by Kiwi AG. The second plant is operated by Limeco near Zurich in Switzerland. The large-scale production of liquid fuels has also started with the opening of the Porsche/Siemens plant in Chile in December 2022 [68], where synthetic methanol is produced and then converted to gasoline using a process developed by ExxonMobil [88]. Technologically, it would be a small step to produce diesel instead of gasoline.

Transport

The technologies for the transport of all energy carriers are available on the market and reliable: power lines, pipelines, trucks, and ships for methane (CH4) and liquid fuels (E-Fuels/HVO) are well established. Only the transport for hydrogen (H2) lags behind as first logistics concepts using road transport and first projects for hydrogen pipelines are established, where standards, know-how and technical experience still must be built up. The big advantage of renewable methane (CH4) as energy carrier is the existing natural gas infrastructure in Europe with available technologies, products, standards and know-how. The existing gas grid allows inexpensive transport of methane over large distances, even if part of this infrastructure will be taken out of service over the next years or will be rededicated to be used for pure hydrogen. In general, whenever **storage** of energy carriers is required the molecule-based energy carriers (gases, liquids) are advantageous due to higher energy densities and lower losses as well as lower costs (especially for low cycling rates of the storages).

Refuelling Stations and Charging Points

When looking at refuelling stations and charging points, diesel refuelling stations are the reference. They are widely established and can be converted for the use of E-Diesel (FT) and hydrogenated vegetable oil (HVO) with little effort. Charging stations for trucks are available commercially and have been installed by operators of fleets of battery electric trucks (BEV). A public infrastructure with fast chargers is a requirement for making long-haul road transport practical with battery-electric trucks (BEV) but is basically inexistent today [44] as described in section 3.4.1. Furthermore, none of the high-power chargers with power of more than 500 kW for heavy-duty vehicles and the Megawatt

Charging System (MCS) has made it to the market yet, and only pilot projects exist. [89,90]. Methane refuelling stations (CNG and LNG) for trucks exist in various countries (Table 7) and are products available from multiple suppliers. It is only a question of investment to quickly increase their number. Hydrogen refuelling stations have recently started to be deployed even if their technology is quite new and shows potential for improvement. Compressors, coolers, or internal storage tanks for example are still being developed and quickly improved.

Powertrains

The technology of diesel powertrains powered with fossil diesel is the reference in this study. The current diesel engines have been used for decades. As a result of political pressure for fuel economy and reduced emissions of pollutants, years of research and development have focused on the optimization of internal combustion engines (ICE). They now can run closer to their maximum theoretical efficiency. In this study, the same powertrain is used for the energy supply paths with the two E-Fuels E-Diesel and hydrogenated vegetable oil (HVO) (see Table 8).

For methane vehicles (CNG and LNG), similar powertrains with some modifications are used. The core technology of these engines is therefore well known, yet less effort went into their optimisation, and they still show potential for further improvement. Auxiliary components for fuel management (storage, pump, injection, measurement system) are considered available since natural gas have been used widely in the industry for decades now.

The technology required for battery electric trucks (BEV) and fuel cell electric trucks (FCEV) are much more recent and still under development: While electrical motors, inverters, and control electronic are widely established, it is less the case for batteries, battery systems, fuel cells, hydrogen storage (pressure tanks and metal hydrides) and auxiliaries. These components start to be available on the market and the global supply chains have recently been and start to be established. Currently, vehicles with the two technologies are difficult to purchase or lease. We assume that this will be solved by 2030 while development is ongoing focusing on reliability, performance, efficiency, capacity and energy use for manufacturing. Nevertheless, the novelty of the technology poses challenges for the implementation until 2030, which don't exist for vehicles with internal combustion engines (ICE).

The summary of the qualitative evaluation on the category "Technology Availability" is shown in Table 17 and is included in Figure 26 together with the quantitative results and the other categories of the qualitative assessment.

Table 17: Qualitative assessment for the criteria "Technology Availability".

Electric Vehicles (EV)		Vehicles with Internal Combustion Engines (ICE)			
Battery Electric Vehicle (BEV)	Fuel Cell Electric Vehicle (FCEV)	Methane (CH_4)		E-Fuels	
		Synthetic Methane (Syn. CH_4)	Biomethane (Bio CH_4)	E-Diesel from Fischer Tropsch (FT)	Hydrogenated Vegetable Oil (HVO)
☹	☹	☺	☺	☺	☺

4.5.2 Required Effort for Infrastructure 2030

This criterion considers the required effort to build the infrastructure necessary for the energy supply paths from Table 8. It is the infrastructure required to produce the energy carrier from the primary energy and to transport it to the vehicle including the stations for charging and refuelling. This criterion indicates the effort from the current infrastructure to the infrastructure required in 2030 for the "Exclusive Scenarios" and how much effort it is to realise it until 2030. The current infrastructure described in section 3.4 is the starting point from which the expansion of the infrastructure can start or continue.

Production

The renewable electricity production capacity from wind and solar discussed in section 3.4.1 is quickly expanding, with rates increasing each year. It is thus estimated that the targets for installed wind capacity in 2030 will be met [50]. When it comes to hydrogen as fuel and as basis for synthetic fuels (Syn. CH_4, E-Diesel), there are already some established renewable hydrogen production sites in Europe (Section 3.4.2). Capacities, however, need to be ramped up substantially to meet the estimated future total demand. The situation is different for biomethane as it is possible to upgrade raw biogas to biomethane in existing production sites. Therefore, the expansion of biomethane is not strictly relying on new biomethane production sites, which is also true for the production of bio-LNG (section 3.4.3).

The current production capacities of E-Fuels discussed in section 3.4.4 is only a start to cover the amount required not only for European long-haul road transport, but also for the other intended uses. This gap is also discussed in [76] and is considered here to be a considerable disadvantage for exclusive scenarios based on E-Fuels. This disadvantage is less relevant for HVO, as a considerable production capacity already exists in Europe and is being further expanded as discussed in section 3.4.4.

Transport and Long-Term Storage

The infrastructure to supply the required charging stations for the battery electric trucks (BEV) with electricity needs strong reinforcements. The transport for hydrogen (H_2) is mostly done by trucks today and hydrogen pipelines are started to be built (section 3.4.2). Long-term storage for electric energy in the form of electricity is not possible to build and the underground hydrogen potential still needs to be unlocked. This is different for methane and the liquid fuels E-Diesel and HVO. Long-term storage are available for both energy carriers.

Refuelling Stations and Charging Points

For battery electric vehicles (BEV), the existing electricity grid must be expanded with fast charging stations where trucks can be charged during the driver’s breaks. To supply the fast chargers with enough power, the existing electricity grid must be reinforced both for connecting the chargers to the grid and for transporting the electric power over wider distances (high-power lines, transformer stations).

Section 3.4.2 shows that for the scenario with hydrogen (H_2) as energy carrier, almost all of the transport and refuelling infrastructure needs to be built. Hydrogen can be transported in a part of the existing European grid for the transmission and distribution of natural gas that is converted to pure hydrogen usage. Newly built dedicated hydrogen pipelines can complement the system. The project of the European Hydrogen Backbone is still under development, and a major effort will have to be made for the network to reach a significant size.

E-Fuels (E-Diesel from Fischer Tropsch (FT) and hydrogenated vegetable oil (HVO)) require additional infrastructure on the production side, but only little additions for the transport and storage since the existing infrastructure for distributing and storing the current fossil fuels can be used.

Using methane as energy carrier (Syn. CH_4 and Bio CH_4) allows to tap into the existing European gas grid which transports and distributes mainly fossil natural gas today (section 3.4.3). Additions are required though, when distributed sources of biomethane are considered, or for the distribution in areas not supplied by the current gas grid. In most countries, there is a basic infrastructure of refuelling stations for methane (CNG and LNG in Table 7). While LNG are only for trucks, many of the CNG refuelling stations are not suited for trucks but need to be adjusted. The effort required to extend the infrastructure in general is thus larger than for E-Fuels, but much lower than for hydrogen.

The summary of the qualitative assessment in the category “Required Effort for Infrastructure 2030” is shown in Table 18. We see challenges in all scenarios. A considerable effort is required to build up the production capacities for synthetic methane (Syn. CH_4) and E-Diesel. An even higher effort is required for the scenario involving the new technologies battery electric trucks (BEV) and hydrogen (H_2) for fuel cell electric trucks (FCEV).

Table 18: Qualitative assessment for the criteria "Required Effort for Infrastructure 2030".

Electric Vehicles (EV)		Vehicles with Internal Combustion Engines (ICE)			
Battery Electric Vehicle (BEV)	Fuel Cell Electric Vehicle (FCEV)	Methane (CH_4)		E-Fuels	
		Synthetic Methane (Syn. CH_4)	Biomethane (Bio CH_4)	E-Diesel from Fischer Tropsch (FT)	Hydrogenated Vegetable Oil (HVO)
					

4.5.3 Energy System Implications, Efficiency, Storability

Production and distribution of the energy carriers considered can interact with the current energy system. Especially the interaction with the electric infrastructure is important because in the electricity grid injected power and used power have to be balanced at each instant in time and electric energy is difficult to store. In this study, the scenario with battery electric trucks (BEV) is directly linked to the European electricity grid. If hydrogen (H_2), and the synthetic fuels methane (Syn. CH_4) and E-Diesel from Fischer Tropsch (FT) are produced in Europe, they are also linked to the electricity grid and can provide flexibility to the grid. Imported fuels are independent of the European electricity grid. Producing hydrogenated vegetable oil (HVO) is less linked to the electricity grid, since only part of the energy input is electricity. The better the storability of these energy carriers, the lower is the link to the electricity grid. Biomethane (Bio CH_4) is independent of the existing electricity system but might be distributed in the existing grid for natural gas.

Operating many battery electric trucks (BEV) leads to additional stress on the electric system. During charging of a truck one fast charger draws power from the gid larger than current typical loads. The extensive use of electricity in the transport sector is a challenge for the stability of the electric grid by increasing demand during the day when trucks drive the most. This stress can be reduced with intelligent management of charging stations, stationary batteries at the charging stations and slower charging with lower power, when more time is available e.g., at night.

The generation of green hydrogen in an electrolyser draws electric power from the grid. Due to the lower efficiency, it requires more electric energy overall than battery electric trucks (BEV). Hydrogen as chemical energy carrier allows decoupling the time and the location of the electricity usage from the delivery of the energy onto the truck. Hydrogen is usually stored for days and maybe weeks pressurised in tanks, liquefied in cryo-tanks or absorbed by metal hydrides. Longer storage periods like seasonal storage will become possible in underground salt caverns. This is tested in Europe for example in project "Hypster" in France [91] and in project "H2-Forschungskaverne" in Germany [92]. Other hydrogen underground storage have been in operation since the 1980s, especially in the USA and the UK [93]. With these storage capacities, electrolysers can provide flexibility to the grid ranging from minutes to weeks and in the future – if the referenced projects are successful – even over the seasons.

The synthetic fuels methane (Syn. CH_4) and E-Diesel from Fischer Tropsch processes (FT) have a lower efficiency than hydrogen and therefore need even more electricity. Consequently, these fuels will be produced at times and in locations with low electricity costs. Costs are low when electricity is available enough or in excess. Storage of methane is possible in underground caverns and E-Diesel in fuel depots, both over periods of several months with existing storage capacities equivalent to several month of current energy use. The storage capacities are existing today as national strategic hydrocarbon reserves. Therefore, the production facilities of the two synthetic fuels can not only help stabilise the electricity grid but can also provide seasonal flexibility. The production is independent of the European electricity system when done abroad, and the fuels are imported with ships.

In terms of Tank-to-Wheel efficiency, battery electric trucks (BEV) have only an advantage over the other options considered (see Figure 11 to Figure 15) if electricity production, transport and charging can occur at the same time. The energy consumption per tkm for the entire energy supply path (Well-to-Wheel, WtW) for battery-electric trucks (BEV, Figure 11) is roughly half of that for fuel cell electric trucks (FCEV, Figure 12) and one fourth of that for trucks with internal combustion engines (ICE) operated with synthetic methane (Syn. CH_4) or E-Diesel (FT). This assumes that electricity production, transport and charging can occur simultaneously, while – as discussed – chemical energy carriers allow for time flexibility and can utilise favourable conditions by producing fuels from wind and solar at remote locations.

The results of the qualitative evaluation for this criterion are shown in Table 19. We consider the scenario “Battery Electric and New Diesel” to put more stress on the energy system than scenarios with chemical energy carriers, who are well storable.

Table 19: Qualitative assessment for the criteria “Energy System Implications, Efficiency, Storability”.

Electric Vehicles (EV)		Vehicles with Internal Combustion Engines (ICE)			
Battery Electric Vehicle (BEV)	Fuel Cell Electric Vehicle (FCEV)	Methane (CH_4)		E-Fuels	
		Synthetic Methane (Syn. CH_4)	Biomethane (Bio CH_4)	E-Diesel from Fischer Tropsch (FT)	Hydrogenated Vegetable Oil (HVO)
😐	🙂	🙂	🙂	🙂	🙂

4.5.4 Potential of Primary Energy Sources

In this category it is discussed whether the primary energy sources for each exclusive scenario have the potential to meet the energy demand. The potential of the primary renewable energy source was discussed in section 2.2. The criteria will be a summary evaluation following the system boundaries of our study with the European perspective as its first condition and then have a look at the situation in each focus country Switzerland (CH), France (FR), Germany (DE), Italy (IT) and Poland (PL) as well as an outlook on the international situation where applicable.

All renewable primary resources are subject to competition between sectors requiring energy. Prices per unit of energy are generally higher when used as fuel for road vehicles compared to other sectors like the heating sector or energy used by industry. We therefore consider it a fair assumption that road vehicles retrieve the required portion of a scarce renewable energy potential in a market competition situation. However, since we consider that the GHG emission reduction targets are met, not only in road traffic but for the complete energy system, there must at least be sufficient overall potential to cover total demand. For the purpose of this qualitative assessment, we refer to the in-depth analysis accompanying the European Commission's “Clean Planet for all” communication [11] summarised in section 2.3 for the total energy demand with the eight scenarios from Figure 5.

Electricity and electricity derived fuels

According to the scenarios accompanying the “Clean Planet for all” [11] shown in section 2.3 Figure 5, the electricity consumption increases and reaches $3{,}000\,\mathrm{TWh/a}$ in 2030 of which wind and solar will contribute almost 40% i.e., $1{,}200\,\mathrm{TWh/a} = 1.2\,\mathrm{PW/a}$. This is still only a fraction of the total potential described in section 2.2 of at least $44.3\,\mathrm{PWh/a}$ from wind (EU-28) and solar. Thus, it does not matter if the electricity demand in our exclusive scenario “battery-electric (BEV) and new diesel” is additional demand or if it is already, at least partly, foreseen in the projections. With the same reasoning, this also holds true for all fuels derived from renewable electricity such as hydrogen, SNG and E-Diesel. In addition to the energy supply paths considered here (Table 8), low carbon hydrogen can also be produced from natural gas by means of pyrolysis or steam reforming with carbon capture and sequestration (CCS) or from nuclear power by means of electrolysers.

In the communication related to the “Clean Planet for all” [11], the energy mix of the final energy consumption in 2030 does not contain E-Fuels nor hydrogen, but $1{,}200\,\mathrm{TWh/a}$ biomass. All scenarios fulfilling the green deal ambition of net zero emissions in 2050 have substantial shares of different chemical energy carriers: liquid E-Fuels 233- $477\,\mathrm{TWh/a}$, hydrogen 709-$791\,\mathrm{TWh/a}$, other gaseous E-Fuels 477-$523\,\mathrm{TWh/a}$ and biomass $1{,}093$-$1{,}233\,\mathrm{TWh/a}$. The highest demand for biomass is in Scenario 5 “Circular Economy (CI)” (see Figure 5) with $1{,}605\,\mathrm{TWh/a}$. The highest demands of E-fuels are in Scenario 3 “Power-to-X (P2X)” with $628\,\mathrm{TWh/a}$ liquid E-Fuels and $989\,\mathrm{TWh/a}$ gaseous E-Fuels. Scenario 2 ”Hydrogen (H2)” estimates a total hydrogen demand of $1{,}547\,\mathrm{TWh/a}$.

Biomass

For comparison the estimated potentials in section 2.2 can be put in relation to the required bioenergy feedstock in the scenarios communicated by the European Commission [11] and summarised in section 2.3. Most scenarios up to the year 2050 requires $3{,}500\,\mathrm{TWh/a}$ bio feedstock, except scenario 4 “Energy Efficiency”, that is in the range of $3{,}000\,\mathrm{TWh/a}$ and the scenario 8 “1.5 Life” requiring $3{,}300\,\mathrm{TWh/a}$ bioenergy. The year 2030 is not included in this overview but is estimated to be in the range of $3{,}000\,\mathrm{TWh/a}$ (final energy consumption in the form of biomass in 2030 and the composition of energy carriers in 2030 are similar in scenario 4 “Energy Efficiency” and in scenario 8 “1.5 Life”). The feedstock required in 2030 is about the amount available in the “medium” scenarios in ENSPRESO [28] and in the Imperial College London [31] and the “high” scenario for DG RTD [30] (see Figure 2). None of the scenarios considers algae potentials nor the import of renewable gases and fuels. The feedstock potential from algae in Europe is estimated to be the second largest potential close to similar to the potential from forestry. But it is also the most expensive type of bio feedstock and in comparison to a relatively low TRL, if the resource is tapped or not depends on the development of the prices on the market. When it comes to the renewable fuels, gaseous or liquid, it is also fair to assume that a world-wide market would emerge in trade-off with national potentials and security of supply considerations. This increases the potentials considerably for the electricity derived fuels (Syn. CH_4 and E-Diesel). When favourable locations can be harvested it increases not only the potential but also the competitiveness of those energy carriers. Looking to the biobased fuels, energy crops have proven to be an ethical difficult field to navigate. Other less controversial sources of bio feedstocks, such as waste, manure and used cooking oil (UCO) are always connected to human activities and is thereby also related to the size of an economy and population. Considering the pressure arising from the commitments to reduce GHG emissions, it must be assumed that these types of bio feedstocks, at least in the longer perspective, will be valorised in the close proximity, presumably even by the country itself. This might not be the case in the shorter timeframe. It is not within the boundary conditions of this study to investigate that.

Looking specifically to the bio feedstocks (see Table 8) considered in our exclusive scenarios in section 4.4, we refer to manure, biowaste and corn for biomethane and used cooking oil (UCO) and rape seed oil for hydrogenated vegetable oil (HVO). Some bio feedstocks also serve as input for synthetic methane as the surplus carbon dioxide from biomethane production is valorised for the methanation of hydrogen. Starting with the exclusive scenario of biomethane from manure, the bio feedstock to satisfy that scenario needs to be sufficient to produce $58\,\mathrm{TWh/a}$ biomethane.

- ENSPRESO indicates total manure feedstock potential in Europe of $344\,\mathrm{TWh/a}$ in the medium scenario in 2030.
- DG RTD however, does not declare the share of manure in their study and states that a very high theoretical potential is noted but a lack of technical potential in most of European regions due to the high demand for manure in agriculture.
- Imperial College London indicates a range of 12-$15\,\mathrm{TWh/a}$ biomethane from manure in 2030. Here it is also clearly declared for the valorisation for biomethane, which indicate that the internal bio feedstock competition is low and liquid biofuels would rather be produced from other bio sources.

- Finally, the projection of biomethane potentials in Europe by Gas for Climate declares a $117\,\mathrm{TWh/a}$ biomethane production potential in Europe until 2030 and is deemed as the largest single bio feedstock for biomethane in Europe in 2030.

In conclusion we have a very diverse picture with regards to the potential of this single bio feedstock. It is clear that it will not suffice to satisfy the total European bioenergy demand in 2030. The internal competition for different energy carriers is low and it would preferably be used for biomethane production rather than for liquid fuels production. However, the literature indicates that, the competition to use this bio feedstock for other not energy related applications is high and although the total biomethane production potential from manure in 2030 is about twice the needed energy amount in our exclusive scenario, literature indicates that it must be considered with a question mark if this total potential can be accounted for as the sole source of renewable energy for decarbonisation of heavy-duty long-haul road transport. Theoretically, this single bio feedstock has the capacity to do so.

Looking to the exclusive scenario to use biowaste as single feedstock for the biomethane, that scenario requires $180\,\mathrm{TWh/a}$ biomethane in 2030. ENSPRESO categorises three types of bio feedstock as waste: public greens (roadside verges), municipal solid waste (i.e. vegetable waste, shells/husks) and other waste (i.e. sewage sludge, degrading spoils). However only the latter is considered for biomethane production as the other two are considered for solid fuel. The other waste feedstock potential is $7\text{-}12\,\mathrm{TWh/a}$ in Europe in 2030. Although, the other two types of feedstocks are estimated with a range of $117\text{-}185\,\mathrm{TWh/a}$ for the same region and year, they cannot be considered by their full value since this number represents the energy potential for use as solid fuel. In the assessment of Imperial College London they indicate a range of $10\text{-}20\,\mathrm{TWh/a}$ biomethane potential from waste in 2030. Finally, Imperial College London inventory indicates a total biomethane potential of suage sludge and industrial wastewater of $40\,\mathrm{TWh/a}$.

The final bio feedstock considered in our exclusive scenario for biomethane is corn. In this case the scenario would need a corn bio feedstock to match $219\,\mathrm{TWh/a}$ biomethane production. Although energy crops are not accounted for in the renewable energy directive, it is the current largest feedstock for raw biogas production with a portion of about 40% in 2022 corresponding roughly to about $35\,\mathrm{TWh/a}$ biomethane equivalent. However, the projections of its energy production potential in 2030 are not included in literature due to its non-conformity with the renewable energy directive. Gas for Climate, however, includes the category of sequential cropping, that allow for energy corps to be considered by cultivating them in sequence with ordinary crops and thus not impacting food or feed markets. Sequential crops are projected as the third largest feedstock for biomethane in 2030 with $72\,\mathrm{TWh/a}$ and the largest in 2050 with $412\,\mathrm{TWh/a}$ biomethane.

Total biomethane potential is also evaluated very differently by Gas for Climate and Imperial College London, where the former estimates a $395\,\mathrm{TWh/a}$ biomethane potential in 2030, the latter only indicates max $37\,\mathrm{TWh/a}$ biomethane in 2030 and even only $18\,\mathrm{TWh/a}$, when considering harder competition for bio feedstocks between different renewable fuels.

When it comes to the bio feedstocks for HVO, used cooking oil is the feedstock for the most competitive scenario. To serve as an exclusive scenario, the used cooking oil must be able to serve a production of hydrogenated vegetable oil (HVO) in the order of $112\,\mathrm{TWh/a}$. This would represent more than double the total amount of hydrogenated vegetable oil (HVO), $52\,\mathrm{TWh/a}$, that could potentially be produced in 2030 according to [31]. Where used cooking oil (UCO) only represent about two thirds of the bio feedstock going into that fuel production. The other share is stemming from animal fats. In [33] imports of used cooking oil (UCO) is also considered but they also estimate a lower European potential and thereby coming to the same total potential. Even if we considered their portion of import on top of the potential estimated by [31] it would only add about $18\,\mathrm{TWh/a}$ additional potential. The overall potential of hydrogenated vegetable oil (HVO) to fulfil the theoretical exclusive scenario by itself is not possible.

However, when looking at the complete family of E-Fuels/HVO that composes the exclusive scenario, E-Diesel and hydrogenated vegetable oil (HVO) in combination are not limited in its potential in relation to required energy demand in the scenarios. That same principle also applies for biomethane.

Raw biogas consists of roughly of 40% CO_2. By combining the biogas plant with hydrogen from electrolyser, it is possible to benefit from that surplus CO_2, otherwise eliminated in the biomethane production to substantially increase the yield per biogas plant of biomethane grade fuel. Additionally renewable hydrogen can also be combined with air carbon capture technologies, so that when these two types of methane are evaluated in combination, there is no restriction of their potentials in relation to the required amount of energy in the exclusive scenarios.

France (FR)

France has substantial renewable electricity theoretical potential with wind and solar corresponding to $3{,}000\,\mathrm{TWh/a}$ as well as in biomethane going beyond $200\,\mathrm{TWh/a}$. Their wind and solar potential are three times higher than the other focus countries (excluding Switzerland). Thus, similar high potentials for fuels derived from renewable electricity. According to Gas for Climate, they could have the second largest biomethane potential for 2030, surpassed only by Germany. France is estimated to have the largest Biomethane potential for 2050. It also ranks high in regard to the potential of used cooking oil (UCO), although this energy potential is substantially smaller than the other potential sources of energy.

Germany (DE)

Germany has a relatively modest wind energy potential and the lowest onshore wind potential of the focus countries considered (except Switzerland). However, it can be compensated a bit with the offshore wind potential. The largest section of the renewable electricity potential stems from solar power. In total the technical potential for renewable electricity that is considered here for comparison reaches almost $1{,}000\,\mathrm{TWh/a}$. Germany has the largest overall biomethane potential for 2030 in Europe with about $80\,\mathrm{TWh/a}$. Germany also ranks the highest amongst the focus countries in relation to its used cooking oil (UCO) potential in 2030 corresponding roughly to $7\,\mathrm{TWh/a}$.

Italy (IT)

Italy ranges in the same area of renewable electricity potential from wind and solar as Germany with approximately $1{,}000\,\mathrm{TWh/a}$ technical potential according to the boundary conditions set. The wind potential is almost completely onshore and somewhat less than in the case of Germany. Solar power is the dominating renewable electricity potential source and stems from the access to large natural agricultural areas with comparable low irradiation. With reference to Gas for Climate, Italy also have well established biomethane production and more potential for biomethane. The potential for 2030 is in the range similar to France corresponding to about $55\,\mathrm{TWh/a}$. Italy also has a substantial potential of used cooking oil (UCO) in the same range as France of approximately $5\,\mathrm{TWh/a}$ per year in 2030.

Poland (PL)

Poland ranks close behind Italy in almost all the compared renewable energy sources. This holds true for renewable electricity from wind and solar according to the set boundary conditions, also corresponding to $1{,}000\,\mathrm{TWh/a}$ although with a larger onshore wind potential in relation to solar power than Italy. Poland also ranks high in its biomass potential that is estimated to about $30\,\mathrm{TWh/a}$ in 2030, which is the fifth largest potential in Europe per country. When it comes to hydrogenated vegetable oil (HVO), however, Poland has a rather average potential in European comparison with only $0.6\,\mathrm{TWh/a}$ in 2030.

Switzerland (CH)

Switzerland is today largely relying on electricity from hydro power and nuclear power. However, it is decided to phase out the nuclear power production and there are natural limitations in the expansion of hydro power. Switzerland often is not included in EU official data and studies and as a relatively small country, does not feature large potentials of renewable resources in wind, solar and biomass in absolute terms. In the literature reviewed, Gas for Climate states a 4 TWh/a biomethane potential for 2030, which is increased to almost 10 TWh/a in 2050.

Summary

The summary of this qualitative assessment for the criterion of “Potential of Primary Energy Sources” is given in Table 20. Most scenarios have more than enough primary energy sources available, except for the two scenarios based on biomethane (Bio CH_4) and hydrogenated vegetable oil (HVO), which both on the other hand have a very low footprint but limited potential.

Table 20: Qualitative assessment for the criteria “Potential of Primary Energy Sources”.

Electric Vehicles (EV)		Vehicles with Internal Combustion Engines (ICE)			
Battery Electric Vehicle (BEV)	Fuel Cell Electric Vehicle (FCEV)	Methane (CH_4)		E-Fuels	
		Synthetic Methane (Syn. CH_4)	Biomethane (Bio CH_4)	E-Diesel from Fischer Tropsch (FT)	Hydrogenated Vegetable Oil (HVO)
					

4.5.5 Practicability

This section covers aspects, which are neither included in the quantitative analysis of annual costs in section 4.4 nor in the previous categories of the qualitative assessment in sections 4.5.1 to 4.5.4. It covers aspects related to the practical handling and everyday use of the technology in comparison to the current state of the art i.e., Diesel. Furthermore, we only consider points not related to the current low market penetration of some of the technologies. On the one hand some of these aspects are partially covered by the other criteria and on the other hand we assume that in 2030 each of the renewable fuel technologies can be widespread enough that such barriers will be overcome by that time.

The infrastructure and the vehicles for the new technologies battery electric (BEV), hydrogen (FCEV) and methane (CH4) are subject to much stricter safety requirements than the infrastructure and vehicles for the liquid fuels introduced decades ago when the world was less technical. The two renewable liquid fuels E-Diesel and HVO in our study can profit from the resulting simplifications. Pressure tanks used for storing compressed hydrogen (H_2) and compressed methane (CNG) need regular inspections and need to be protected from being rammed by vehicles. Refuelling with liquefied methane (LNG) requires the operator to wear personal protective equipment like googles and gloves. The safety around hydrogen refuelling stations is also more elaborated requiring sensors and their regular calibration.

The larger charging times of battery electric vehicles (BEV) compared to the refuelling times for fuel cell electric trucks (FCEV) and trucks with internal combustion engines (ICE) fuelled by methane (CNG or LNG) or the liquid fuels E-Diesel or hydrogenated vegetable oil (HVO) adds complications in the handling of the trucks and the co-ordination of loading stops, drivers and their resting periods. Depending on the truck’s application, the loading stops need to be equipped by charging stations and/or the distribution of fast chargers along the main transport route is critical. Longer charging times leads to larger areas needed to charge the trucks.

Due to the weight of the large batteries required in long-haul road transport, the payload of a truck is reduced, since a truck’s total weight is limited. This payload reduction is not important for fleet operators where the loading limit is given by the volume and not by the weight. For the case that weight is the loading limit, the regulations for maximum weight have been altered to allow two extra tons for batteries ([94] and [95] Annex 1 for the EU and [96] for Switzerland).

The qualitative assessment for the technologies used in this study in terms of “Practicability” is given in Table 21. All technologies are and will be practical with some minor restrictions for battery electric vehicles (BEV) related to the longer charging times and also some minor restrictions for fuel cell electric trucks (FCEV) due to the safety measures related to hydrogen handling and storage.

Table 21: Qualitative assessment for the criteria “Practicability”.

Electric Vehicles (EV)		Vehicles with Internal Combustion Engines (ICE)			
Battery Electric Vehicle (BEV)	Fuel Cell Electric Vehicle (FCEV)	Methane (CH_4)		E-Fuels	
		Synthetic Methane (Syn. CH_4)	Biomethane (Bio CH_4)	E-Diesel from Fischer Tropsch (FT)	Hydrogenated Vegetable Oil (HVO)
					

5 Results and Discussion

The conclusion from section 2.1 is that there is no clear cut overall GHG emissions reduction goal for 2030 for long-haul heavy-duty road transport in Europe. Central pieces of regulation, such as the "CO_2 Performance Standard for Heavy Duty Vehicles" [19,26] and "Renewable Energy Directive" (RED, [18,27]) only target portions of the complete life cycle emissions – Tank-to-Wheel (TtW) and Well-to-Tank (WtT) respectively. This obscures their presumed combined real impact on the overall life cycle emissions and can also have dramatic other effects than an aspired level playing field for GHG emission reduction impact [20]. This is especially the case with the new suggestion for a updated "CO_2 Performance Standard for Heavy Duty Vehicles" from February 2023 life cycle analysis (LCA) or at least Well-to-Wheel (WtW) approach and thus the regulation remains a pure Tank-to-Wheel (TtW) regulation. As such, it has an immediate impact on the drivetrain technologies produced. Real lifetime emissions reduction is neglected by the definition of so called Zero-emission Vehicles and in practice the regulation is ruling out options with internal combustion engines (ICE) in future fleets. It is interesting to note that one of the focus countries in this study, Switzerland, allows for consideration of 20% renewable methane guaranteed by the Swiss gas suppliers in the fleet emissions calculations of CNG-vehicles [97] (In force for vehicles up to $3.5\ \mathrm{t}$ and drafted for trucks in the current legislative process).

In contrast to the European "CO_2 Performance Standard", the "Renewable Energy Directive" (RED, [18,27]) regulates the supply of energy, i.e. the Well-to-Tank (WtT) path, but is much more technology neutral and clear in the real reductions of GHG-emissions to be achieved. The aspired target of 14.5% is defined as an "overall reduction achieved by the means of the implementation of renewable energies". The actual reduction in GHG emission in 2030 is more uncertain with the optional target set in the "Renewable Energy Directive" (RED) of a 29% share of renewable energy in the final energy consumption of the sector since the resulting reduction in GHG emission depends on the technology mix.

To have a clear reference for the targeted Well-to-Wheel emissions reduction in this study, the "Effort Sharing Legislation" and the current suggestion for the "Emissions Trade System" (ETS) to include the transport sector was referenced. The legislations demand reduction of GHG emissions of 40% and 43% respectively in relation to 2005. The "Effort Sharing Legislation" covers all sectors not regulated in the "Emissions Trade System" (ETS) and the current suggestion for the "Emissions Trading System" (ETS) is specific to the transport sector. In comparison, the European Green Deal states 55% GHG emissions reduction in 2030 in relation to 1990. It is much more ambitious both in terms of the reduction and in terms of the reference year, which is earlier. Unlike the "Effort Sharing Legislation" it lacks binding qualities for each member state. In the study, the reduction targets for GHG emissions from the Effort Sharing Legislation was applied and the ambition from the European Green Deal is used as an additional point of reference.

This aligns well with the ambitions of the focus countries included in the study Switzerland, France, Germany, Poland and Italy. France and Germany have specified explicit GHG emission reduction targets for the mobility and transport sector. Switzerland has gone beyond other European countries with 20% renewable share in the methane used for vehicles fuelled with compressed natural gas (CNG). Poland rather emphasises the social compatibility aspects and security of supply, but still also states an overall GHG Emission reduction target of 30% in 2030 in relation to 1990. Italy has no defined targets for 2030, but according to the projections accompanying the strategy, 42% GHG emissions reduction in transport in 2030 with reference to 2005 should be met. In summary it was concluded that while some European countries have more ambitious targets for GHG emissions reduction in transport and mobility than the "Effort Sharing Legislation", they are often not explicitly specified for the sector in other countries and in some cases even less ambitious. This is still the case if we assume general emissions reduction targets to apply also completely on the transport sector and for long-haul heavy-duty road transport in particular. On a European level, a recent compilation and evaluation of data by the European Environmental Agency indicates that current legislation is far from sufficient to reach the ambition to reduce GHG emissions by 90% in 2050, even with additional measures current in planning [21].

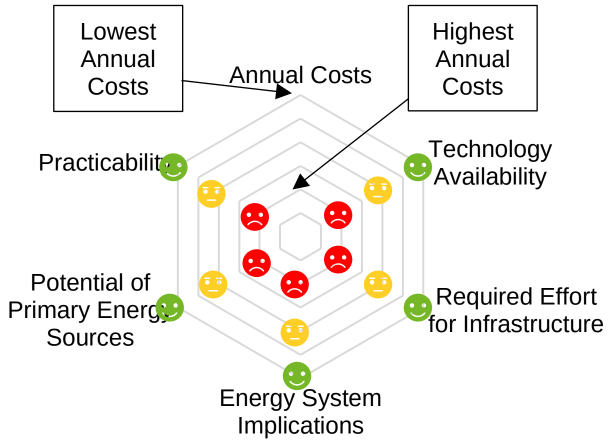
In conclusion we estimated that a Well-to-Wheel GHG emission reduction target of 40% in 2030 in relation to 2005 is a good overall European estimate for the long haul heavy duty road transport sector for the purpose of the calculations and reference in this study.

Our calculations in section3.4 show that the GHG emission goals cannot be reached with the latest Diesel technology available in 2030 alone: The resulting $101\,\mathrm{MtCO_{2eq}/a}$ exceed the limit of $64\,\mathrm{MtCO_{2eq}/a}$ according to the “Effort Sharing” approach from section 3.2. Technologies for renewable energies in heavy-duty long-haul road transport are needed of which we have focused on the four technologies from Table 6. Each of the renewable fuel technologies allows to have an operating fleet that fulfils Europe’s GHG goals for 2030 based on a Well-to-Wheel (WtW) approach under the assumptions made in this report. It should however also be stated that this approach, though being closer to the real GHG emission impacts than Well-to-Tank (WtT) and Tank-to-Wheel (TtW) are still not a complete Life Cycle Assessment (LCA) and neglects GHG emissions from both production of vehicles and infrastructure and their end of life. For each of the technologies (Table 6) and energy supply paths (Table 8), we created a hypothetical “Exclusive Scenarios” with an operating fleet with a share of renewable fuel trucks using only one additional technology and new diesel trucks for the remaining share. This combined fleet fulfils the targets for GHG emissions. In all scenarios, at least 37 % of the operating fleet needs to be renewable (Table 9), which means that a significant effort is required until 2030. Only when using biomethane from manure combined with new diesel, only 15% of the fleet must be renewable. But this assumes that the negative GHG emissions from biomethane from manure are officially credited towards heavy-duty road transport.

By calculating the annual costs in section 4.4 and applying the qualitative assessment in five categories in section 4.5, we have quantified and discussed six different dimensions of each scenario. To show all six dimensions including the qualitative ones in one plot, spider diagrams are chosen. The upper left part of Figure 26 explains how the diagrams are produced from the six dimensions such that the better the evaluation, the further out the corner point in the diagram is drawn. The lowest annual costs are represented by the respective corner point at the outer edge of the spider diagram and the highest annual costs with a corner point in the centre. The values in the middle of ranges given by the Max. and Min. values from Table 15 and Table 16 are used. A green smiley is represented by a corner point at the outer edge a red one results in the respective corner point in the centre of the graph. The larger the area, the more advantages there are. Nevertheless, this representation is not meant to give a weighting to the costs or the five qualitative criteria, nor does it mean that they are equally important. For annual costs, the results of the sensitivity analysis from section 4.4.8 is also shown in a slightly different tone.

Figure 26 shows six spider diagrams each with six radial axes representing the annual costs (section 4.4) and the five qualitative criteria (section 4.5). In combining quantitative and qualitative results in one figure, the authors want to emphasise that all aspects have to be considered at the same time. In the context of annual costs, it is important to remind that these were evaluated with the cost models and input parameters described in this report. Therefore, they are subject to the advantages and disadvantages of these models. As explained above, they show projected annual costs for 2030 and not prices. This means, they exclude any market effects, which could lead to high energy prices in times of energy scarcity and to low prices in times of energy surplus.

Figure 26: Spider Diagrams showing qualitative assessment from section 4.5 as well as annual costs from section 4.4 for the exclusive scenarios.



- Every «Exclusive scenario» represents an operating fleet in 2030 fulfilling the EU's goals for GHG emissions and which is composed of one renewable technology and new diesel.
- No Life Cycle Analysis: the emissions from the production of the vehicles are excluded from the GHG emissions targets.
- Annual Costs include costs for electricity, fuel production and transport, refuelling and fleet. Sensitivity: electricity costs reduced to 50%
- Details on qualitative criteria are given in section 4.5.

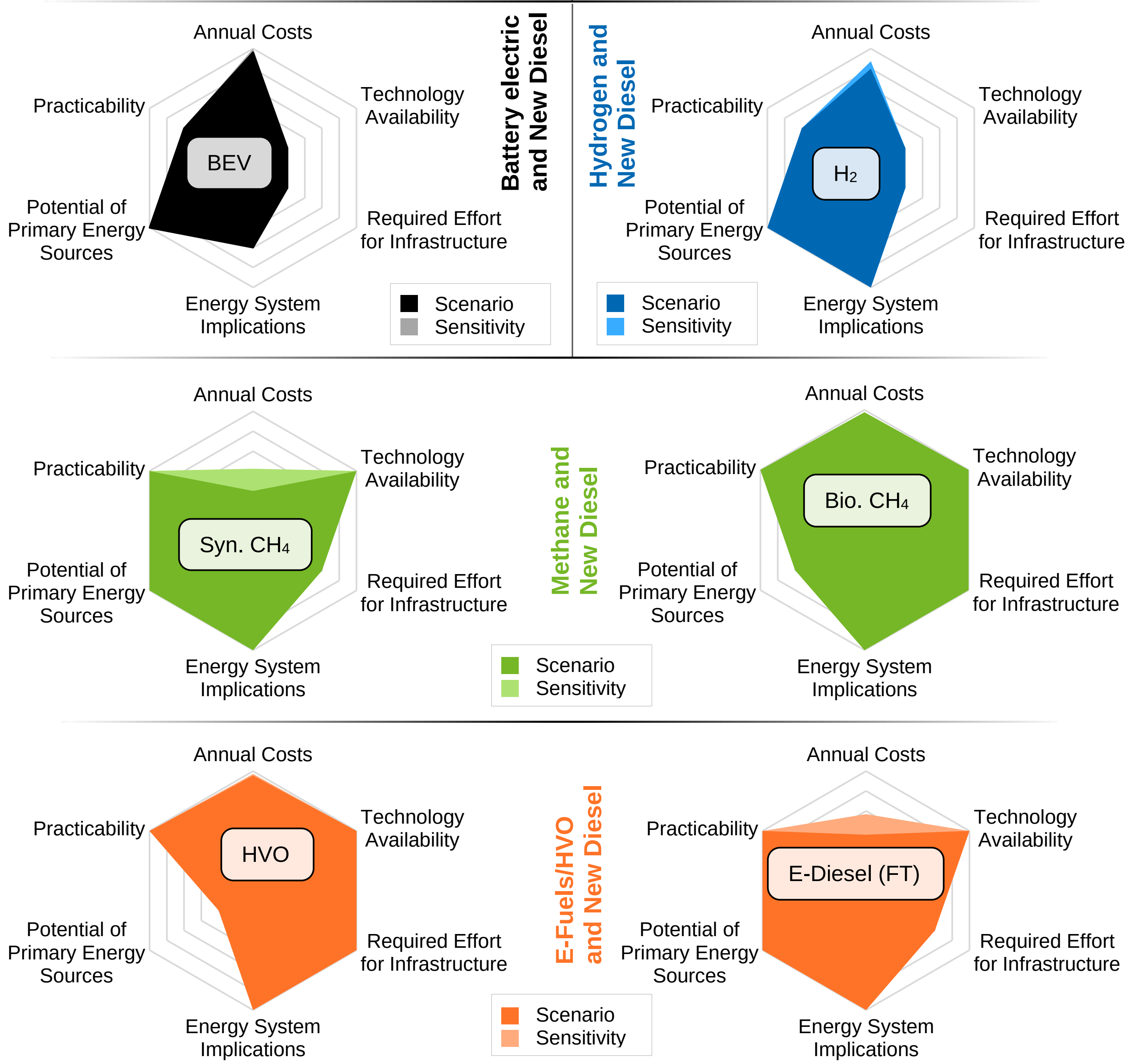


Figure 26 shows on the "annual costs" axis at the top that energy supply paths based on electricity with higher efficiencies i.e., battery-electric (BEV) and hydrogen (H_2) and the energy supply paths based on biomass (Bio CH_4) and hydrogenated vegetable oil, HVO) have advantages in lower annual costs. Based on the modelling assumptions used in the estimation of annual costs, the synthetic energy carriers have the highest annual costs. This is mainly attributed to the fuel production costs (see section 4.4.7), which predominantly consist of electricity costs. This means that to be competitive, synthetic fuels need cheap electricity as primary energy source. This is possible in choosing good locations with high full load hours and/or where wind and PV can be combined in an ideal way, an option not considered in the quantitative analysis of this study. Furthermore, hydrogen for synthetic fuels can be produced when the price for electricity is low due to an abundancy of renewable energy, which helps stabilising the electricity grid. Alternatively due to their transportability they can be produced in locations not considered in this study.

The four fuels synthetic methane (Syn. CH_4), biomethane (Bio CH_4), E-Diesel from Fischer-Tropsch (FT) and hydrogenated vegetable oil (HVO) have all an advantage in the criteria "technology availability" and "required effort for infrastructure" since vehicles and infrastructure components are commercially available, and part of the infrastructure is already built. Both allows fast implementation with fast reduction of GHG emissions. The two synthetic fuels methane (Syn. CH_4) and E-Diesel (FT) have challenges in the criterion "required effort for infrastructure" when it comes to the infrastructure for producing the fuels.

The fourth dimension on the vertical axis downwards in Figure 26 shows that all the chemical energy carriers – hydrogen (H_2), methane (Syn. CH_4 and Bio CH_4), E-Diesel from Fischer-Tropsch (FT) and hydrogenated vegetable oil (HVO) – have advantages in the criterion "energy system implications". This is due to their better storability and transportability in comparison to electricity.

Our analysis of the potential of renewable energies in Europe in section 2.2 and 4.5.4 shows that all technologies relying on renewable electricity as primary energy source have large primary energy potentials,. Only the two fuels based on waste streams i.e., biomethane (Bio CH_4) and hydrogenated vegetable oil (HVO) are constrained in this regard. This can, however be compensated already within each of these two exclusive scenarios as they also encompasses synthetic alternatives in E-Fuels and Synthetic Methane.

The disadvantages in three criteria "technology availability", "required effort for infrastructure" and "practicability" for battery-electric trucks (BEV) and fuel cell electric trucks (FCEV) running on hydrogen (H_2) are related to the novelty of the technologies. Consequently, vehicles and infrastructure components are currently difficult to acquire on the market (section 4.5.1) and the related infrastructure (section 3.4) remains to be built to a large extent. The conventional technologies are able to be implemented quickly and to reduce GHG emissions on a short term already before the new technologies are ready to unfold their full potential.

Looking again on Figure 26 from a distance shows that all technologies have advantages and disadvantages and that combining all spider diagrams on top of each other fills the entire space. This means that all technologies and energy supply paths can complement each other in an ideal way. The conventional technologies can run on renewable energy and can make a difference short-term, while at the same time also include new renewable fuels derived from electricity allowing for a long-term perspective in compliance with the continued efforts for GHG emissions reductions. Newer technologies are recognised to have strengths in overall efficiency and costs, while commercialisation and infrastructure build up are continued it is estimated that they can have an effect in medium- to long-term.

Looking at the two combined exclusive scenarios "Methane and New Diesel" and "E-Fuels/HVO and New Diesel" shows a very strong case for each of these scenarios, where "technology availability", "energy system implications" and "practicability" are strong for all options and the other criteria complement each other's strengths and weaknesses already within the respective exclusive scenario to almost fill out the spider diagram completely.

In the larger perspective, heavy-duty long-haul road transport also needs to decarbonise outside of Europe and countries will look for different ways to do that. It can be assumed, the more diverse the technological options within the EU, the more chances there will be for European technology providers to innovate and export climate-neutral technologies fitting the needs also for other countries.

5.1 Germany

Germany, with its population of 83 million inhabitants [98], is the most populated country of the European Union and the largest economy. Thanks to its automobile industry, it is also one of the most advanced countries when it comes to low-emission mobility, for heavy-duty as well as for light-duty vehicles. The country is committed to reach its emission reduction targets and even wants to lead the EU in GHG reduction and to be an example representing the direction taken by the European industry. The 530,000 German trucks [99] correspond to 6.4 trucks per 1,000 inhabitants, which is below EU-27's average of 9.8 trucks per 1,000 inhabitants [98,99]. This figure is expected to stay stable for the next years, as shown in Figure 7.

From an energy point of view, Germany is also representative of the challenges faced by the rest of the EU. The country does not own favourable assets such as particularly powerful sunshine, winds, or large dimension hydropower. With its decision in 2011 to phase out nuclear energy and its strong development of renewable electricity, Germany now faces the challenge of intermittence, and has made itself dependant of coal again.

In terms of infrastructure, Germany is also one of the most advanced European countries with most of the hydrogen refuelling stations and a lot of CNG stations operating on its territory, as presented in section 3.4. Germany is additionally one of the few countries benefitting from first hydrogen pipelines networks, and is, as discussed in section 3.4.2, at the centre of its future extension.

5.2 France

Although France is one of the largest countries in Europe, its economy is less oriented towards industry.

One of the particularities of France is its energy mix: Roughly 70% of its electricity comes from nuclear power plants, making it one of the countries in the world depending the most on nuclear, and the largest net exporter of electricity in Europe. Nuclear being considered as a low-emission technology, the knowledge and the existing industry could give France a certain advantage compared to other European countries when it comes to powering electric vehicles, producing hydrogen or synthetic fuels with highly available low-carbon electricity. Obviously nuclear energy also has its disadvantages, mainly radioactive waste and safety issues.

In terms of infrastructure for renewable long-haul road transport, France is not in the lead. Although it is almost seven times larger than Switzerland, both countries have roughly the same number of refuelling stations for compressed and liquefied methane (CNG and LNG, Table 7) and hydrogen.

5.3 Italy

Italy is the leading country in Europe when it comes to gas vehicles. Passenger cars running on natural gas or biomethane have been around for decades, which explains the high number of existing CNG and LNG refuelling stations (Table 7). The best solution for the country might therefore be to keep fostering gas vehicles, transport infrastructure and refuelling stations. Italy also benefits from its southern location, allowing a high solar energy yield and a proximity to MENA countries for importation through pipelines network, of which Italy is therefore a key player. When it comes to hydrogen, Italy lacks behind the other large countries as the respective transport and distribution infrastructure is near to inexistant.

5.4 Poland

Poland is also one of the largest European countries in terms of surface, but it only has roughly half Germany's population density. This makes Poland more challenging to cover with charging points and/or refuelling stations as the distances driven are larger than in other countries.

Poland has the highest number of trucks per habitant of the countries presented here with 19 trucks per $1{,}000$ inhabitants. This figure is almost double the European average. Poland is also in the top 5 most populated countries in the EU, making it the country with the overall highest number of registered heavy-duty vehicles (HDV). This does not necessarily mean though, that polish trucks drive on average smaller distances, or that more goods are transported. This situation is most probably due to polish trucks driving long distances all over Europe for international companies because they're significantly cheaper to operate than trucks registered in their own country. Of course, other states probably offer trucking services as cheap as Poland, but these countries are smaller and therefore do not weight as much as Poland in the statistics.

In addition to having the highest number of trucks in Europe, Poland relies heavily on coal, and fossil fuels [100] for its electricity supply, making it therefore one of the most challenging countries to decarbonize with battery electric vehicles (BEV) or locally produced synthetic fuels. Green electricity is indeed a prerequisite to the usage of the technologies mentioned in this report, with the exception for biomethane.

5.5 Switzerland

Switzerland has a strong economy compared to its surface area. Its gross domestic product (GDP) per capita is more than twice the European average [101] and one of the highest in the world. Switzerland is also known for its cutting-edge innovation, research and development in high-tech areas. Switzerland's mix of electricity production is 60% hydro and 30% nuclear. But on the contrary to what one could have been expected, Switzerland is neither leading in terms of new renewable electricity production nor sustainable mobility. It has decided to phase out of nuclear and the replacement with PV and wind is far behind. The construction of new renewable sources has been very slow until recently but is now picking up slowly. This creates a gap between electricity production and consumption in winter, at the same time electricity is scarce in other parts of Europe.

The first mass-produced hydrogen trucks from Hyundai Motors where first tested in Switzerland. This allowed to reach a high number of fuel cell electric trucks (FCEV) and hydrogen refuelling stations compared to the country's size. The high taxes for road transport for fossil vehicles with reductions for renewable traffic also helped this development. $4\ \mathrm{MW_{el}}$ of electrolyser capacity in two locations produce green hydrogen [102,103]. This new hydrogen ecosystem is a private initiative with public funding only at the start of the activities. Today, $4\ \mathrm{MW_{el}}$ of electrolyser capacity distributed in two locations produce green hydrogen [102,103].

Alternative Drives for Construction, Agricultural and Forestry Machinery

In the EU, several million machines are used in construction, agriculture, forestry and mining. This machine class needs to be decarbonized as all other energy consuming sectors. As in heavy-duty road transport alternative drive technologies must be made available.

The energy and power requirements of this group of machines vary greatly depending on the application and size of the machine. As in the road sector, it is also the case that small and light machines can be easier converted to battery-electric rather than heavy construction machines or agricultural vehicles that often have very high operating hours and high power requirements.

If high performance must be achieved, fuels with high energy density have an advantage such as liquid biofuels and future E-Fuels. An example of this are agricultural machines such as harvesters, which are in use 24/7 during the harvest season and depend on fast refueling. The conversion to these fuels is easily possible ,since vehicle technology and fuel supply do not have to be adapted or only insignificantly. The refueling is an important factor with these machines, as they are usually refueled on site and cannot drive to loading points/gas stations.

Overall, the choice of decarbonization option will depend on the specific needs of the application, including factors such as power requirements, range, availability of infrastructure, and cost considerations. Each option has its own set of advantages and disadvantages, and a careful analysis of these factors will be necessary to determine the most appropriate solution for a given application.

The table below gives a general overview on decarbonisation options for heavy machinery:

Option	Advantages	Disadvantages	Availability of Technology
Battery Electric Drives	Zero tailpipe emissions (TTW), low noise levels, high torque at low speeds, lower operating costs, potential for energy recapture through regenerative braking	Limited range and charging time or complex battery exchange, limited availability of charging infrastructure, heavy batteries that can affect weight and balance, high upfront costs	Battery electric drives are commercially available for some heavy machinery applications, further development is needed to improve battery technology and charging infrastructure for larger and more powerful machinery
Hydrogen Fuel Cell Drives, hydrogen combustion engines	Zero tailpipe emissions (TTW), potential for long ranges and fast refuelling times, water is the only byproduct	Limited availability of hydrogen refuelling infrastructure, high upfront costs of fuel cells and hydrogen storage tanks, hydrogen production can be energy-intensive and may rely on fossil fuels, complexity of fuel cell technology	Hydrogen fuel cell drives for heavy machinery are in the development phase. Significant progress has been made in recent years, but further research is needed to allow scale up to heavy machinery
Biofuels	Biofuels have very low greenhouse gas emissions and can be used in existing internal combustion engines, widespread availability of biodiesel and ethanol, significant emissions reductions on WTW basis	Limited availability, must be efficiently integrated into crop farming and feedstock production, otherwise conflicts with food production, land use and problems with monocultures.	Biofuels are already widely used in internal combustion engines especially in the agricultural sector. Supply infrastructure and engine technology exists and is fully developed
E-Fuels	E-fuels are compatible with existing internal combustion engines, significant emissions reductions compared to fossil fuels on WTW basis	Production costs, limited availability of fuel production infrastructure	E-fuels are still in the early stages of development. Production of smaller quantities of E-Fuels is in place, research and development is needed to scale up production and make it more cost-effective. Supply infrastructure and engine technology exists and is fully developed.
	assessment varies depending on the specific application and implementation.		

The table shows that for example battery electric drives may be an option for machinery used in urban environments, if there is direct access to charging infrastructure eg. at the construction site itself, while biofuels or later E-Fuels may be a better option for machinery used in areas and locations with limited charging infrastructure.

Summarizing, decarbonizing construction and agricultural machinery requires a multi-faceted approach. There is no one-size-fits-all solution and different decarbonization options will be better suited for certain applications and circumstances. It is therefore important to adopt a technology-open approach to decarbonize the sectors of construction and agricultural machinery. This allows for flexibility and the ability to tailor solutions to specific needs and circumstances. As a consequence, emissions in this vehicle class must (just like all other classes) be assessed based on a well-to-wheel (WTW) basis.

6 Recommendations

The discussion of our exclusive scenarios using different renewable fuel technologies (Table 6) and energy supply paths (Table 8) shows that there is no “one fits all” solution. All discussed scenarios have their advantages or disadvantages as becomes visible in the spider graphs of Figure 26. To reach targets in reducing GHG emissions a mix of all technologies seems suitable and the challenge to reach these targets in long-haul road transport in 2030 seems easier to meet. Multiple aspects are important when deciding for a technology. Our key recommendations are to have strict and fair regulations to allow all renewable fuel technologies to contribute to the GHG targets:

- Give long-term security for investments into vehicles and infrastructure in defining European rules quickly and definite.
- Set strict rules such that the technologies can compete within fair boundaries. Technology-neutral regulations demanding the same strict goals on GHG emissions from all technologies. Strict rules must make green-washing impossible.
- When setting goals for GHG emissions, at least Well-to-Wheel (WtW) approaches should be followed if considering the entire life cycle (LCA) turns out not to be practically possible. A Well-to-Wheel (WtW) approach has the advantage that battery electric trucks (BEV) are charged with renewable electricity, fuel cell electric trucks (FCEV) are refuelled with green hydrogen and when fuelling vehicles with internal combustion engines (ICE) with renewable fuels, that are (almost) carbon-neutral, the same rules apply. This is not the case in a Tank-to-Wheel (TtW) approach, which only considers tailpipe emissions.

The effects of such regulations are:

- The rules set by politics define the future composition of long-haul road transport fleet. The incentives and tax exemptions for renewable long-haul road transport of any technology can “kick-off” technologies both immediately as well as long-term.
- In short term, the conventional technology of internal combustion engines (ICE) with their respective renewable fuels can bring a faster reduction of GHG emissions in comparison to the newer technologies of the battery-electric vehicles (BEV) and fuel cell electric vehicles (FCEV). Stable regulation pushes the industries supplying trucks with internal combustion engines (ICE) with sustainable fuels: Production capacities, transport infrastructure and refuelling infrastructure.
- At the same time, commercialisation of vehicles and infrastructure components and the infrastructure build up can take place with the newer technologies battery electric trucks (BEV) and fuel cell trucks (FCEV).
- A variety of technologies allows different countries and fleet operators with different requirements and use cases to find the best fitting pathway to their renewable long-haul heavy-duty road transport.

For the transition to a climate neutral energy system, it is not enough to rethink a single sector on its own (e.g., long-haul road transport), but is it necessary to have a holistic view at the entire system, not only the energy system but also the input of raw materials for the industry, heavily relying on fossil sources today. Energy use has to be reduced and the remaining demand has to be covered by renewable energies produced in Europe and imported from abroad. To achieve this, a massive expansion of renewable energy production is necessary, resulting imbalances between production and consumption have to be solved and investments in infrastructure abroad and in Europe is necessary. This only occurs if regulations allow long-term planning.

The large-scale introduction of zero-emission trucks to establish a renewable long-haul road transport can only be solved on a European level with clear political framework conditions, subsidies and incentives. Besides that, measures for reducing the total amount of long-haul road transport have to be implemented (decoupling from economic growth, shifting to rail, increasing the vehicle utilization).

Further, the research, development and commercialisation of the new technologies for battery electric trucks (BEV) and trucks running on hydrogen (H_2) (e.g., hydrogen internal combustion engines (ICE), liquefied hydrogen or liquid organic hydrogen carriers LOHC) must be intensified. At the same time, fair regulations allow that research, development and commercialisation in the field of trucks with internal combustion engines (ICE), related technologies and the related fuels (Bio CH_4, Syn. CH_4, E-Diesel/HVO, hydrogen) to be pursued further.

Appendix

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A.2 Terminology

a	Time unit year from “annum”
Advanced biofuels:	Biofuels with raw material of non-food origin. Biofuels that are not in competition to food production.
AFID	“Alternative Fuels Infrastructure Directive” or “Directive on Alternative Fuels Infrastructure” from 2014.
AFIR	“Alternative Fuels Infrastructure Regulation” or “Regulation for the deployment of alternative fuels infrastructure”, agreed in March 2023 replacing the AFID from 2014.
Annual costs:	All the cost in this report was calculated as annual cost by using VDI 6025 guidelines (see section 1.3.4). The results show the annual amount in 2030 which needs to be paid to reach the emission target.
BEV:	Battery electric vehicle
Bio CH4:	Biomethane
Biofuels	Biofuels are used in the transportation sector (in gaseous or in liquid form) to reduce the emissions. They are produced from biomass. Thus, they are considered as renewable alternative to the fossil fuels. In the context of this study, gaseous (biomethane produced from corn) and liquid (HVO produced from rapeseed oil) form of biofuels are considered.
Biogas	Is sometimes understood as raw biogas consisting of methane CH_4 and CO_2 but also as biomethane. To avoid misunderstandings, this report uses the terms “raw biogas” and “biomethane” and uses the term only in the sense of a biogas plant.
Biomethane:	Biomethane is produced from an anaerobic digestion process of biodegradable materials. The energetic value of biomethane is processed to match the quality and purity of natural gas. This allows for limitless injection of biomethane into the natural gas network.
Blue hydrogen	Blue hydrogen is gained from fossil natural gas with the climate-impacting carbon being captured and stored safely. To be able to meet the overall gas demand in the future, carbon-neutral blue hydrogen should be considered as part of the supply as well as, given its carbon capture and storage capacities.
CBG	Compressed biogas meaning compressed biomethane using the standardised CNG technology.
CC:	Carbon Capture, capturing CO2 from the atmosphere (DAC) or from concentrated sources. In this context, the abbreviations CCS for carbon capture and storage and CCU for carbon capture and utilisation are also used.
CH:	Switzerland
CNG	Compressed natural gas, a standardised technology to store methane under pressures of up to 200 barg. The methane can not only be natural gas but also biomethane (CBG) or synthetic methane produced in a power-to-gas process. If the latter uses renewable electricity, the methane is considered renewable.
CONCAWE	“Conservation of Clean Air and Water in Europe”, an organisation whose members are oil and gas companies
DE	Germany

DAC	Direct Air Capture, technologies allowing to take carbon dioxide from the atmosphere (in contrast of using concentrated sources of carbon dioxide).
Decarbonisation:	Avoiding the use of carbon in fuels. In a strict semantic meaning, the term also includes the avoidance of carbon from biological origin. However, most of the times, the term is used in the sense of avoidance of fossil carbon only and therefore is identical to the term defossilisation. This reports also uses "Decarbonisation" in the meaning of "Defossilisation".
Defossilisation:	Avoiding the use of fossil fuels.
DG RTD	"European Commission Directorate-General for Research and Innovation"
E-Fuel:	Chemical liquid or gaseous fuel produced in a Power-to-X plant from renewable electricity.
ENSPRESO	"Energy System Potential for Renewable Energy Sources" [28]wable
ETS	Emissions Trading System, in our study the EU ETS
EU-27:	All member countries of the European Union from 1 February 2020.
EU-28:	EU member countries including UK
EU ETS:	"European Union Emissions Trading System"
EU-KP:	EU member countries including UK and Iceland (Kyoto-Protocol)
FR:	France
FCEV:	Fuel cell electric vehicle for the use of hydrogen, sometimes also called hydrogen fuel cell electric vehicle, HFCEV
FT	Fischer Tropsch is a conversion process to produce E-Diesel from Hydrogen and Carbon monoxide.
GHG:	Greenhouse gases. In the context of this study, the greenhouse gases are carbon dioxide (CO_2), methane (CH_4), fluorinated gases and nitrous oxide (N_2O) emitted to the atmosphere. Other gases than CO_2 are converted into mass of CO_2 equivalent.
Green hydrogen:	Green hydrogen is generated via power-to-gas in a carbon-neutral way, using renewable energy sources such as solar or wind for the electrolyser.
Grey hydrogen:	Grey hydrogen is hydrogen produced using fossil fuels such as natural gas, and thus has a negative climate impact.
HDV:	Heavy-duty vehicles
HFCEV:	Hydrogen fuel cell electric vehicle
HVO:	Hydrotreated vegetable oil, a fuel with the quality of diesel.
IT:	Italy
ICE:	Internal combustion engine
JRC	European Commission's "Joint Research Centre"
LBG	Liquefied biogas meaning liquefied biomethane using the standardised LNG technology.
LCA:	Life cycle analysis
LCV:	Light commercial vehicles
LDV:	Light duty vehicles (passenger cars and LCV)

LH2:	Liquefied hydrogen. Method of storing hydrogen in liquid form in cryo-tanks after cooling it to $-253\ °C$ (at a pressure of $1\ \mathrm{bara}$).
Liquid fuels:	Fuels, which are in liquid form at environmental conditions, i.e. at pressures of around $1\ \mathrm{bara}$ and temperatures of around $20\ °C$. Methane becomes liquid at temperatures of $-162\ °C$ (at a pressure of $1\ \mathrm{bara}$) called “liquefied natural gas” (LNG). Hydrogen becomes liquid at temperatures of $-253\ °C$ (at a pressure of $1\ \mathrm{bara}$), which is called “liquefied hydrogen” (LH2). Both are not called “liquid fuels” in this study.
LNG:	Liquefied natural gas, a standardised technology to store methane in liquefied form in cooling it to minus $160\ °C$. The methane can not only be natural gas but also biomethane, synthetic methane or renewable methane of different origin.
Long-haul:	Transport over distances of more than $150\ \mathrm{km}$ without delivery and without interim charging/fuelling stops with 40-ton trucks (type 5).
LPG:	Liquefied petroleum gas, a mixture of mainly propane and butane which is stored in tanks at pressures above the vapour pressure. The latter is between 2 bara and 20 bara depending on the exact composition and the temperature.
LULUCF	“Land use, Land Use Change or Forestry” regulation
MCS	Megawatt Charging System
Megawatt Charging System	A standard for charging commercial vehicles with up to $3.75\ \mathrm{MW}$ (3,000 A at 1,250 V DC) [46,47]
MENA	Middle East and Northern Africa
Methanation	In the process of methanation, hydrogen is combined with carbon dioxide and transformed into methane. For the catalytic methanation method, a metallic catalyser is needed. Alternatively, biological methanation, employing micro-organisms, can also be used as methanation method.
Methane	The colourless, flammable, odourless gas CH_4 which is the major component of natural gas and an important source of hydrogen in various industrial processes.
Mt	Unit megaton, which is 1 million tons.
NEDC	New European driving cycle
Payload	weight of material transported (for road transport)
PL	Poland
PtX	Power-to-X, the transformation of electricity into a chemical product, mostly hydrogen or any hydrocarbon chain.
RED	“Renewable Energy Directive”, RED II is currently in force (Directive (EU) 2018/2001).
RES	Renewable energy source.
TtW = Tank-to-Wheel	Concept to determine the environmental impact of a vehicle in only considering emissions while the vehicle is in use and the energy available in the vehicle's tank or battery is transmitted through the drivetrain to the wheels

tkm	The number of ton-kilometres is the weight in tons of material transported (payload) multiplied by the number of kilometres driven. An alternative definition would be if tkm was related to the total weight of the vehicle (i.e. not just the payload = weight of material transported)
TRL	Technology Readiness Level, a scale to express the maturity of a technology ranging from TRL1 for basic principle observed to TRL9 for system proven in a real environment.
UCO	Used cooking oil for the production of hydrogenated vegetable oil (HVO)
WtT = Well-to-Tank	Concept to determine the environmental impact of fuel production or extraction (including electricity) through the fuelling station or charging station until the energy is stored in the vehicle
WtW = Well-to-Wheel	Concept to determine the environmental impact of a vehicle in combining Well-to-tank and Tank-to-wheel

A.3 Details on European Plans

1. More Details on EU's "Sustainable and Smart Mobility Strategy" [14] published in December 2020 containing ten flagship areas:

   Flagship 1 "Boosting the uptake of zero-emission vehicles, renewable & low-carbon fuels and related infrastructure". Zero-emission in this case, refers to the tank-to-wheel emissions and the flagship sets out to stimulate the demand for these type of vehicles from several angles. First and foremost, by revising the CO_2 standards for cars and vans by June 2021 and later also for heavy-duty vehicles. Furthermore, research programmes should support innovation for these types of vehicles. Carbon pricing, taxation road charging and the revision of rules for weight and dimensions of heavy-duty vehicles are further tools to generate incentives in favour of zero emission vehicles. Furthermore, actions to boost these types of vehicles in cooperate and urban fleets will be suggested. This is said to be accompanied with higher demands for sustainability of batteries such as "end-of-life cycle requirements, Carbon footprint and ethical and sustainable sourcing of raw materials.

   The flagship area further states that there must be clear signals that transport fuels must become carbon neutral and deployed on large scale. Tools mentioned for this are minimal shares or quotas in the revisions of the "Renewable Energy Directive" (RED).

   Regarding the heavy-duty transport hydrogen fuel-cell vehicle is mentioned as a particularly viable option. This is further supported by the "Recharge and refuel" in the Recovery and Resilience Facility with the aim to build half of the 1,000 hydrogen stations and 1 million of the 3 million recharging points. The commission outline a set of complementary actions to support the rapid deployment of alternative fuels infrastructure in collaboration with the Sustainable Transport Forum. More binding targets and requirements for interoperability and seamless cross-border payments, amongst others, will be addressed in the replacement of the Directive on Alternative Fuels Infrastructure (AFID) from 2014 by the "Alternative Fuels Infrastructure Regulation" (AFIR) and the Trans-European Transport Network (TEN-T) policy.

   Flagship 5 "Pricing carbon and providing better incentives for users" addresses how to internalise the cost CO2 emissions immobility. It suggests extending the EU Emission Trading System (EU ETS) to maritime, aviation and road transport. Revenues from the system would be invested in supporting research and innovation to decrease the emissions further. Further tools mentioned in this flagship area is the amendment of the Eurovignette Directive in line with the Green Deal and utilise smart, distance-based road charging with varied rates for the type of vehicle and time-of-use. This has the intention to manage traffic and reduce congestion for more efficient use and financing of infrastructure as well as air pollution.

Flagship 6 “Making connected and automated multimodal mobility a reality” addresses the opportunities addressed under the label of “Connected, Cooperative and Automated Mobility (CCAM) with the vision to make Europe a world leader in this field to support safe and sustainable road transport. Harmonisation and coordination of relevant traffic rules and the liability of automated vehicles are mentioned as examples for areas of relevance. It will be investigated if there should be a new body or an existing agency to develop and coordinate development and management of ITS and be a central point for relevant data collection, prepare relevant technical rules and other cross Europe legislation suggestion. It would also manage major disruptive events, such as the consequences of the COVID-19 pandemic in a harmonised across Europe way.

There are also accompanying milestones defined for the flagship areas. The ones most relevant in regard to impacting heavy-duty road transport are: 1) stating that there should be at least 80 000 zero-emission lorries in operation by 2030, 2) that nearly all heavy-duty vehicles will be zero-emission by 2050, 7) Rail freight traffic will increase by 50% by 2030 and double by 2050, 8)Transport by inland waterways and short sea shipping will increase by 25% by 2030 and by 50% by 2050, 9) by 2030, rail and waterborne-based intermodal transport will be able to compete on equal footing with road-only transport in the EU, 10) all external costs of transport within EU will be covered by the transport users at the latest by 2050, 11), 12) and 13 by 2030, freight transport will be paperless and automated mobility will be deployed on large scale with a core network of high speed connectivity operational (a comprehensive network by 2050).

In the action-plan the majority of actions in Flagship area 1 were due for 2021, Flagship area 5 in 2022 and Flagship area 6 equally in 2021 and 2022.

2. More proposals and intended packages consulted for this study without any influence on the targets for GHG emissions used in this study:

   In December 2021 four new proposals to target greater efficiency and more sustainable travel was published. It is a package of suggestion with the intention to set the transport sector on track to cut emissions by 90%. It builds on the “Trans-European Transport Network” (Ten-T) plans and consists of four packages of measures: The new European Urban Mobility Framework, Improving Road Safety and Driver Comfort through Digitalisation, Boosting Long Distance and Cross Border Passenger Rail, Creating a Green and Efficient Trans-European Transport Network. [104–107]

   These packages have little direct relation to heavy-duty road transport and specifying ambitions levels for GHG-emissions reduction. Rail transport is the mode of transport of attention both in regard to passenger and freight transport and would indirectly impact long-haul road transport. One example is that it suggests that it should become possible for lorries to be transported by rail, network wide, and creating modal shifting opportunities by Multimodal Hubs. This is part of Creating Green and Efficient Tans-European Transport Network, with an estimated impact on GHG-emissions of up to 0,4% reduction by 2050.

   In 2022 the European Environment Agency published its “Transport and Environment Report 2021 – Decarbonising road transport, the role of vehicle, fuels and transport demand” [108] The key questions addressed are: How does the EU road transport sector perform in terms of the specific goals for vehicles and the energy they use?, How is this sector currently contributing to achieving the overarching GHG reduction goals and how will they be reached in the future? and What are the main policy levers, challenges, obstacles and prospects?

   It considers Tank-to-Wheel and Well-to-Tank emissions and makes short excursion into Well-to-Wheel considerations. Finally it presents a catalogue of measures to „avoid, shift and improve“ road transport emissions.

A.4 Input Data

Table 22: Input data for the calculations

Row	Input Variable	Value	Unit	Sources
100	**Electricity Costs**			
101	CAPEX PV	392	€/kW	[109][62]
102	OPEX PV	9	€/kW	[109][62]
103	Lifetime PV	35	year	[110][63]
104	Full load hours - PV MENA	1,800	h/a	[111][64]
105	Full load hours - PV EU	1,000	h/a	[111][64]
106	CAPEX wind onshore	1,000	€/kW	[110][63]
107	OPEX wind onshore	20	€/kW	[110][63]
108	Lifetime wind onshore	25	year	[110][63]
109	Full load hours - wind onshore EU	2,200	h/a	[112][65]
110	CAPEX wind offshore	2,580	€/kW	[110][63]
111	OPEX wind offshore	77	€/kW	[110][63]
112	Lifetime wind offshore	25	year	[110][63]
113	Full load hours - wind offshore EU	3,800	h/a	[112][65]
114	GHG emissions PV	33	gCO_2-eq/kWh_{el}	GEMIS 5.0
115	GHG emissions wind onshore	8.7	gCO_2-eq/kWh_{el}	GEMIS 5.0
116	GHG emissions wind offshore	4.4	gCO_2-eq/kWh_{el}	GEMIS 5.0
200	**Battery-Electric Vehicle (BEV)**			
201	CAPEX transmission line	0.61	€/kW/km	[113][66]
202	OPEX transmission line	0.01	€/kW/km/a	[113][66]
203	Transmission line efficiency	98.4	%	[113][66]
204	Lifetime transmission line	50	year	[113][66]
205	Full load hours transmission line	8,760	h/a	Assumption
206	CAPEX converter	180	€/kW	[113][66]
207	OPEX converter	1,8	€/kW	[113][66]
208	Converter efficiency	98.6	%	[113][66]
209	Lifetime converter	50	year	[113][66]
210	Full load hours converter	8,760	h/a	Assumption
211	CAPEX charger (750 kW)	180	€/kW	[114][50]
212	OPEX charger	2%	of CAPEX p.a.	[114][50]
213	Lifetime charger	20	year	[114][50]
214	Full load hours charger	3,650	h/a	[114][50]
215	Power charger	750	kW	[114][50]
216	Efficiency charger	86	%	[114][50]
217	Transmission line transport distance – PV-EU & wind onshore	500	km	Assumption
218	Transmission line transport distance – wind offshore	1,000	km	Assumption
300	**Hydrogen (H_2)**			
301	CAPEX compressor	3,400,000	€	[59]
302	OPEX compressor	1	%	[59]
303	Lifetime compressor	25	year	[59]
304	CAPEX electrolyser	400	€/kW	[115][49]
305	OPEX fix electrolyser	3	% CAPEX p.a.	[115][49]
306	Full load hours electrolyser	2,475	h/a	[112][65]

Row	Input Variable	Value	Unit	Sources
307	Electricity cemand electrolyser	47.8	kWh el./kg H_2	Own calculations
308	Efficiency electrolyser	70	%	[112][65]
309	Lifetime electrolyser	25	year	[112][65]
310	CAPEX desalination	816	€/t$H_2$0/a	[113][66]
311	OPEX desalination	4	%	[113][66]
312	Electricity demand desalination	0.11	TWh/a	Own calculations
313	Lifetime desalination	30	year	[113][66]
314	Refuelling cost H_2	0.8	€/kgH_2	[114][50]
315	Distance between compressors	250	km	[115][49]
316	Pipeline transport distance - MENA	3,000	km	Assumption
317	Pipeline transport distance - EU	500	km	Assumption
318	Specific CAPEX pipeline	22,500	€/km	[59]
319	Specific CAPEX pipeline	2,500,000	€/km	[59]
320	Lifetime pipeline	40	year	[59]
400	**Methane (CH_4)**			
401	CAPEX compressor	3,120,000	€/MW	[115][49]
402	OPEX compressor	2	% CAPEX p.a.	[115][49]
403	Lifetime compressor	25	year	[115][49]
404	CAPEX methanation	220	€/kW	[115][49]
405	OPEX fix methanation	4	% CAPEX p.a.	[115][49]
406	Full load hours methanation	6,000	h/a	[112][65]
407	Efficiency methanation	78	%	[113][66]
408	Lifetime methanation	30	year	[113][66]
409	CAPEX carbon capture (DAC)	378	€/tCO_2/a	[116][67]
410	OPEX carbon capture (DAC)	4	% CAPEX p.a.	[116][67]
411	CAPEX carbon capture (from industry)	7.59	€/tCO_2/a	[117][118]
412	CAPEX carbon capture (from raw biogas)	25.3	€/tCO2/a	[117][118]
413	Electricity demand carbon capture (DAC)	1,458	kWh el./tCO_2	[116][67]
414	Electricity demand carbon capture (from industry)	612	kWh el./tCO_2	[117][118]
415	Electricity demand carbon capture (from raw biogas)	204	kWh el./tCO_2	[117][118]
416	Lifetime carbon capture	30	year	[116][67]
417	CAPEX refuelling station – CNG	0.005	€/kWh	[9]
418	OPEX refuelling station – CNG	3	% CAPEX p.a.	[9]
419	Lifetime refuelling station – CNG	20	year	[9]
420	Efficiency refuelling station – CNG	99	%	[115][49]
421	CAPEX refuelling station – LNG	0.013	€/kWh	[9]
422	OPEX refuelling station – LNG	3	% CAPEX p.a.	[9]
423	Lifetime refuelling station – LNG	20	year	[9]
424	Efficiency refuelling station – LNG	99	%	[115][49]
425	CAPEX liquefaction	0.2	€/m^3 SNG/a	[119][48]
426	Refuelling losses CH_4	1	%	[115][49]
427	OPEX liquefaction	4	% CAPEX p.a.	[119][48]
428	Lifetime liquefaction	25	year	[119][48]
429	Efficiency liquefaction	92	%	[119][48]
430	Distance between compressors	150	km	[115][49]
431	Pipeline transportation distance – MENA	3,000	km	Assumption

Row	Input Variable	Value	Unit	Sources
432	Pipeline transportation distance - EU	500	km	Assumption
433	Specific CAPEX pipeline	2,360,000	€/km	[115][49]
434	Specific OPEX pipeline	5,000	€/km	[115][49]
435	Lifetime pipeline	40	year	[115][49]
436	Production cost of biomethane from manure	4.2	€cent/kWh	[8]
437	Production cost of biomethane from corn	6.2	€cent/kWh	[8]
438	Transport cost of LNG	0.96	€/km	[9]
439	Transport distance of LNG	2,000	km	[9]
500	**E-Fuels from Fischer-Tropsch (FT) and hydrogenated vegetable oil (HVO)**			
501	CAPEX Fischer-Tropsch reactor	652	€/kW	[115][49]
502	OPEX Fischer-Tropsch reactor	4	% CAPEX p.a.	[115][49]
503	Full load hours Fischer-Tropsch reactor	6,000	h/a	Assumption based on [112]
504	Efficiency Fischer-Tropsch reactor	68	%	[115][49]
505	Lifetime Fischer-Tropsch reactor	25	year	[110][63]
506	CAPEX HVO reactor	1,200	€/tHVO	[120]
507	OPEX HVO reactor	10	€/tHVO	[120]
508	Electricity demand HVO reactor	107	MJ/tHVO	[120]
509	Efficiency HVO reactor	84	%	[120]
510	Lifetime HVO reactor	25	year	[120]
511	Cultivation cost	60	€/MWh HVO	[121]
512	Feedstock cost for used cooking oil (UCO)	40	€/MWh HVO	[121]
513	CAPEX HVO pre-treatment	44	€/m^3	[120]
514	OPEX HVO pre-treatment	3	% CAPEX p.a.	[120]
515	Electricity demand HVO pre-treatment	50	MJ/tHVO	[120]
516	Lifetime HVO pre-treatment	30	year	[120]
517	Transport distance ship	2,500	km	Assumption
518	Transport distance truck	200	km	Assumption
519	Average speed ship	30	km/h	[122]
520	Average speed truck	80	km/h	Assumption based on [115]
521	OPEX transportation ship	0.0001	€/kWh	[115][49]
522	Capacity transportation ship	200,000	t	[115][49]
523	Lifetime ship	30	year	[115][49]
524	Loading / unloading time ship	48	h	[122]
525	Fuel consumption ship	2,500	MJ/km	[122]
526	Cost heavy fuel oil	450	$/t	[122]
527	Fuel consumption truck	0.23	l/km	[122]
528	Cost diesel	2	€/l	[123]
529	Refuelling losses FT/HVO	0	%	[115][49]
530	Diesel production cost	0.461	€/l	[123]
600	**Fleet cost**			
601	Total mileage	1660	Btkm	Own Calculation
602	Total number of trucks	2,040,036	Trucks	Own Calculation
603	Lifetime truck	8	years	[115][49]
604	CAPEX BEV	155,200	€/Truck	[82]
605	Consumption BEV	0.0802	kWh_{el}/tkm	[82]
606	System interest rate	10	%	Assumption

Row	Input Variable	Value	Unit	Sources
607	CAPEX H_2 fuel cell electric truck	144,800	€/Truck	[82]
608	Consumption H_2 fuel cell electric truck	0.13	kWh H_2/tkm	[82]
609	CAPEX CH_4 truck	126,777	€/Truck	[82]
610	Consumption CH_4 truck	0.231	kWh CH_4 (LHV)/tkm	[82]
611	CAPEX E-Fuel truck	115,252	€/Truck	[82]
612	Consumption E-Fuel truck	0.183	kWh FT (LHV)/tkm	[82]

A.5 Research Partners

The European Research Institute for Gas and Energy Innovation (ERIG a.i.s.b.l.) is a European research and development organisation with the objective to guide gas in the transition process towards a future renewable based energy system. It is a non-profit association for European cooperation in research and innovation in the field of sustainable and innovative gas technologies and the use of natural gas with renewable energies. Contributors to the ReHaul study:

- Hans Rasmusson, General Secretary of ERIG
- Dr. Dietrich Gerstein, Senior Expert
- Dr. Tobias Weide, Project Manager

OST University of Eastern Switzerland is a higher education and research organisation.
The IET Institute for Energy Technology has 40 scientific employees researching in different areas including power-to-gas and chemical energy carriers. Contributors to the ReHaul study:

- Prof. Dr. Markus Friedl, Head of IET
- Dr. Cristina Antonini, Researcher
- Boris Kunz, Researcher

The Institute WERZ currently has 15 employees and focusses on energy and resource management and corporate sustainability development, e.g. in the field of mobility solutions. Contributors to the ReHaul study:

- Prof. Dr.-Ing. Elimar Frank, Deputy head of WERZ
- Florin Thalmann, Researcher

The DVGW Research Center at Engler-Bunte-Institut of Karlsruhe Institute of Technology (KIT) is a main research facility of the German Technical and Scientific Association for Gas and Water. Scope of the activities are research and consulting for the safe and environment-friendly processing, distribution and application of natural gas, SNG, biogas, H_2. Contributors to the ReHaul study:

- Wolfgang Köppel, head of systems and grid department
- Volkan Isik, Researcher

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