# State of the Art on Alternative Fuels Transport Systems in the European Union

Update 2020

Written by the Joint Research Centre and DG Mobility and Transport
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*EUROPEAN COMMISSION*

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Please note that this report had been developed before the outbreak of coronavirus crisis

Directorate-General for Mobility and Transport
Joint Research Centre

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# 1 INTRODUCTION

The Commission adopted on 11 December 2019 the "European Green Deal"[1]. The Green Deal sets the overall ambition of transforming the EU into a fair and prosperous society, with a modern, competitive economy, where there are no net-emissions of greenhouse gases (GHG) in 2050, a decoupling of economic growth from resource use and a preservation of natural capital.

Prior to the Green Deal, the Commission analysed possible pathways to a climate-neutral economy as part of the work carried out in the context of the Commission's proposal for a Long-Term Climate Strategy in line with the Paris Agreement[2]. The analysis demonstrates the needs for substantive efforts in all parts of the economy, also for transport

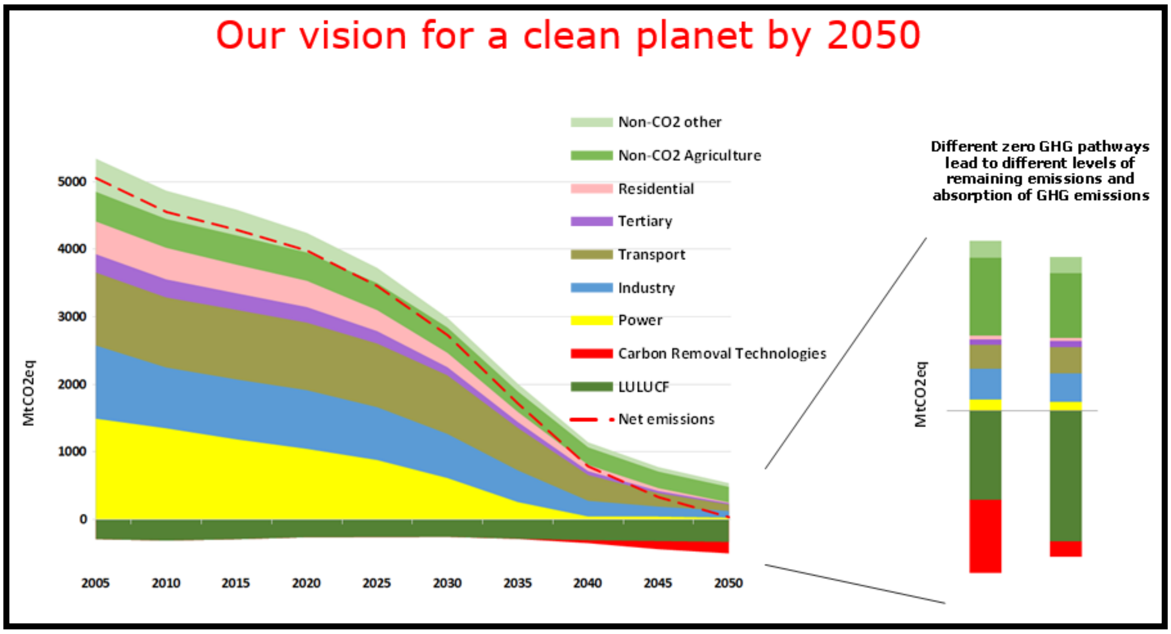


**Figure 1-1. Pathway to zero GHG emissions by 2050.**
**Source: Adapted from the long-term strategy "Clean Planet for all"**

Transport produces today a quarter of the overall GHG emissions in the EU. In order to bring it onto a pathway in line with the transition to a climate-neutral economy, the Green Deal notes that the transport sector has to decrease its emissions by 90% by 2050. Road, rail, aviation, and waterborne transport all have to make a significant effort to decarbonise in order contribute to this transition.

In addition to significantly increasing the overall efficiency of the transport system, production and deployment of sustainable alternative transport fuels, vehicles and infrastructure in the EU will need to be ramped up. Transport fuels themselves will need to be almost completely decarbonised by 2050. The deployment of related vehicles, vessels and aircraft as well as infrastructure and services needs to happen everywhere in the EU, in an interoperable manner. Use of sustainable alternative fuels (incl. electricity) needs to accelerate quickly in all transport modes. This would help to deliver the necessary significant reduction in greenhouse gas emissions and in most cases of air pollutant emissions and even noise pollution. We need all sustainable alternative fuels, each to be used according to its potential environmental benefits and

[1] COM/2019/640 final

[2] Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy COM/2018/77

to the specific needs of the different transport modes. In addition, investments in alternative fuels and relevant transport systems would make the EU a leader in these technologies increasing the competitiveness of the EU industry.

As announced in the "European Green Deal", the Commission will present a strategy for sustainable and smart mobility and transport as well as the revision of a set of legislative initiatives in order to achieve the needed reduction in emissions from transport by 2050.

All modes have to find pathways for emission reduction in line with their respective modal specific needs. It is clear that we need a full long-term switch to alternative and net-zero carbon fuels for transport, against the backdrop of fundamental increases of the efficiency of the transport system. Alternative fuel technologies should compete under a common policy framework, which focuses on the need for emission reductions.

In view of the needed transition, it is relevant to understand the state of play and future prospects for the production and distribution of alternative fuels in all modes of transport. It is furthermore important to understand their potential respective contribution to decarbonisation pathways in the different modes of transport.

The objective of this report is to update and review the report "State of the Art on Alternative Fuels Transport Systems in the EU" issued in 2015, providing comprehensive and exhaustive information on the development of alternative fuels transport systems in the EU and market projections for the horizons 2020, 2030 and beyond as well as to assess the results in the context of the objectives for decarbonisation of transport established in the long-term strategy "Clean Planet for all".

The quantitative analysis of the environmental performance of the different alternative fuels in this report is focused on the reduction of greenhouse gas emissions. The report does not include a comprehensive assessment of other pollutant emissions from alternative fuels. The impact on air quality and air emissions from alternative fuels may be very different for different fuels (for instance biomass based electricity generation has high particle emissions). Similarly, the impact of alternative fuels production on biodiversity is not within the scope of this report.

The information contained in this report builds on a comprehensive review of the literature on alternative fuels as well as on efforts to draw data from a broad range of public and private stakeholders by means of a questionnaire, carried out in cooperation by Directorate-General for Mobility and Transport and Joint Research Centre (JRC). The quantifiable assessment of the energy use and GHG emissions of road fuel and powertrain configurations in Europe is based on the version 5 of the Well-to-Wheel JEC (JRC, Eucar, Concawe) report.

The report is structured as follows:

- Chapter 1: Introduction
- Chapter 2: Current EU transport fuel supply and projections
- Chapter 3: Elements used for the analysis
- Chapter 4: Analysis of fuels
- Chapter 5: Market development for transport systems and infrastructure
- Chapter 6: Synthetic presentation of results
- Chapter 7: Promoting alternative fuels in the EU: assessment of results
- Chapter 8: Financing mechanisms.

# 2 CURRENT EU TRANSPORT FUEL SUPPLY AND PROJECTIONS

The EU transport sector, excluding international aviation and maritime, was responsible for 30.8% of final energy consumption (327 Mtoe) in 2017[3] (see **Figure 2-1**). Adding aviation and maritime bunker fuels, energy used in transport totalled about 423 Mtoe (Eurostat, 2019).

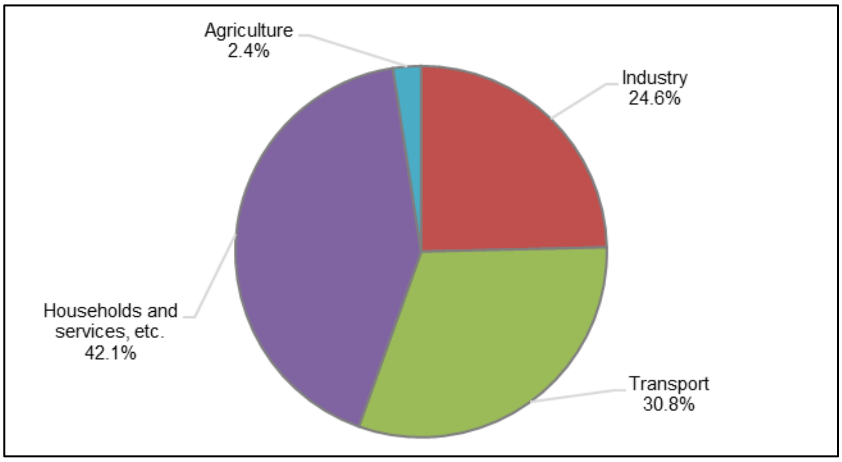


**Figure 2-1. Final Energy Consumption in 2017, by sector (EU28)**
**Source: Eurostat, 2019**

When looking at total EU transport energy demand (see **Figure 2-2**), covering domestic, intra-EU and intercontinental traffic, road transport was in 2017 by far the largest energy consumer (72.5% of the total). Aviation contributed around 13.6% of the energy use in transport, followed by international maritime transport (10.5%). Rail transport accounted for 1.5% and inland navigation consumed around 1.2%.

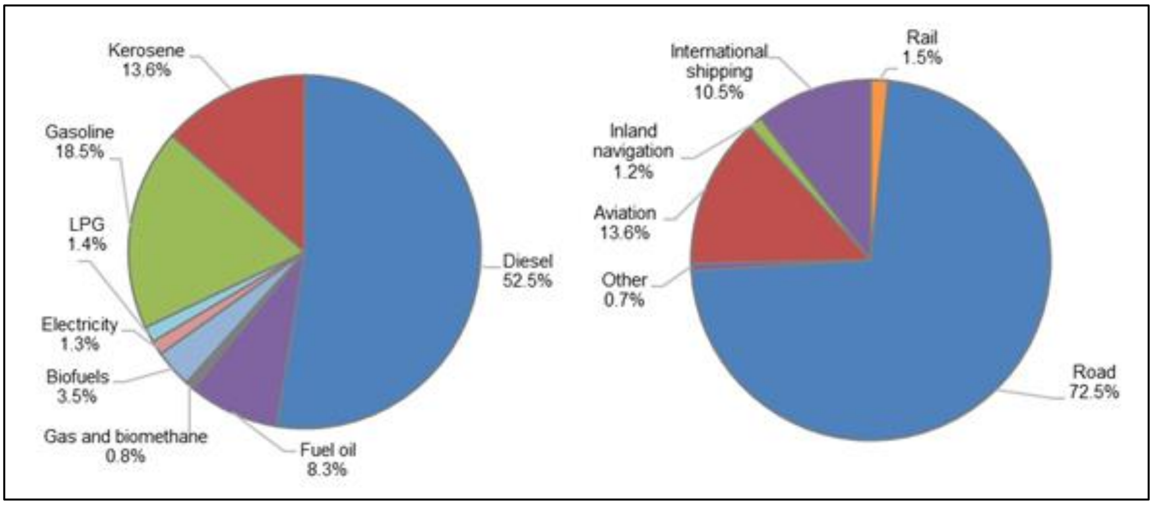


**Figure 2-2. Share of EU28 transport energy demand by source and mode in 2017 (%)**
**Source: Eurostat, 2019**

[3] Final energy consumption covers energy use in industry, transport, residential and services, agriculture and fishing. For transport, it includes energy use in road, rail, domestic aviation, domestic navigation (inland waterways and national maritime), pipeline transport and other. Both international aviation and maritime (bunker fuels) are outside the scope of final energy consumption, according to the recent methodological changes of the energy balances by Eurostat.

In 2017, EU transport depended on oil products for about 94% of its energy needs (Figure 2-2). Europe imports around 86.7% of its crude oil and oil products from abroad, with a bill up to EUR 500 million per day[4]. Almost all energy consumed in air and waterborne transport was petroleum-based in 2017. Road transport depended on oil products for 95% of its energy use and rail transport for about 30% (the remaining 70% came from electricity).

Strong efforts are required to drastically reduce the oil dependency and the greenhouse gas (GHG) and air pollutant emissions in the transport sector, in line with the goals put forward by the Commission in the 2011 White Paper on Transport[5], and reinforced by the 2016 European Strategy for Low Emission Mobility[6] and the 2018 "Clean planet for all" long term strategy[7].

## 2.1 DEVELOPMENTS UNDER CURRENT TRENDS AND ADOPTED POLICIES

Under current trends and adopted policies (the so-called *"Baseline" scenario*)[8], *oil* is expected to remain the main energy source for transport in the medium to long term, although gradually declining over time (see **Figure 2-3**). Oil products, with diesel still dominating over gasoline, would still represent about 88% of energy use in transport (excluding international maritime but including international aviation)[9] in 2030 and 75% in 2050 (88% of the total energy demand in 2030 and 77% in 2050[10]). However, energy use in transport excluding international maritime is projected to decrease significantly, by about 24% by 2050 relative to 2005, mainly driven by the impact of $CO_2$ emission standards for new cars, light commercial vehicles (LCVs) and heavy commercial vehicles (HCVs) on overall vehicle fleet efficiency, but also by improvements in the efficiency of the transport system.

*Electricity* would provide around 4% of the transport energy consumption by 2030 and 11% by 2050, due to the uptake of electrically chargeable vehicles or electric vehicles (EVs) (battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)) and further progress in the electrification of rail. Driven by EU and national policies such as incentives schemes, EVs are projected to see a faster growth beyond 2020 in particular in the light-duty vehicle (LDV) category. The deployment of high power recharging infrastructure would also facilitate long distance trips. The share of EVs in the total car stock is projected to reach about 14% by 2030 and 54% by 2050, and for LCVs 11% by 2030 and 45% by 2050. Part of this uptake is related to technology improvements in batteries and in information and communication technologies.

*Hydrogen* is projected to represent around 2% of the transport energy demand by 2050 in the Baseline scenario. Hydrogen powered fuel cells would represent slightly more than 4% of the car stock by 2050 and around 1% of the LCV stock.

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[4] COM(2019) 1

[5] COM(2011) 144

[6] COM(2016) 501

[7] COM (2018) 773

[8] COM (2018) 773

[9] Energy use in transport is defined in this section as including international aviation but excluding international maritime. The very recent change in the definition of the final energy demand in transport in the energy balances by Eurostat was not available at the time of the modelling exercise.

[10] Oil dependency in this case is calculated including both international aviation and maritime.

*Liquid biofuels* would maintain a relatively stable share over time (around 6% of the fuel mix) in the Baseline, while *gaseous fuels including biomethane* would also provide around 6% of energy demand by 2050. Natural gas (in the form of CNG and LNG) is projected to be increasingly used in road freight and waterborne transport from 2020, facilitated by the increasing availability of refuelling infrastructure.

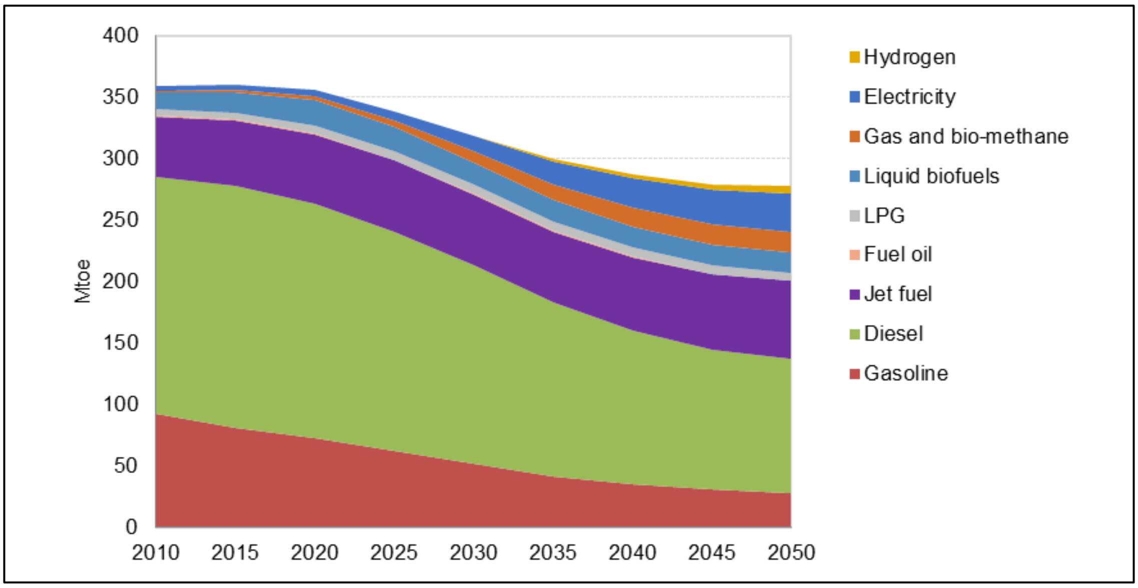


**Figure 2-3. Energy use in transport (including international aviation and excluding international maritime) under current trends and adopted policies by 2050 (EU28)**
**Source: Baseline scenario, PRIMES-TREMOVE model, E3-Modelling[11]**

Given the dominance of oil, the Baseline $CO_2$ emissions from transport (including domestic and international aviation but excluding international maritime) would go down by about 19% between 2005 and 2030 and 38% by 2050. However, relative to 1990 levels, emissions would still be 4% higher by 2030 and only 21% lower by 2050, owing to the fast rise in the transport emissions during the 1990s.

## 2.2 ACHIEVING DEEP REDUCTIONS IN GHG EMISSIONS

The deep decarbonisation of the transport system, in line with the vision of achieving net-zero GHG emissions by 2050 set out in the 2018 "Clean planet for all" long term strategy[12], requires large-scale deployment of alternative fuels produced from renewable energy sources by 2050. **Figure 2-4** provides a comparison of the energy use in transport (excluding international maritime but including international aviation) under current trends and adopted policies with the climate neutral scenarios (so-called *"1.5TECH" and "1.5LIFE" scenarios*), developed in the context of the in-depth analysis accompanying the "A Clean Planet for all**:** A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy"[13].

The *"1.5TECH" and "1.5LIFE" scenarios* reach net zero GHG emissions by 2050 and thus *pursue efforts to achieve a 1.5°C temperature change*. In the 1.5TECH and 1.5LIFE scenarios emissions from transport are projected to be 91-92% lower in 2050 relative to 2005 (89-90% lower in 2050 relative to 1990).

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[11] COM (2018) 773

[12] COM (2018) 773

[13]https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

To achieve these GHG emissions reductions, energy demand in transport (including international aviation but excluding international maritime) would need to reduce significantly by 2050 relative to 2005 (45% in 1.5TECH and 50% in 1.5LIFE scenario), driven by the large-scale electrification of the road transport sector and improvements in the efficiency of the transport system. In addition, electricity, hydrogen, biofuels and e-fuels (e-liquids and e-gas) would need to make significant inroads in energy demand by 2050.

*Electricity* would provide around 26% of the transport energy consumption in 2050 in 1.5TECH and 1.5LIFE scenarios, while the *hydrogen* share is projected at 16% and 15% respectively[14]. The share of EVs in the total car stock is projected to reach around 81% by 2050 in 1.5TECH and 1.5 LIFE scenarios and 81-82% in the total LCV stock (81% in 1.5TECH and 82% in 1.5LIFE scenarios). Fuel cell electric vehicles (FCEVs) are projected to represent 16% of the total car stock and 13-14% of the total LCV stock in 2050 in the two net zero GHG emissions scenarios.

For HCVs, both 1.5TECH and 1.5LIFE scenarios show moderate uptake of electric drivetrains and fuel cells (between 11 and 14% of the stock by 2050), while hybrids would represent around 20-29% of the stock and gas-fuelled vehicles between 19 and 32% of the stock. Gaseous fuels would represent between 21 and 34% of their fuel mix (of which 12-19% is e-gas, 5-8% biomethane and 4-6% natural gas). Both scenarios would require significant deployment of refuelling infrastructure for hydrogen and gaseous fuels.

For buses and coaches, the scenarios reaching net zero GHG emissions by 2050 show shares of electric buses in the range of 79-80%, while fuel cells would represent around 14% and gas-fuelled vehicles between 6% and 7%. In addition, e-gas, e-liquids, liquid and gaseous biofuels play a significant role in reducing the carbon intensity of fuel used in internal combustion engine (ICE) powertrains. For coaches, the outcome is relatively similar to that for HCVs, although fuel cells gain significant market shares in the 1.5TECH and 1.5LIFE scenarios.

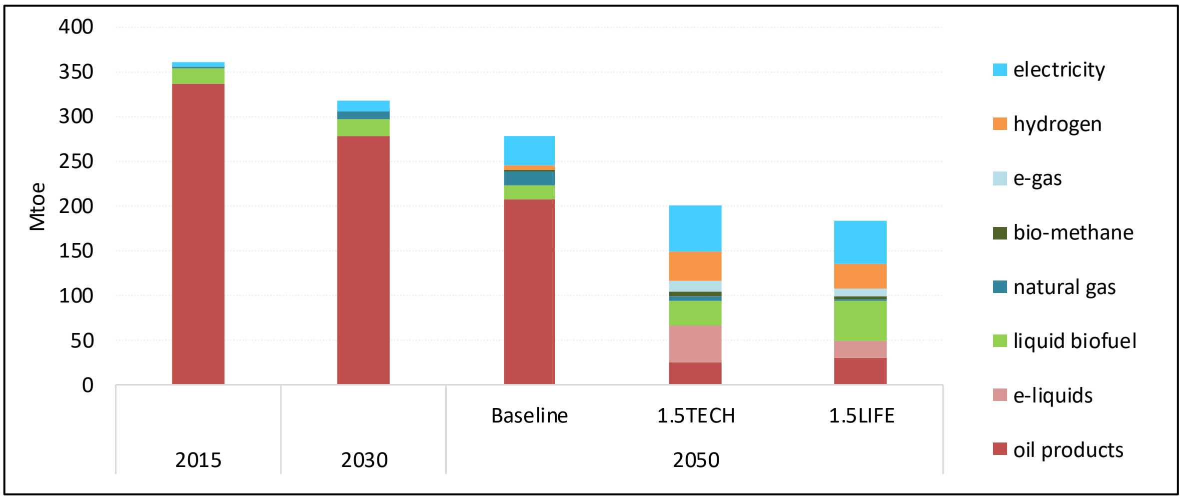


**Figure 2-4. Fuels consumed in the transport sector (including international aviation but excluding international maritime) in 2050 in the Baseline, 1.5TECH and 1.5LIFE scenarios**
**Source: Baseline scenario, PRIMES-TREMOVE model, E3-Modelling[15]**

[14] Other scenarios of the in-depth analysis accompanying the "A Clean Planet for all" long term strategy show higher uptake.

[15] COM (2018) 773

Increased electrification takes place in most sectors (services, industry, residential and transport) by 2050. Transport sees however, the most spectacular development of electricity use, which multiplies 9 to 10 fold in the 1.5TECH and 1.5LIFE scenarios by 2050 compared to 2015 (see **Figure 2-5**). Electricity use in transport in these scenarios would thus represent 15% to 16% of the total final electricity demand by 2050, compared to 9% in the Baseline.

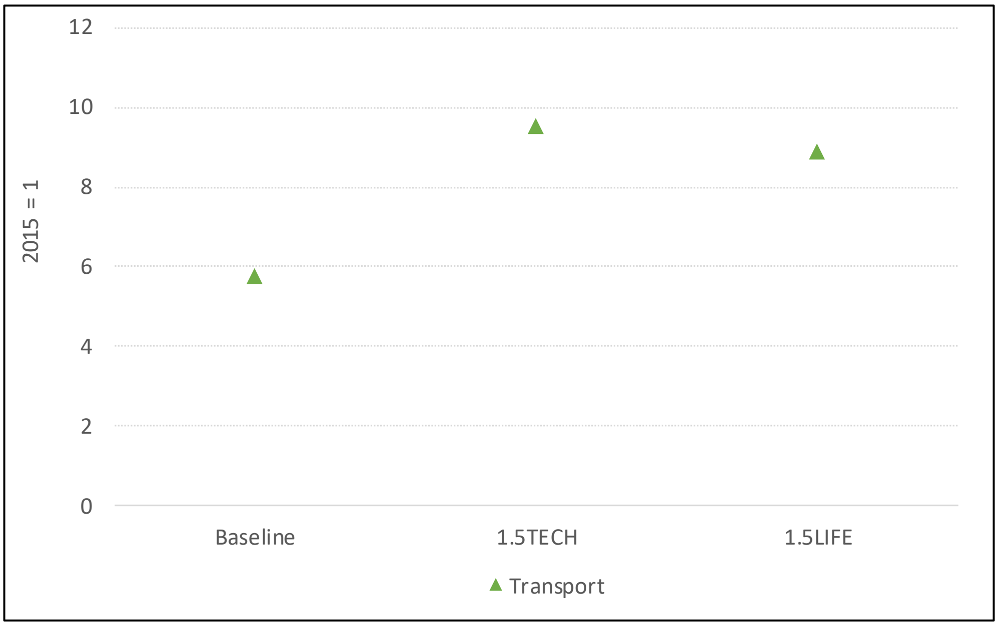


**Figure 2-5. Ratio between 2050 and 2015 electricity consumption in transport in the Baseline, 1.5TECH and 1.5LIFE scenarios**
**Source: PRIMES model, E3-Modelling**

In addition to increased final demand of electricity, the development of e-fuels also creates a new need for electricity supply. As a consequence of both changes in the final energy demand in all sectors of the economy and the production of e-fuels, the gross electricity generation increases strongly. Overall, the gross electricity generation is projected to go up by more than 100% in the 1.5LIFE scenario and by close to 150% in 1.5TECH scenario relative to 2015 (see **Figure 2-6**).

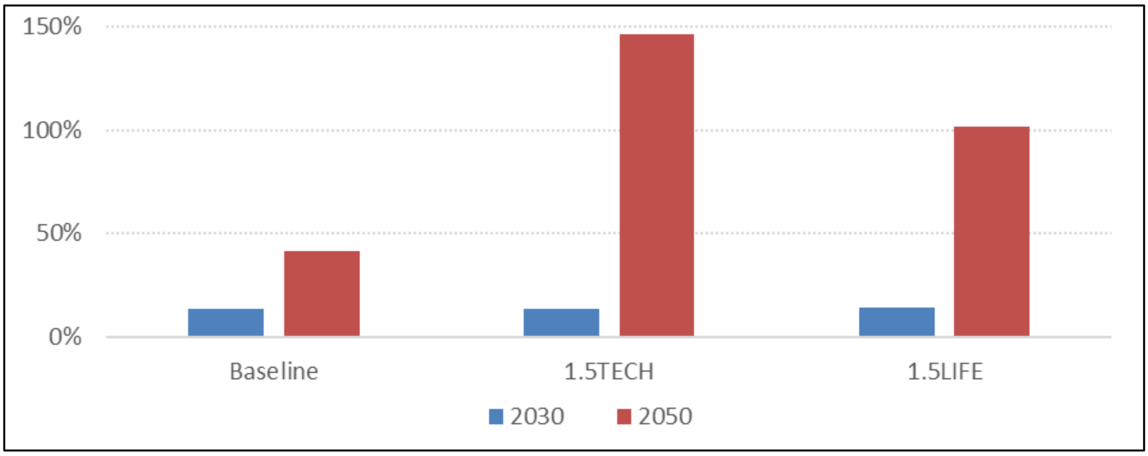


**Figure 2-6. Increase in gross electricity generation compared to 2015 in the Baseline, 1.5TECH and 1.5LIFE scenarios.**
**Source: Eurostat (2015), PRIMES (E3-Modelling)**

Changes in electricity generation mix illustrate the strong shift towards carbon-neutral energy sources, in a context of an overall increase in electricity production. The share of renewables in gross electricity generation is very similar across all decarbonisation scenarios reaching 81%-85% in 2050 (compared to 57% in 2030 and 30% in 2015). Among renewables, wind is clearly the dominant technology, representing 51-56% of the power production in 2050 in all decarbonisation scenarios. This is a spectacular growth from 26% in 2030 and 9% in 2015. The share of solar grows up to 15-16% in 2050, from 11% in 2030 and 3% in 2015.

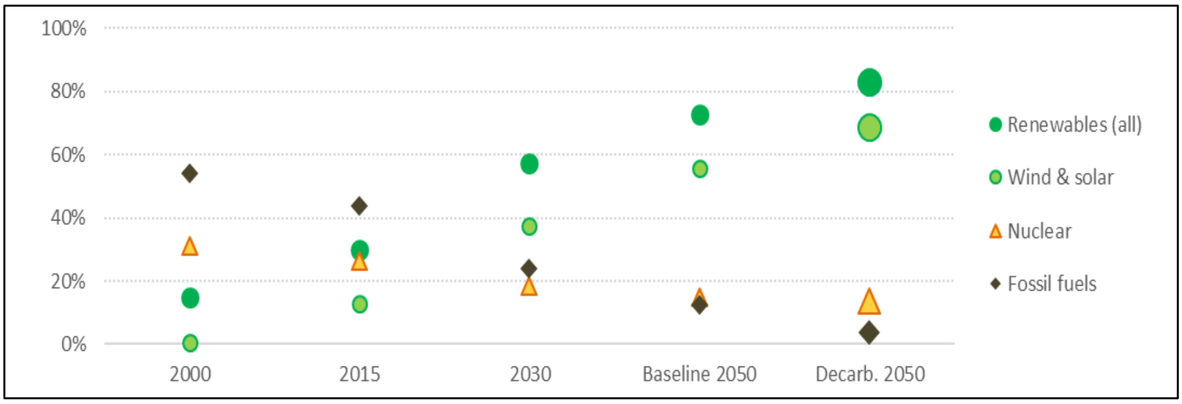


**Figure 2-7. Shares in power generation[16] in the Baseline and decarbonisation scenarios. Source: Eurostat (2000, 2015), PRIMES (E3-Modelling)**

*Liquid biofuels* consumption is projected to increase in both net zero GHG emissions scenarios (14-24% of energy demand) relative to the Baseline, mainly driven by their use in the air transport, road freight and inland navigation sectors. Together with bio-methane, the shares of liquid and gaseous biofuels would be around 17-26%.

*E-fuels (e-liquids and e-gas)* are projected to represent between 15% and 26% of the fuel mix in the scenarios reaching net zero GHG emissions. E-gas would be mostly used in road freight and, to more limited extent, in inland navigation, while e-liquids are projected to be used in air transport, road freight and inland navigation. The advantage of e-liquids is their high energy density but also their direct use in conventional vehicle engines, relying on the existing refuelling infrastructure.

E-fuels and hydrogen require, however, significant amounts of electricity for their production. For e-fuels electricity is also needed for the capturing of $CO_2$. Thus, reserving the consumption of e-fuels and hydrogen for the transport modes that need them most would help limiting the power sector resources, which increase with their production and deployment.

*Gas* can play an important role, particularly in road freight transport and shipping as long as the gas supply is gradually decarbonised. By 2050 the role of natural gas in energy demand excluding international maritime would be limited (1-2% of the energy demand). However, it is projected to still represent around 11% of the energy use in international shipping.

Reducing the oil dependence by diversifying into alternatives is a major challenge for the transport sector, with benefits for both society and industry. Success remains nevertheless dependent on major technological breakthroughs and consumer acceptance.

[16] Notes: 1. The shares of renewables, nuclear and fossil fuels sum to 100%. Wind & solar is a component of renewables. 2: The "Decarb. 2050" points are the averages across all decarbonisation scenarios per category. These scenarios provide very similar power mix in 2050, with renewables ranging from to 81% to 85% (wind & solar alone from to 65% to 72%), nuclear from 12% to 15% and fossil fuels from 2% to 6%.

The use of alternative fuels in the transport sector can provide multiple benefits in terms of security of supply, reduction of GHG emissions and air pollution emissions in some cases. The potential of a fuel candidate to make significant inroads into the market depends on several elements like e.g. the availability of potential feedstock and the complexity of the production process, the compatibility with engine technologies and distribution infrastructure, and the GHG savings potential.

# 3 ELEMENTS USED FOR THE ANALYSIS

In this report, the assessment is structured per fuel type. The analysis is divided between fuel production (**Chapter 4, p. 19**), and the use of fuels in transport systems (**Chapter 5, p. 113**).

**Chapter 4** covers greenhouse gas (GHG) emissions, energy performance, the potential supply of fuels, the maturity of fuels production, and production costs. Based on these elements, different pathways for producing fuels are assessed.

**Chapter 5** is also structured by fuel type. The focus is on the use of the fuels. **Chapter 5** covers the infrastructure needed to deliver the fuels to vehicles or vessels, infrastructure maturity, costs related to infrastructure and vehicles. The current market status and the future potential of fuels in different transport markets are outlined.

Although not all analysis aspects are equally relevant or important for each fuel, most of the analysis criteria are covered for all fuels. Moreover, the experiences with different fuels and information about the assessment criteria vary. This also applies to data availability and reliability, which influence the possibility of presenting alternatives and information. Hence, there are variations in the information presented for each fuel.

In this report, the previous 2011 and 2015 reports are mentioned without being referenced in the text. The corresponding references are (EGFTF, 2011) and (EC, 2015).

For the purpose of this study, a targeted questionnaire was sent to 170 stakeholders. By mid-2019, 30 stakeholders replied (see the Appendix A.1 Questionnaire). The replies are referenced as 'personal communication'. When the stakeholder's answer to a specific question was considered useful but not fully justified or supported through the provision of data and/or source, we used the expression 'according to'.

## 3.1 ELEMENTS USED FOR THE DESCRIPTION OF FUELS

The elements covered in **Chapter 4 (p. 19)** for each of the fuels are:

- **Definition and general description**: A description of the fuel and its uses in the transport system is given, with more details on its use in **Chapter 5 (p. 113)**.

- **Well-to-Tank Greenhouse Gas emissions**: Life cycle analysis (LCA) as defined by ISO 14040 considers the entire life cycle of a product from a raw material extraction and acquisition, through material production and manufacturing, to use and end of life treatment and final disposal. However, **Chapter 4** of this report is devoted to a Well-to-Tank (WTT) analysis, referring to all the steps for the production of the fuel. Therefore, the GHG emissions of fuels is limited to the GHG emissions along the supply chain from feedstock production to its delivery (to point of refuelling/recharging). The in-use performance in terms of GHG emissions and energy efficiency of the fuel in the vehicle/vessel/aircraft is not addressed in **Chapter 4**, in order to allow comparability of fuel options across transport modes. However, in **Chapter 6 (p. 244)** of this report, a summary of the Well-to-Wheel (WTW) GHG and energy efficiency for the most representative production pathways is presented; this allows for a better comparison among the different fuels. WTW values are obtained by summing WTT (production of the fuel) and Tank-to Wheel (TTW) (use of the fuel).

The WTT and WTW GHG results presented in **Chapter 4** and **Chapter 6** are taken from the JEC (2019) study. Conversely to a full LCA approach, the JEC consortium uses a simplified attributional method focused on energy consumption and GHG emissions. The JEC-WTW method is therefore a simplified type of LCA with system boundaries set to focus exclusively on energy consumption and GHG emissions. A description of the main assumption of the JEC approach is provided in the **Appendix to Chapter** 3**, p. 16**.

WTT GHG emissions of different fuels are calculated by JEC-WTT (2019) capturing "industry averages", without describing any operator-specific production process. The steps included in the analysis consist of: feedstock extraction/recovery/growth; gathering, processing, and transportation to fuel production facilities; fuel production at conversion facilities; subsequent transportation/distribution of fuels for use. While the LCA scope in this effort includes all operation-related activities (e.g., operation of a petroleum refinery, farming activities), infrastructure-related activities (e.g., construction of a petroleum refinery, manufacturing of agricultural equipment) are not included. Amortised over the lifetime of a facility, the emissions from building and disposal of facilities and machinery are generally small.

GHG emissions considered are: $CO_2$, $CH_4$, and $N_2O$ (with Intergovernmental Panel on Climate Change (IPCC) adopted global warming potentials (GWPs)), expressed as $CO_2$eq.

The functional unit for results of individual pathways is per MJ of fuel produced (lower-heating value).

GHG intensities of the fossil fuel baselines serving as benchmark are those of the Renewable Energy Directive - recast (2018/2001, RED II).

A given process along a fuel supply chain may produce multiple products. The choice of co-product methods is one of the most critical issues in life cycle analysis: results can be influenced more by co-product method choice than by conversion processes and their energy efficiencies. The RED and the RED II allocate GHG emissions to biofuels and co-products by energy content (LHV), i.e. emissions are allocated to the main product and to co-products on the basis of their respective energy contents. While the substitution method has been used by JEC-WTT (2019). The co-product generates an energy and emission credit equal to the energy and emissions saved by not producing what the co-product is most likely to displace. The advantage of this approach is the closer representation of "real-life" because it reflects the economic choices of stakeholders.

- **Well-to-Tank energy performance:** the concept of energy performance of a fuel supply chain is based on the energy demand ($E_{Tot.Dem}$) for fuel production; this is defined as the primary energy required to produce one MJ of final fuel (on LHV basis). In order to facilitate the comparison among the various fuel pathways, it has been decided to present the energy performances of a certain fuel production as the sum of the energy content of the fuel ($E_{FuelContent}$) and the energy required for all the steps of its production chain ($E_{WTT}$).

$$E_{Tot.Dem}=E_{WTT} + E_{FuelContent}$$

For example, the production of biodiesel from waste cooking oil requires 1.25 MJ of primary energy per MJ of final fuel. This means that 1+1.25 MJ of primary energy are required to have available 1 MJ of biodiesel.

The main inputs are from JEC-WTT (2019). However, it should be noted that JEC-WTT (2019) focuses only on energy expanded, while in this report the energy in the feedstock, which appears in the final fuel, is included. Therefore, the figures are 1 MJ higher in this report compared to JEC-WTT (2019).

- **Maturity of fuel production**: The maturity of the fuel production in **Chapter 4 (p. 19)** is presented in terms of Technology Readiness Level (TRL) and Commercial Readiness Level (CRL). JRC is using the version of the TRL adapted for H2020: DG RTD WP2014-15[17]

Each fuel is classified in a 9-grade scale concerning its technology readiness level:

- **TRL 1** – Basic principles observed.
- **TRL 2** – Technology concept formulated.
- **TRL 3** – Experimental proof of concept.
- **TRL 4** – Technology validated in lab.
- **TRL 5** – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- **TRL 6** – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- **TRL 7** – System prototype demonstration in operational environment.
- **TRL 8** – System complete and qualified.
- **TRL 9** – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

In the same way, a 6-grade scale is used for the description of the commercial readiness levels[18]:

- **CRL 1** – Hypothetical commercial proposition: Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.
- **CRL 2** – Commercial trial: Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
- **CRL 3** – Commercial scale up occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors.
- **CRL 4** – Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.
- **CRL 5** – Market competition driving widespread deployment in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.
- **CRL 6** – "Bankable" grade asset class driven by same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.

The way the two scales mentioned overlap can be found in **Table 3-1** and **Figure 3-1**:

[17] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[18] https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf

**Table 3-1. Overlap of TRL and CRL**

<table>
<tr><th colspan="2">TRL</th><th colspan="2">CRL</th></tr>
<tr><td>1</td><td>Basic principles observed</td><td colspan="2">N/A</td></tr>
<tr><td>2</td><td>Technology concept formulated</td><td rowspan="6">1</td><td rowspan="6">Hypothetical commercial proposition</td></tr>
<tr><td>3</td><td>Experimental proof of concept</td></tr>
<tr><td>4</td><td>Technology validated in lab</td></tr>
<tr><td>5</td><td>Technology validated in relevant environment</td></tr>
<tr><td>6</td><td>Technology demonstrated in relevant environment</td></tr>
<tr><td>7</td><td>System prototype demonstration in operational environment</td></tr>
<tr><td>8</td><td>System complete and qualified</td><td>2</td><td>Commercial trial, small-scale</td></tr>
<tr><td rowspan="4">9</td><td rowspan="4">Actual system proven in operational environment</td><td>3</td><td>Commercial scale-up</td></tr>
<tr><td>4</td><td>Multiple commercial applications</td></tr>
<tr><td>5</td><td>Market competition driving widespread development</td></tr>
<tr><td>6</td><td>Bankable asset class</td></tr>
</table>

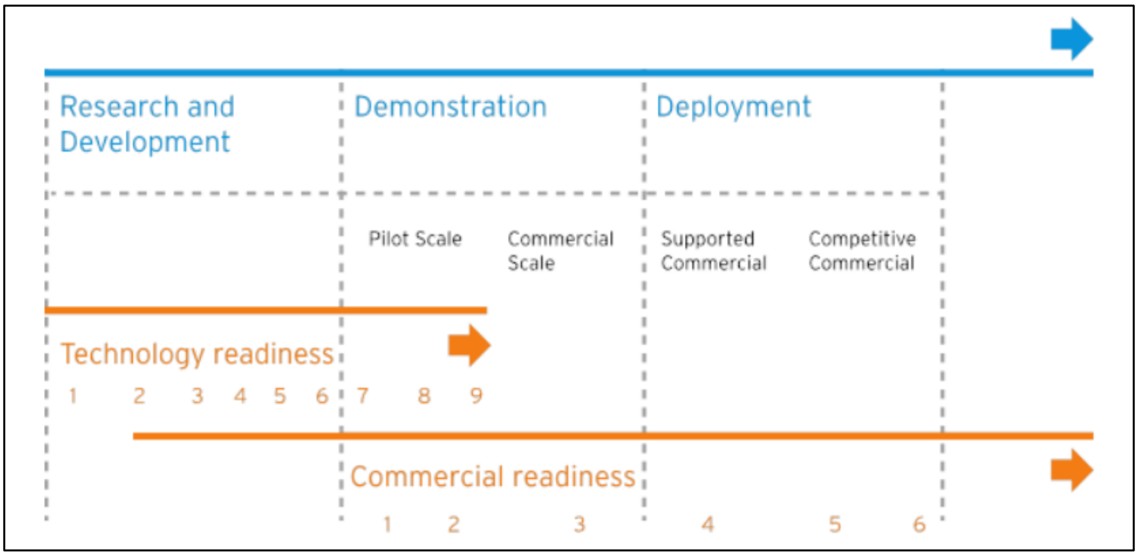


**Figure 3-1. TRL and CRL mapped on the Technology Development Chain**
**Source: ARENA**

- **Costs**: The WTT (production and distribution) costs are assessed. Generally, costs are assessed without taxes and excise duties although this may have an important impact on user prices. It should be noted that it is difficult to find figures, which are consistent across different fuels and thus comparisons might be risky. In order to allow for comparisons, the same unit is used (€/MWh).

- **Potential capacity and actual production:** An assessment of the annual production capacity of the specific fuels and of the development trend in the short (2020), medium (2030) and long term (2050) is given, when relevant data are available. Information has been collected from a variety of sources (international organisations reports, scientific papers, industry data etc.).

## 3.2 ELEMENTS FOR FUELS' TRANSPORT INFRASTRUCTURE AND TRANSPORT MARKETS

**Chapter 5 (p. 113)** focuses on the current (i.e. state-of-the-art) and future (i.e. perspectives) market development for transport systems, including their infrastructure. The exposition in this chapter for each alternative fuel generally begins with vehicles and ends with infrastructure.

Definitions

By 'transport system' it is meant land, water and air transport, both in their passenger and freight/goods variants. The 'land transport' system consists of the 'road transport' and 'rail transport' sub-systems. The 'water transport' system comprises 'inland waterways transport' and 'maritime/sea- or ocean-going transport' sub-systems. In each of the analysed sub-systems, both equipment and infrastructure are considered. In this report, transport equipment means:

Vehicle: "*A thing used for transporting people or goods, especially on land, such as a car, lorry, or cart*" (OED, 2019). The same source also considers that locomotives ("*a powered railway vehicle used for pulling trains*") and railcars ("*a powered railway passenger vehicle*") are vehicles. In this report, a distinction between 'road vehicles' and 'railway vehicles' is made.

Vessel: "*A ship or large boat*", where a boat is defined as "*a vessel of any size*" (OED, 2019).

Aircraft: "*An aeroplane, helicopter, or other machine capable of flight*" (OED, 2019). The focus of this paper will, however, be on aeroplanes/airplanes and not on drones or other flying machines.

In this report, technologies that have been introduced in the market and are readily commercially available are regarded as mature. However, the fact that a certain technology is mature does not necessarily mean that its market deployment will be successful. **Figure 3-2** schematically illustrates the hypothetical market evolution of successful technologies.

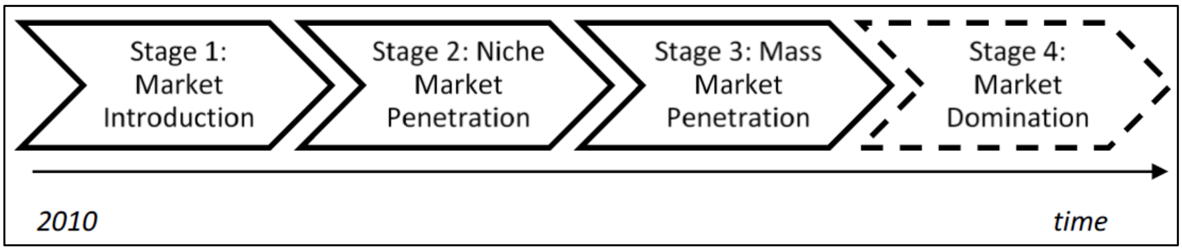


**Figure 3-2. Successful evolution of technologies in the market**
**Source: J. J. Gómez Vilchez & Jochem, 2019**

According to (OED, 2019), a market is mature when it "*has developed to a point where substantial expansion and investment no longer takes place*". Adopting this definition, the European market for alternative fuel technologies is not fully mature yet. Thus, there is a difference between a technology being commercially mature and its market maturity, which should be kept in mind when analysing these data.

Vehicle categorisation

In this work, transport activity is split into passenger and freight and road vehicles are disaggregated into light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). Whereas LDVs consist of passenger cars and light commercial vehicles (LCVs; or vans), HDVs comprise buses and coaches and heavy commercial vehicles (HCVs; or trucks/lorries (i.e. heavy goods vehicles)). Due to space and data availability limitations, it is not possible to systematically further disaggregate these categories (by e.g. size or segment) or distinguish between types of vessels or aircrafts.

Sources of information

This chapter draws on preliminary research reported by (J. J. Gómez Vilchez, 2019) and expands it by incorporating additional information and the responses of stakeholders to the aforementioned questionnaire. Furthermore, the following main sources of information were used: Transport and Research and Innovation Monitoring and Information System (TRIMIS) analysis and revision of Strategic Transport Research and Innovation Agenda (STRIA) for Alternative Fuels and Electrification, as reported in (JRC, 2019b), data from the European Alternative Fuels Observatory (EAFO), available information under the EU Long-Term Strategy for GHG emissions reduction as well as other publicly available information.

Elements

Specifically, the elements covered for each of the fuels in **Chapter 5 (p. 113)** with respect to refuelling/recharging infrastructure and vehicles/vessels are:

- **MATURITY OF VEHICLE/VESSEL AND INFRASTRUCTURE TECHNOLOGY**. An overview of the market status of the technological development of vehicles/vessels and the recent infrastructure development is presented. For some fuels, focus is more on the fuel production (e.g. biofuels), which is thus covered in **Chapter 4 (p. 19)**, and for other fuels more focus is on the vehicles and/or infrastructure (e.g. electric vehicles). Given the increasingly important role electric vehicle batteries are playing to decarbonise transport, this vehicle component features prominently in **section 5.1.1, p. 119**.

- **MARKET SIZE**. The current number of vehicles/vessels using the different fuels and their corresponding refuelling infrastructure in the Member States are presented. Figures per country are generally not presented in the report. The market structure of the different sub-systems vary. This has implications for the nature and number of actors active in a particular sector (e.g. the European inland waterways industry consists of a majority of small firms (CCNR, 2018) with more limited financial capabilities than the players in the maritime sector) and in turn for the speed of diffusion of alternative fuel technology.

- **COSTS OF VEHICLES/VESSELS AND INFRASTRUCTURE**. The costs of vehicle production and refuelling infrastructure are presented and cost-related aspects are described.

- **MARKET ASPECTS**. What market areas can be expected to develop in relation to the different fuels? Are there specific aspects for different fuels and how may the markets develop by 2030 and beyond?

<u>Beyond the scope of the chapter</u>

**Chapter 5 (p. 113)** is very ambitious in scope. As a result, simplifications were often needed. Moreover, the following topics were beyond the scope of the work reported in this chapter: thorough total cost of ownership calculation, supply-demand analysis on raw materials and their status (e.g. critical or not), among others. Further consideration of these aspects may be needed in targeted follow-up reports.

## 3.3 APPENDIX TO CHAPTER 3

### 3.3.1 SUMMARY OF THE JEC WELL-TO-WHEELS APPROACH

JEC (2019) uses a methodology split to show the energy expended and GHG emissions: (i) the energy used (including energy losses) for transforming the primary energy source (fossil or renewable) into a transportation fuel (WTT), (ii) the energy consumed, and (iii) GHG emitted when simulating the use of the vehicle (TTW).

The Well-to-Tank (WTT) evaluation accounts for the energy expended and the associated GHG emitted in the steps required to deliver the finished fuel into the on-board tank of a vehicle.

The Tank-to-Wheels (TTW) evaluation accounts for the energy expended and the associated GHG emitted by the vehicle/fuel combinations.

In any Well-to-Wheels study, there are many sources of uncertainty. A large part of the data pertains to systems or devices that do not yet exist or are only partly tested. Future pathways may include existing components that are well characterised, but also new aspects where performance figures are expectations rather than firm figures. Estimates of uncertainty are included for each individual element in a pathway and these will naturally be wider for future options that are not yet well characterised.

**Table 3-2. The primary energy sources and the use in transportation (WTT). Replicated from JEC (2019)**

| | | Fuel | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Resource | | Gasoline, Diesel (2017 quality) | Gasoline E10 / Gasoline High octane | Synthetic gasoline (Pyrolysis-based Naptha) | Diesel B7 (2017 market blend) | Synthetic gasoline | Synthetic diesel | Synthetic diesel (Pyrolisis-based diesel) | DME | OME | Ethanol | Methanol | MT/ETBE | ED95 | Pure vegetable oil | FAME / FAEE | HVO | CNG | CBG | Bio-CH4 for electricity | SNG | LNG | LPG | Hydrogen (Comp., liquid) | Electricity | Heat |
| Crude Oil | | x (1) | x (1) | | | | | | | | | | | | | | | | | | | | | | x (5) | x (6) |
| Coal | | | | | | | x | | x | | | x | | | | | | | | | | | | x | x | |
| Natural gas | Piped | | | | | | x | | x | x | | x | | | | | | x | | | | | | x (1) | x | |
| | Remote | | | | | | x (1) | | x (1) | | | x | | | | | | x (1) | | | | x (1) | | x | x | |
| Shale gas | | | | | | | | | | | | | | | | | | x | | | | | | | | |
| LPG | Remote (3) | | | | | | | | | | | | x | | | | | | | | | | x | | | |
| Biomass | Sugar beet | | | | | | | | | | x | | x (11) | | | | | | | | | | | | | |
| | Wheat | | | | | | | | | | x | | x | x | | | | | | | | | | | | |
| | Barley/rye | | | | | | | | | | x | | | | | | | | | | | | | | | |
| | Maize (Corn) | | | | | | | | | | x (4) | | | | | | | | x (2) | | | x (2) | | | x (2) | |
| | Wheat straw | | | | | | | | | | x | | | x | | | | | | | | | | | | |
| | Sugar cane | | | | | | | | | | x | | | | | | | | | | | | | | | |
| | Rapeseed | | | | | | | | | | | | | | | x | x | | | | | | | | | |
| | Sunflower | | | | | | | | | | | | | | | x | x | | | | | | | | | |
| | Soy beans | | | | | | | | | | | | | | | x | x | | | | | | | | | |
| | Palm fruit | | | | | | | | | | | | | | | x | x | | | | | | | | | |
| | Double crooping | | | | | | | | | | | | | | | | | | x (2) | | | x (2) | | | | |
| | Wood waste (8) | | | x | | | x (9) | x (1) | x (9) | x | x | x (9) | | | | | | | | | x (7) | x (7) | | x (9) | x (9) | x |
| | Farmed wood (poplar) | | | x | | | x | x (1) | x | x | x | x | | | | | | | | | x (7) | x (7) | | x | x | x |
| | Waste veg oils | | | | | | | | | | | | | | | x | x | | | | | | | | | |
| | Tallow | | | | | | | | | | | | | | | x | x | | | | | | | | | |
| | Palm oil mill effluent | | | | | | | | | | | | | | | | x | | | | | | | | | |
| | Municipal organic waste | | | | | | | | | | | | | | | | | | x (2) | | | | | | x | x |
| | Manure | | | | | | | | | | | | | | | | | | x (2) | | | x (2) | | | x | x |
| | Sewage sludge | | | | | | | | | | | | | | | | | | x (2) | | | x (2) | | | | |
| Renewable electricity (Wind) | | | | | | | x | | | x | | | | | | | | | | | x | x | | x | x | |
| Nuclear | | | | | | | | | | | | | | | | | | | | | | | | x | x | |
| Electricity mix | | | | | | | | | | | | | | | | | | | | | | | | x | x | |

The coverage of the WTT and TTW paths are illustrated in **Table 3-2** for the WTT aspects and in **Table 3-3** for the use of the alternative fuels. JEC (2019) outlines both figures at 2015 and 2025+ time horizons. However, in this report only the 2025+ figures are used.

Both the WTT calculations and the TTW calculations are built upon a number of assumptions. There are different methodological choices regarding by-products of fuels, that are relevant in understanding the production pathways and specific allocation of $CO_2$ emissions per main product and co-products/by-products (as described in this chapter).

**Table 3-3. Automotive fuels and powertrain combinations used in JEC (2019)[19][20]**

| EUCAR V5: 2015 Investigation Matrix | 2015 Powertrain Variants | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | DISI | DICI | Hybrid DISI | Hybrid DICI | PHEV50 DISI | REEV100 SI | PHEV50 DICI | BEV150 | FCEV | PHEV50 FC | REEV100 FC |
| Gasoline (E5) | ■ | | ■ | | ■ | ■ | | | | | |
| Gasoline E10 market blend | ■ | | ■ | | ■ | ■ | | | | | |
| Gasoline high RON (var. 1) | ■ | | ■ | | ■ | ■ | | | | | |
| Gasoline high RON (var. 2) | ■ | | ■ | | ■ | ■ | | | | | |
| Diesel (B0) | | ■ | | ■ | | | ■ | | | | |
| Diesel B7 market blend | | ■ | | ■ | | | ■ | | | | |
| LPG | ■ | | | | | | | | | | |
| CNG | ■ | | | | | | | | | | |
| E100 | ■ | | ■ | | ■ | ■ | | | | | |
| FAME (B100) | | ■ | | ■ | | | ■ | | | | |
| DME | | ■ | | ■ | | | ■ | | | | |
| FT-Diesel* | | ■ | | ■ | | | ■ | | | | |
| HVO* | | ■ | | ■ | | | ■ | | | | |
| Electricity | | | | | ■ | ■ | ■ | ■ | | ■ | ■ |
| Hydrogen (CGH2) | | | | | | | | | ■ | ■ | ■ |

| EUCAR V5: 2025+ Investigation Matrix | 2025+ Powertrain Variants | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DISI | DISI MHEV | DICI | DICI MHEV | Hybrid DISI | Hybrid DICI | PHEV100 DISI | REEV200 SI | PHEV100 DICI | REEV200 DICI | BEV200 | BEV400 | FCEV | PHEV100 FC | REEV200 FC |
| Gasoline (E5) | ■ | ■ | | | ■ | | ■ | ■ | | | | | | | |
| Gasoline E10 market blend | ■ | ■ | | | ■ | | ■ | ■ | | | | | | | |
| Gasoline high RON (var. 1) | ■ | ■ | | | ■ | | ■ | ■ | | | | | | | |
| Gasoline high RON (var.2) | ■ | ■ | | | ■ | | ■ | ■ | | | | | | | |
| Diesel (B0) | | | ■ | ■ | | ■ | | | ■ | ■ | | | | | |
| Diesel B7 market blend | | | ■ | ■ | | ■ | | | ■ | ■ | | | | | |
| LPG | ■ | ■ | | | | | | | | | | | | | |
| CNG | ■ | ■ | | | | | | | | | | | | | |
| E100 | ■ | ■ | | | ■ | | ■ | ■ | | | | | | | |
| FAME (B100) | | | ■ | ■ | | ■ | | | ■ | ■ | | | | | |
| DME | | | ■ | ■ | | ■ | | | ■ | ■ | | | | | |
| FT-Diesel* | | | ■ | ■ | | ■ | | | ■ | ■ | | | | | |
| HVO* | | | ■ | ■ | | ■ | | | ■ | ■ | | | | | |
| Electricity | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ |
| Hydrogen (CGH2) | | | | | | | | | | | | | ■ | ■ | ■ |

* EN15940 synthetic diesel standard to allow optimized engines

*Model vehicle configuration*

The TTW analysis is based on the definition of relevant parameters for a theoretical vehicle representative of the European passenger car fleet. The vehicle platform is then defined according to the specific passenger car configurations relevant for the entire range of fuel/energy/powertrain combinations and evaluated using the New European Driving Cycle to estimate energy expenditure and GHG emissions.

Vehicle simulations were carried out using the AVL CRUISE vehicle software which is a development from the ADVISOR vehicle simulation tool used in earlier versions of the WTW study.

*Applicability to other vehicle configurations*

Apart from the passenger cars, the last version of the JEC study (2019) includes also a section covering Heavy-Duty Vehicles (Class 4 and 5). WTT data can be directly

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[19] **DISI**: Direct Injection Spark Ignition, **DICI**: Direct Injection Compression Ignition, **HEV**: Hybrid Electric Vehicle, **MHEV**: Mild Hybrid Electric Vehicle (48v), **PHEV**: Plug-In Hybrid Electric Vehicle, **REEV**: Range Extender Electric Vehicle, **BEV**: Battery Electric Vehicle, **FCEV**: Fuel Cell driven Electric Vehicle, **LPG**: Liquefied Petroleum Gas, **CNG**: Compressed Natural Gas, **FAME**: Biodiesel (B100), **DME**: dimethyl ether, **FT-Diesel**: Paraffinic diesel (EN15940), **HVO**: Hydro-treated Vegetable Oil.

[20] **BEV range:** 150km (2015), 2 variants (2025+) 200km and 400km, **PHEV EV range:** 50km (2015), 100km (2025+), **REEV EV range:** 100km (2015), 200km (2025+).

applied to any other engine and vehicle applications. However, WTW data are dependent on the specific vehicle configuration. A heavy-duty WTW study would also need to include additional vehicle/fuel combinations, e.g. dual fuel concepts for carbon intensity (CI) with LNG or CNG as the main fuel.

In a qualitative manner, and with regard to the general ranking of the different fuel pathways, the results from the conventional powertrain TTW simulations (internal combustion engine (ICE)) are reasonably relevant also for heavy-duty.

# 4 ANALYSIS OF FUELS

## 4.1 ELECTRICITY

### 4.1.1 DEFINITIONS AND GENERAL DESCRIPTION

Electricity can be generated from a range of primary energy sources, some of which renewable, which together contribute to define the carbon intensity and the energy profile of the electricity mix used as an intermediate energy source concurring to the conversion of other primary energy sources (both renewable and non-renewable) for their conversion into final transportation fuels. At the same time, electricity also competes directly with other fuels for primary energy sources.

Electricity is produced as a primary or secondary product in power plants. The total amount of electricity produced is referred to as gross electricity production. Net electricity production deducts from the gross value the electricity consumed internally by power plants. Net electricity production is then distributed through transmission and distribution grids, transformed, stored, or traded (exported or imported).

Final consumption of electricity covers the electricity delivered to the consumer's door (industry, transport, households and other sectors); it excludes deliveries for transformation and/or own use of energy producing activities, as well as network losses at each step.

Energy use and associated emissions are accounted in the production steps of electricity whereas it is considered that electricity in transport, that is in the in-use of this energy carrier in vehicles and vessels, does not emit GHGs.

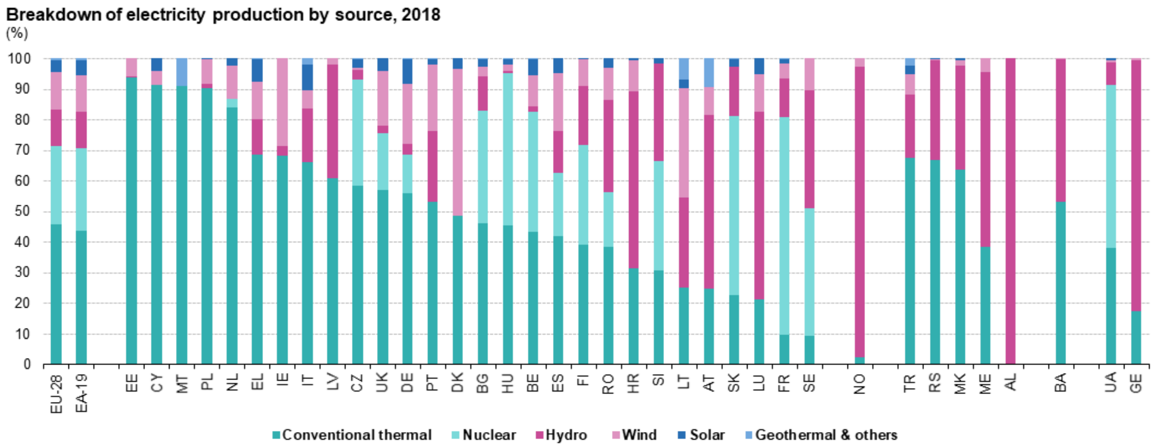



**Figure 4-1. Breakdown of electricity production by source per the EU Member States[21]**
**Source: Eurostat, 2019**

Considering EU-28 average on the **Figure 4-1**, 46% of the electricity comes from power stations burning fuels (conventional thermal), including combustion of biomass[22]. Approximately 28% from other renewable energy sources (hydro, wind, solar and geothermal), and 26% from nuclear power plants. Among the renewable energy sources, the highest share of electricity comes from hydropower plants (12%), wind turbines (12%), solar power (4%) and biomass (4%). Several sources of

[21] EA-19 refers to the euro area

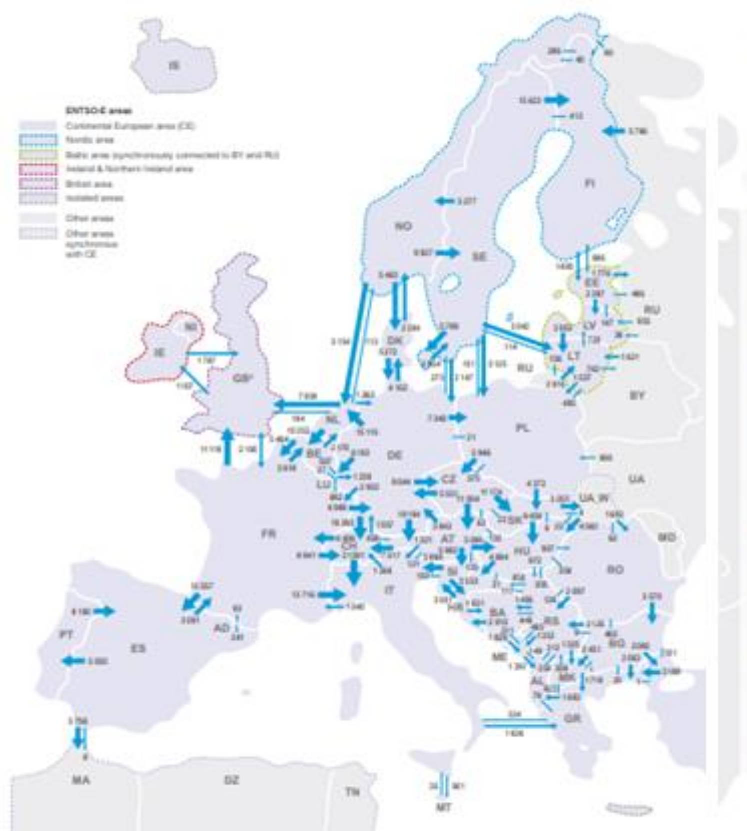
[22] The authors note that the total conventional thermal figure in Eurostat [nrg_105m] differs from the sum of the disaggregated thermal categories (coal, oil, natural gas, renewables and other non-renewables) and hence the shares may differ slightly.

information are available including data reported by EU Member States to Eurostat, the International Energy Agency (IEA), Eurelectric (the Union of the electricity industry) and the European Network of Transmission System Operators for Electricity (ENTSO-E). All sources report slightly different figures for the past years and for the current situation when it comes to the mix of primary energy sources used to generate electricity.

It is worth noting that the electricity mix is based on reported performances of electricity generation capacity that is in operation today: this means that older plants are included, which typically display lower-than-optimum efficiency levels.

As shown in **Figure 4-1**, the sources used for electricity generation vary among the Member States: around 90% of electricity production comes from fossil fuels in Estonia and Cyprus, while 72% of electricity production comes from nuclear power plants in France, followed by 55% in Slovakia and 51% in Belgium. In Croatia and Austria, around 60% of electricity production comes from hydro power plants, while 42% of electricity production in Denmark comes from wind energy.

Electricity trade across countries in Europe (**Figure 4-2**) plays a role in defining the carbon intensity of the electricity consumed. It is also worth noting that the system is steadily evolving towards increased cross-border interdependency. This situation carries with it consequences when considering the carbon intensity of the electricity consumed at any given location.



| | Sum of imports[1] | Sum of exports[1] | Balance (imp - exp) |
|---|---|---|---|
| AL | 3402 | 486 | 2916 |
| AT | 31039 | 23310 | 7729 |
| BA | 3348 | 5188 | -1840 |
| BE | 14198 | 8170 | 6028 |
| BG | 3701 | 9190 | -5489 |
| CH | 36001 | 29967 | 6034 |
| CZ | 15074 | 28104 | -13030 |
| DE | 28076 | 83443 | -55367 |
| DK | 15334 | 10620 | 4714 |
| EE | 2328 | 5059 | -2731 |
| ES | 23759 | 14588 | 9171 |
| FI | 22590 | 2147 | 20443 |
| FR | 21125 | 61361 | -40236 |
| GB[2] | 19917 | 3526 | 16391 |
| GR | 8685 | 2460 | 6225 |
| HR | 12157 | 4780 | 7377 |
| HU | 19803 | 6926 | 12877 |
| IE | 1107 | 1787 | -680 |
| IT | 42881 | 5131 | 37750 |
| LT | 11926 | 3249 | 8679 |
| LU | 7541 | 1366 | 6175 |
| LV | 4072 | 4136 | -64 |
| ME | 3331 | 2202 | 1129 |
| MK | 4199 | 2227 | 1972 |
| NL | 22633 | 18736 | 3897 |
| NO | 5904 | 20830 | -14926 |
| PL | 13271 | 10984 | 2287 |
| PT | 5507 | 8190 | -2683 |
| RO | 3192 | 6087 | -2895 |
| RS | 7021 | 5679 | 1342 |
| SE | 13831 | 32982 | -19151 |
| SI | 9133 | 9556 | -423 |
| SK | 15565 | 12535 | 3030 |
| TR | 2688 | 3291 | -603 |
| ENTSO-E | **454337** | **448291** | **6047** |

Physical flow values in GWh.

**Figure 4-2. Physical electricity flows in 2017**
**Source: ENTSO-E, 2018**

As illustrated in Moro & Lonza (2018), the electricity imported by a country affects the carbon intensity of its mix in three possible ways: a "neutral effect" when the carbon intensity of the electricity imported is either similar to that of the electricity produced in the country, or when the amount of electric energy imported is modest; a "beneficial effect" when imported electricity has a lower carbon intensity than that of the electricity produced (e.g. Estonia, producing electricity mainly from a very GHG intensive source (peat) and importing it from Finland, which relies on renewables and nuclear energy); a "negative effect" when imported electricity has a higher carbon intensity than that of the electricity produced in the domestically (e.g. Latvia, worsening its mix because of relevant imports from Estonia).

A "neutral effect" can be discounted when considering EU-28, because the sum of total trade only impacts the average carbon intensity of the electricity available for consumption in EU-28 by approximately 1%. This makes it acceptable to use a discrete variable over the full range of available values when it comes to computing the GHG emissions and energy performance profiles of energy conversion pathways where electricity is an intermediate input.

Carbon intensity has been steadily decreasing in Europe over the past decade (EEA, 2017). This is in part due to improved efficiency for electricity generation and trading as well as the steady transition towards the use of primary energy sources characterised by lower carbon intensities: not only moving slowly away from coal and towards natural gas among fossil sources, but also with a steady increase of wind and solar as renewable sources for power generation.

According to the draft National Energy and Climate Plans[23] in the context of the Governance of the Energy Union, several EU Member States introduced or confirmed ambitious objectives and timelines to phase out coal for electricity generation. France intends to do so by 2022; Italy and Ireland by 2025; Denmark, Finland, the Netherlands, Portugal and Spain by 2030; Germany has also indicated that it would set an end date for coal-based electricity.

The in-depth analysis accompanying the "Clean Planet for all" long term strategy shows that under current trends and policies (i.e. baseline scenario) the EU power generation mix changes considerably in favour of renewables, with the increase in wind being the most spectacular. By 2050, 73% of the electricity is generated from renewable resources (compared to 57% in 2030), while nuclear and natural gas maintain their role in the power generation mix (see **Figure 4-3**). By contrast, electricity produced from oil and solids becomes marginal (EC, 2018b).

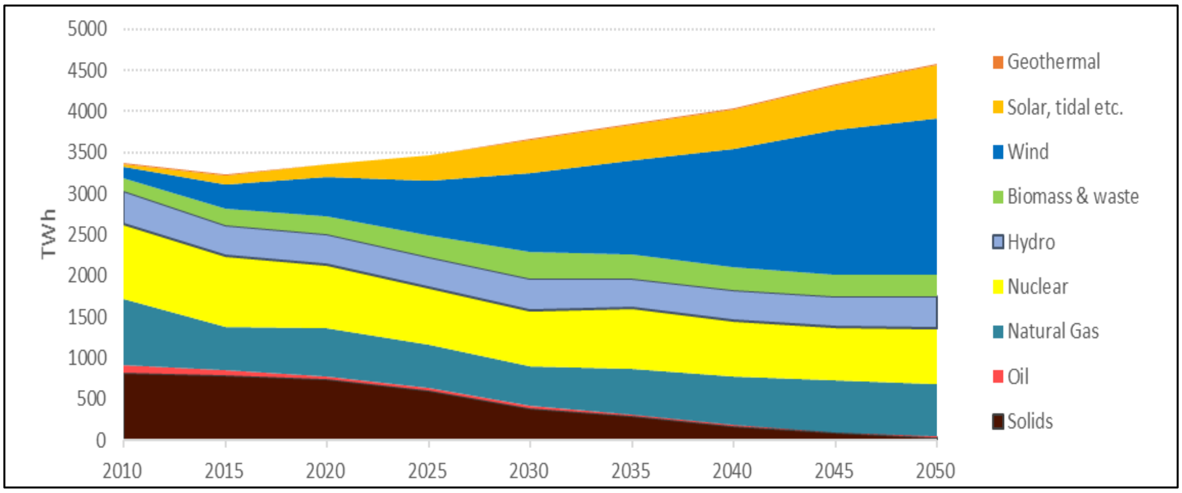



**Figure 4-3. Gross electricity generation in the Baseline.**
**Source: (EC, 2018b)**

[23]https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans

### 4.1.2 WELL-TO-TANK GREENHOUSE GAS (GHG) EMISSIONS

Electricity used in electric vehicles has zero emissions at tailpipe. The carbon footprint of electricity depends on the primary energy sources used for its production.

The 'EU-mix' pathway that reflects the performance of the current EU electricity generation is considered in the (JEC-WTT, 2019) study, as representative of the current electricity supply (**Figure 4-4**).

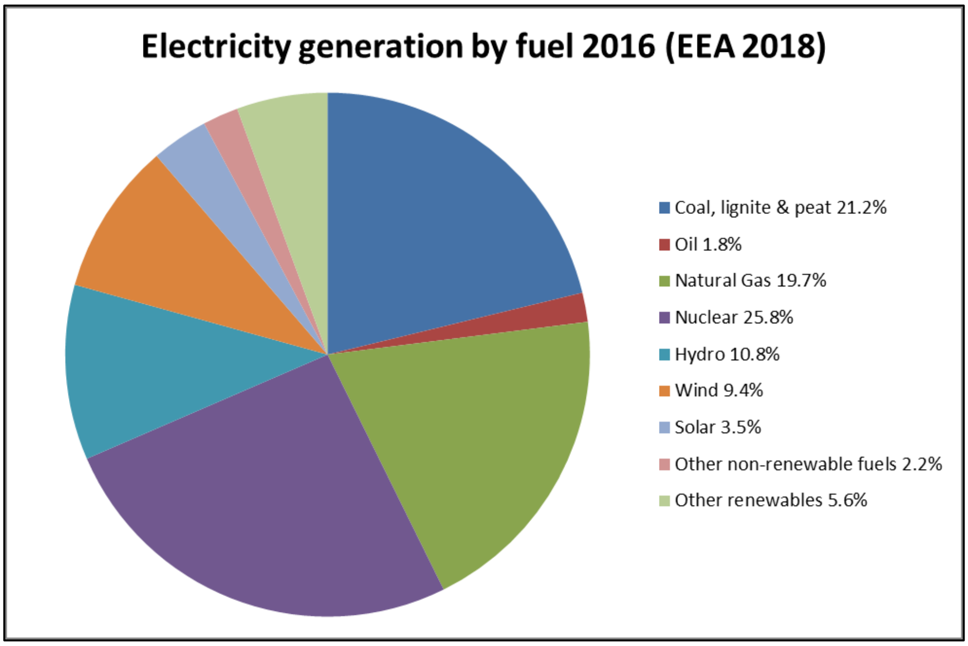



**Figure 4-4. EU-mix electricity generated by fuel in 2016**

For the current EU-mix emissions, the JEC study (JEC-WTT, 2019) used statistical data as provided in (Moro & Lonza, 2018) for 2013 updated with 2016 data[24] from the European Environment Agency (EEA 2018). The (JEC-WTT, 2019) results are based on a detailed country-by-country analysis of electricity consumption, where both combustion and upstream emissions of the different type of fuels are included.

Predicting the EU-mix of electricity for a future period (**Figure 4-5**) requires knowledge of both the generating capacity and the efficiency gains per technology. This report makes use of the assumptions of (JEC-WTT, 2019) which uses as a reference the 2030 electricity mix defined in the 2017 World Energy Outlook by the International Energy Agency in their New Policies Scenario (IEA 2017).

According to this study, the share of natural gas expected to be used in 2030 as primary energy source for electricity generation in Europe is expected to expand, in consideration of the growing total demand for electricity (despite its relative share remaining almost stable); oil is expected to shrink to almost negligible levels, nuclear to contract steadily; renewable sources to expand substantially.

[24] **Figure 4-4** is based on 2016 figures from EEA 2018. The electricity EU-mix emissions for 2016 are estimated starting from 2013 data from (Moro & Lonza, 2018) (that include **upstream emissions**) and applying an improvement factor based on **generating** emissions from EEA.

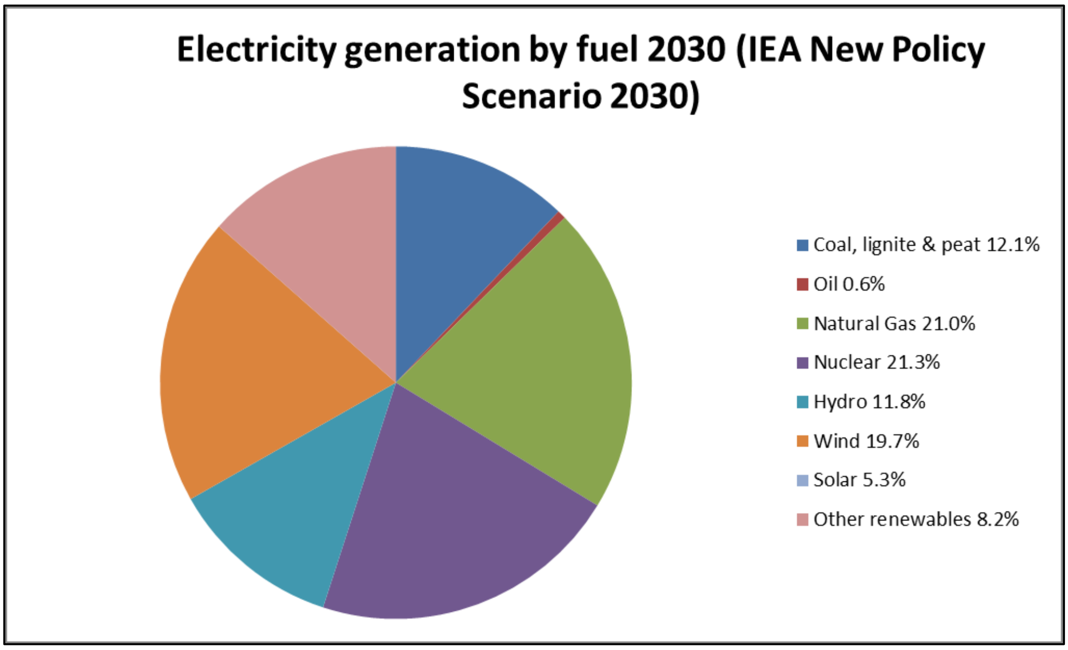



**Figure 4-5. EU-mix electricity generated by fuel in 2030**

In **Figure 4-6**, the GHG emissions for the EU electricity mix (low voltage, medium voltage and high voltage) in 2016 and 2030 are presented. In the three cases, significant savings of GHG emissions are observed. These projections are in line with the observed trend mentioned in the long-term strategy (EC, 2018b): GHG emissions from the power sector were decreased by 26% from 2005 to 2016. It should be also noted that the same study foresees higher penetration of RES by 2030 under current trends and policies (i.e. baseline scenario). Moreover, according to the same source, the power sector is expected to be nearly decarbonised by 2050 with the strong penetration of RES facilitated by system optimisation (demand-side response, storage, interconnections, role of prosumers).

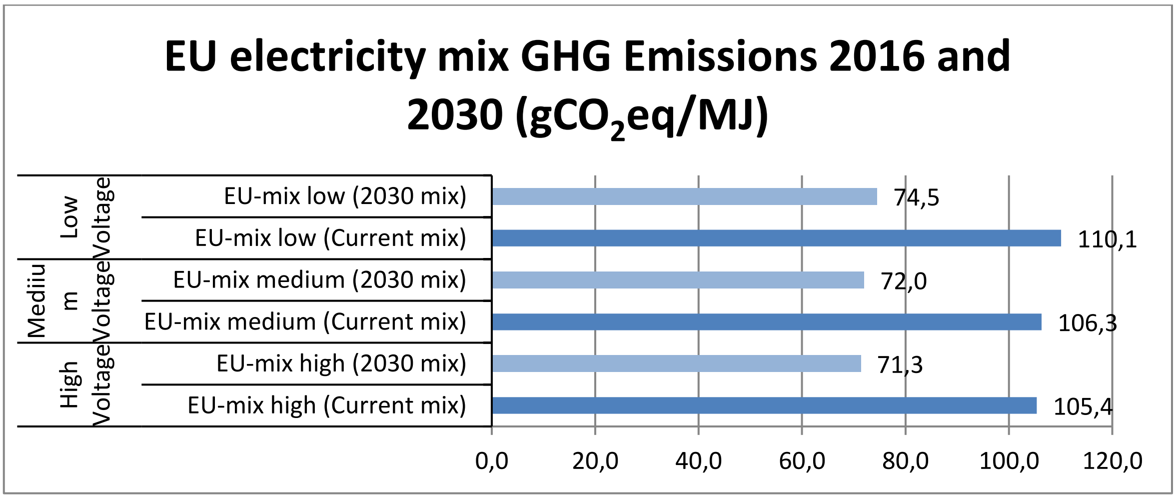



**Figure 4-6. 2016 and 2030 EU-mix electricity High, Medium, Low Voltage: GHG emissions ($gCO_2eq/MJ$)**
**Source: JEC-WTT, 2019**

It should be noted that presenting detailed data for each EU Member State (MS) is out of the scope of this report which focuses on the status of the electricity production at the EU level. However, it is interesting to mention the significant differences observed across Europe as each country has its own grid defined by its own resources and by trade (see also **Figure 4-2**). Indicatively, the carbon intensity in the EU vary from less than 13 $gCO_2eq/MJ$ for MS with an extensive deployment of renewable energy to more than 260 $gCO_2eq/MJ$ for MS relying on fossil resources for their energy production (figures for 2013 from Moro and Lonza, 2018). The interested reader is advised to look up detailed real-time information at https://www.electricitymap.org.

#### 4.1.2.1 FOSSIL PRIMARY ENERGY SOURCES TO GENERATE ELECTRICITY: GHG EMISSIONS

Natural gas production pathways

The use of natural gas for electricity generation is routine today and is expected to increase in the next decade in part replacing outgoing coal and nuclear power plants and mostly satisfying increasing demand. Natural gas is fuelling conventional thermal steam cycles. New large-scale capacity is based on the combined cycle gas turbine (CCGT) characterised by better efficiency (JEC WTT V5 assumes this conversion efficiency to be 58%). High efficiency is only possible in state-of-the-art plants, not in existing plants undergoing a "switch to gas", where only marginal improvements can be expected. Carbon capture and storage (CCS) may be an additional future option for this process[25]. Natural gas can reach the European market via different routes, so **Figure 4-7** reports the costs in terms of the carbon intensity of three pathways, two reaching Europe via pipelines and one LNG. Additionally, a forward-looking option for CCS for piped natural gas is also displayed in the same Figure although no such case is currently in operation (in this case the lowest GHG emissions are observed). It is also worth noting the 4,300km distance from point of extraction to the EU border; it is then assumed that gas is further transported via high-pressure pipelines over 700km to reach central EU locations.

Oil

In the EU-electricity mix, oil is also decreasingly used to produce electricity. The share of oil as primary energy source is expected to shrink to almost negligible quantities in the coming decade.

Coal

Coal is associated with high emissions. However, there are cases in which coal can be converted “cleanly” into electricity: gasification in a combined cycle (IGCC) can deliver the best overall efficiency (with an average conversion efficiency of 48%) and technological advances have also improved the conventional thermal cycle (with an average conversion efficiency of 43.5%). A CCS option is also displayed for IGCC.

Nuclear

Nuclear electricity is produced using a primary energy source which is neither fossil nor renewable, although large reserves of Uranium exist: as Uranium does not contain carbon, this source of energy is carbon-free. Associated GHG emissions are to be found in mining, transportation and enrichment into isotope $U^{235}$ as well as for the maintenance of nuclear power plants.

[25] For more information on CCS projects in Europe please see http://www.ccsassociation.org/new-about-ccs/proven-technology/

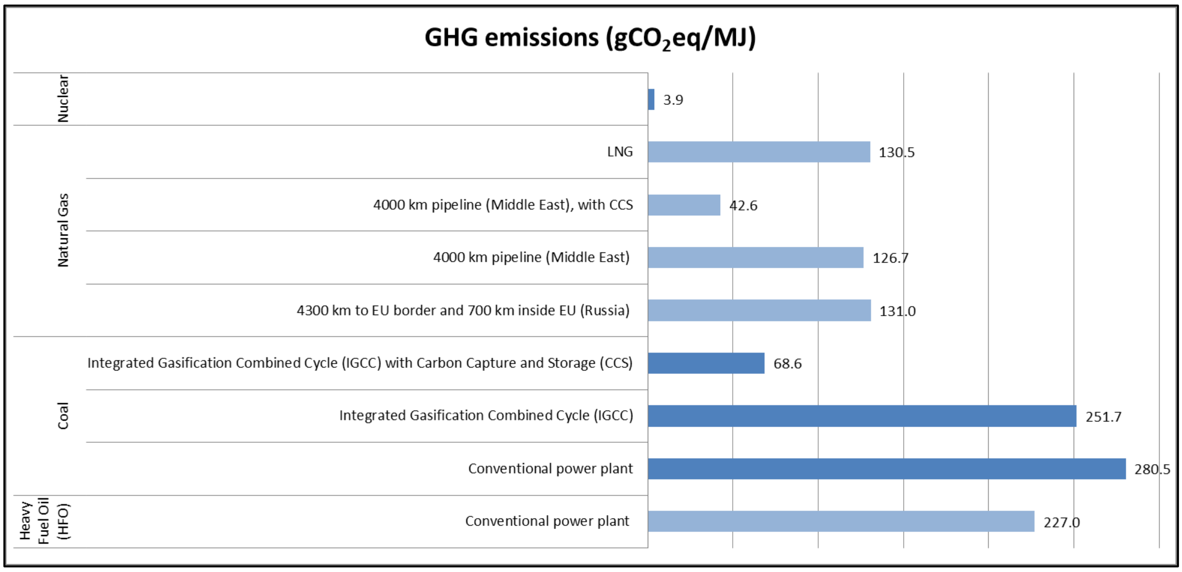



**Figure 4-7. Fossil primary energy sources and nuclear fission to electricity: GHG emissions ($gCO_2eq/MJ$)**
**Source: JEC-WTT, 2019**

#### 4.1.2.2 RENEWABLE SOURCES TO GENERATE ELECTRICITY: GHG EMISSIONS

<u>Wood</u>

Wood is a primary source for electricity generation at both large and small scale power plants via either a simpler technology using a boiler and a steam turbine, or via a more complex scheme as in use when using coal as a primary source. Conversion efficiency is higher in the latter case, but costs are higher too. Co-firing of wood in coal plants is also a possibility which is in operation today; black liquor represents an interesting opportunity to turn waste wood into electricity, since the use of black liquor gasification has the potential to achieve higher overall energy efficiency than the conventional recovery boiler, while generating an energy-rich syngas from the liquor.

<u>Electricity via biomass combustion and biogas (either raw or upgraded to biomethane) using organic waste</u>

Organic waste, such as manure and municipal solid waste (MSW), can be used to generate electricity, either on-site or via injection of upgraded biomethane to the gas grid, which is relevant when gas from the grid fuels a large power plant. On-site exploitation implies using biogas in a local combined heat and power (CHP) plant using a gas engine, with the heat used in the biogas production process or other close coupled heating applications.

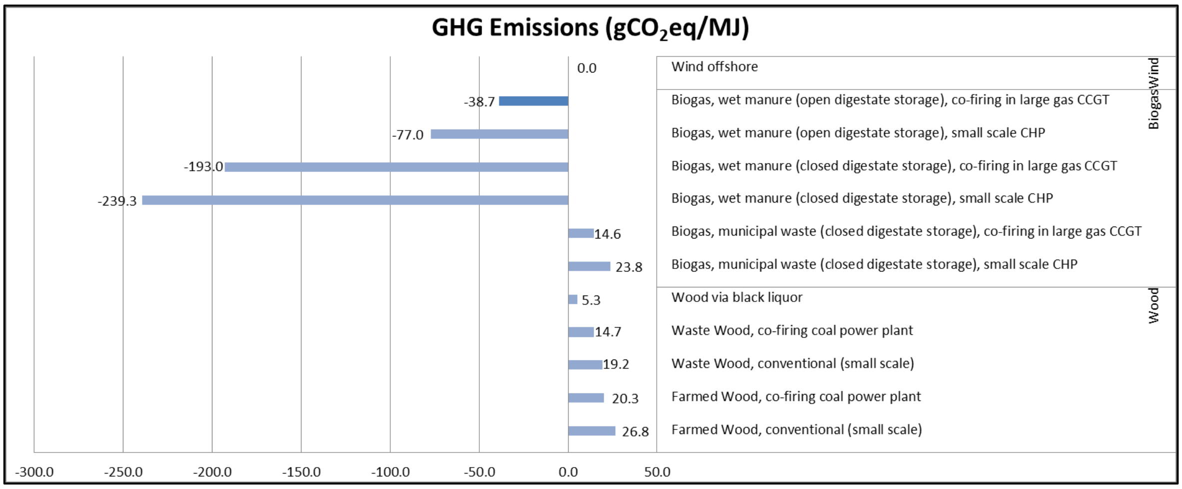



**Figure 4-8. Renewables to electricity: GHG emissions (gCO2eq/MJ)**
**Source: JEC-WTT, 2019**

Wind

There is a very high potential to produce electricity from wind power with full development constrained partly by the availability and social acceptance of suitable sites for large-scale wind farms and partly by the difficulty to integrate wind electricity in the existing electricity grid due to the intermittence and limited predictability of wind, which implies the need for back-up capacity. Wind turbine technology has been improving rapidly with increasingly efficient, large, and flexible solutions providing larger, cheaper, quieter, more efficient and flexible options and re-defining the viability of new wind farm developments.

Wind power is growing rapidly: in 2016 wind electricity contributed 9.4% of the total net electricity generation in the EU (EEA 2018). This percentage has risen to 12% in 2018 (Eurostat, 2019). In its New Policies Scenarios 2030, the IEA assumes that wind electricity will contribute about 20% of total electricity generation (IEA, 2017). With the exception of the wind farm development, wind electricity causes no GHG emissions.

With respect to its energy balance, the only, very limited, fossil energy required is used for maintenance activities of the wind farm.

Solar

In 2018, photovoltaic electricity contributed 4% of the total net electricity generation in the EU (Eurostat, 2019). The IEA expects about 5% by 2030 (IEA, 2017). Wind and solar energy tend to be complementary with high wind power availability at times of low solar irradiation and vice versa.

Hydropower

In 2016, hydroelectricity represented the largest portion of Europe’s renewable electricity generation (about 11%) (EEA 2018). No expansion of capacity is expected in Europe.

### 4.1.3 WELL-TO-TANK ENERGY PERFORMANCE

The energy performance refers to the total amount of energy input needed to generate 1 MJ of net electricity using the primary fuels, including the electricity used for the power station itself. Energy performance varies significantly across the EU. On average, the energy efficiency of the electricity sector in the EU was estimated at 44.7% in 2016.[26] However, there is high diversity among the MSs with the energy efficiency ranging from 34% (for Estonia) to 71.8% (for Austria).

In **Figure 4-9** and **Figure 4-10** the WTT energy performance is presented when fossil primary energy sources and renewable sources, respectively, are used. Specific assumption on the energy efficiency used in the WTT study can be found in JEC-WTT (2019).

#### 4.1.3.1 FOSSIL PRIMARY ENERGY SOURCES TO GENERATE ELECTRICITY: ENERGY PERFORMANCE

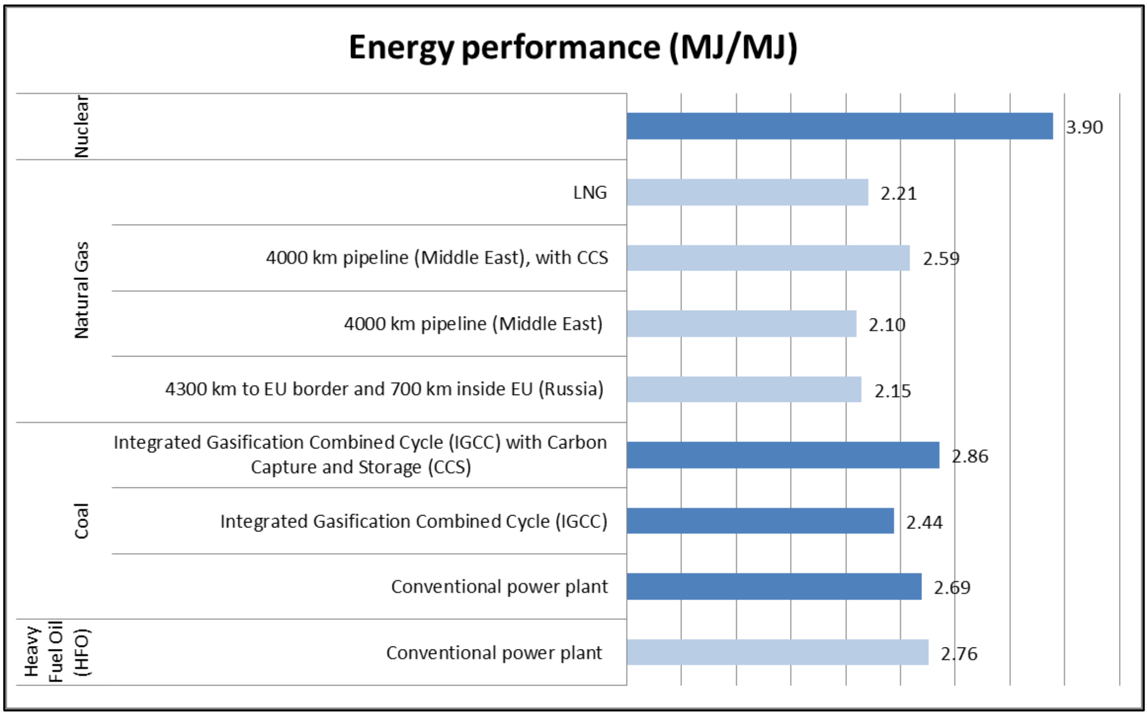



**Figure 4-9. Fossil primary energy sources and nuclear fission to electricity: energy performance (MJ/MJ)**
**Source: JEC-WTT, 2019**

[26]https://www.eea.europa.eu/data-and-maps/daviz/average-efficiency-of-the-electric-4#tab-chart_1_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_date%22%3A%5B2016%5D%7D%7D

#### 4.1.3.2 RENEWABLE SOURCES TO GENERATE ELECTRICITY: ENERGY PERFORMANCE

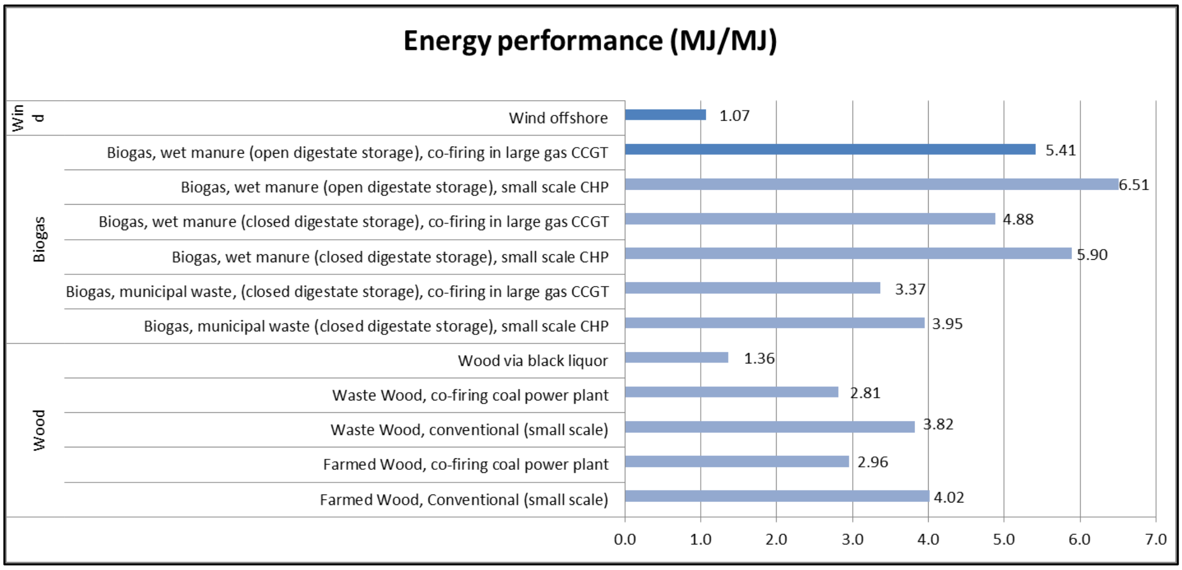



**Figure 4-10. Renewables to electricity: energy performance (MJ/MJ)**
**Source: JEC-WTT, 2019**

### 4.1.4 MATURITY OF FUEL PRODUCTION

All technologies in use for electricity production have the highest grade both for TRL and CRL: a TRL 9 (Actual system proven in operational environment), and CRL 6 (Bankable asset class). **Chapter 3 (p. 10)** provides details on the TRL and CRL scales.

### 4.1.5 WELL-TO-TANK COSTS

In the coming years, additional investments are expected in renewable electricity, network expansion (national and interconnection within European countries), as well as market coupling. Already today, market coupling between European countries has created price convergence (EC, 2019). As illustrated in **Figure 4-11**, wholesale electricity prices in Europe became 21% less spread-out over the last decade. Electricity prices are partly set by fossil fuel prices (mainly coal and gas prices) with other national or regional factors also affecting them (EC, 2019). The true costs of energy supply are reflected in the wholesale price.

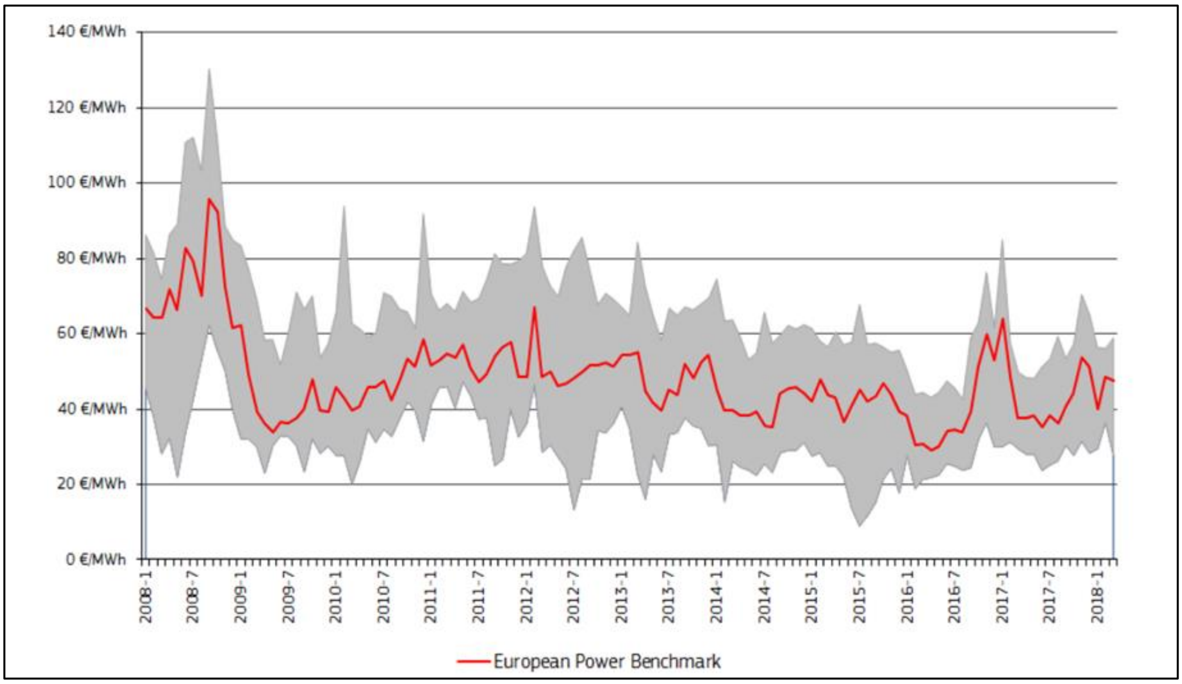



**Figure 4-11. Monthly wholesale electricity prices: range of maximum and minimum prices Source: Platts, European power markets. Reprinted from EC (2019)**

Electricity prices for consumers will depend on the choice and configuration of the charging infrastructure. For instance, residential charging is subject to household electricity tariffs, while commercial charging stations may be subject to industrial tariffs. Moreover, depending on the consumption band (range of yearly consumption) electricity prices can be different.

**Figure 4-12** and **Figure 4-13** show the different components of households and industrial retail prices respectively, in the EU and each Member State in 2017. Retail electricity prices consist of: energy supply production costs, network costs, taxes and other levies. As the figure show, in some countries, taxes have significant contribution to the total price. Taxes and levies represent 40% of the average EU electricity prices. Detailed information on the taxation on electricity can be found in **Appendix to Chapter** 4**, p. 79**.

Tax exemption or low taxation schemes on electricity for vehicles could significantly impact electro-mobility competitiveness.

The different tax components by Member State are available in Eurostat[27]. They include the VAT tax, renewable taxes, environmental taxes, capacity taxes and other. Considering e.g. the total amount of taxes for household consumers[28] by Member State, Denmark appears to have the highest level of taxation, while Malta has the lowest. Environmental taxes are the larger component of the total tax in Denmark (55%), while for Malta they represent 16 % of the total. Denmark's taxes include also a share (14%) destined to renewable that appear to be 0 in Malta.

[27] Eurostat data, table nrg_pc_204 and table nrg_pc_204_c.

[28] The total amount of taxes for household consumers was calculated as the average of the most representative Eurostat bands. However, please note that the amount of taxes by Member State is different for non-household consumers and the results in terms of the Member State with highest and lowest level of taxation would be different.

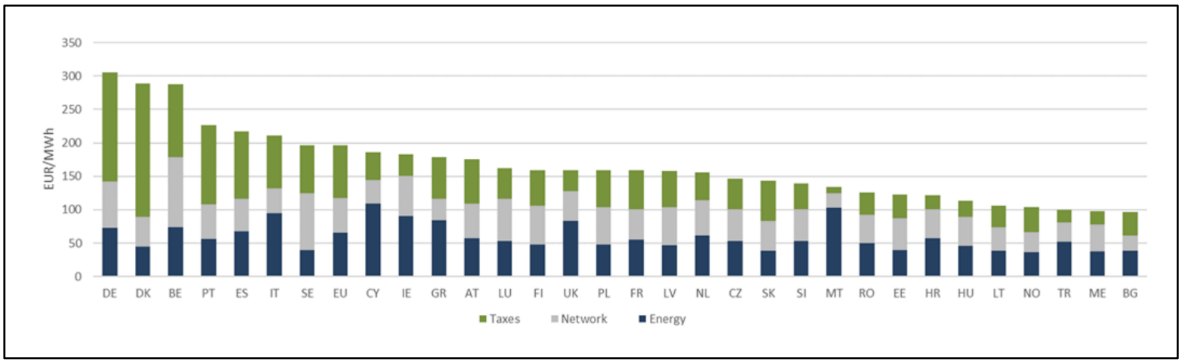



**Figure 4-12. Household electricity prices in 2017 (Note: most representative consumption band)**
**Source: DG ENER in house data collection. Reprinted from EC (2019)**

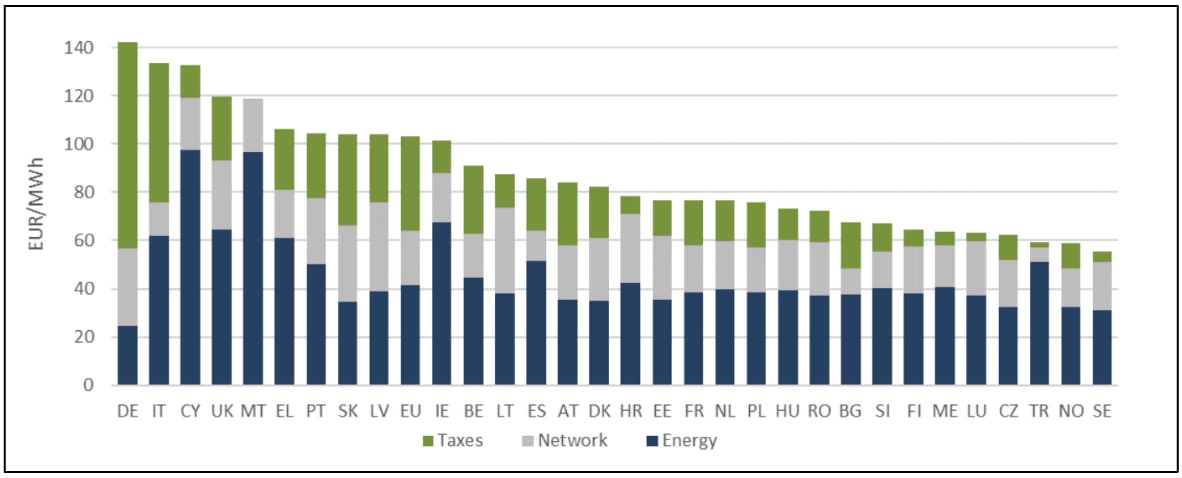



**Figure 4-13. Industrial electricity prices in 2017**
**Source: DG ENER in house data collection. Reprinted from EC (2019)**

As a consequence of a combination of different factors, including the need of significant investments, the market is not always capable of financing investments in the power sector, and prices are not always sufficient to cover costs. The levelised cost of electricity (LCOE) includes both capital and operating costs of electricity generation from different sources. The decreasing costs of renewable energy technologies, in combination with the improved operation of the European power market, should result in the market being able to cover the investment costs of most new capacities in the coming decade (EC, 2019).

As new data become available, cost reductions, especially for solar PV and onshore wind, appear to be higher than expected. Recent estimates from the International Renewable Energy Agency (IRENA, 2019a), using data from their Renewable Cost Database[29], show that the global weighted-average LCOE for some commissioned renewable power projects are already competing with fossil fuels, even without financial support. The weighted average LCEO, as well as the weighted average for renewable power generation plants commissioned in 2018 at global level and in Europe are reported in **Table 4-1** together with the fossil fuel-fired power generation cost range. LCEO estimates for Europe appear to be generally higher than the global average.

[29] The database contains cost and performance data for around 17,000 renewable power generation projects globally (with a total capacity of around 1,700 GW) and around half of all renewable power generation projects commissioned by the end of 2018 (IRENA, 2019a).

**Table 4-1. Weighted-average LCOE for renewable power generation plants commissioned in 2018**
**Source: IRENA, 2019a**
*** Converted from original values expressed in USD using the 2018 exchange rate from the European Central Bank**

| | **Global** weighted-average LCOE for renewable power generation plants commissioned in 2018<br><br>(5th and 95th percentiles)<br><br>€/MWh* | Weighted-average LCOE for renewable power generation plants commissioned in 2018 in **Europe**<br><br>€/MWh* |
|---|---|---|
| Bioenergy | 52<br><br>(41-206) | 68 |
| Geothermal | 61<br><br>(51-121) | NA |
| Hydro | 40<br><br>(25-115) | Large projects: 102;<br><br>Small projects: 161 |
| Solar photovoltaics | 72<br><br>(49-185) | UK: 127; Germany: 93;<br><br>France: 76; Italy: 59 |
| Concentrating solar power | 157<br><br>(92-230) | NA |
| Offshore wind | 107<br><br>(86-168) | 113 |
| Onshore wind | 47<br><br>(37-85) | 61 |
| Fossil fuel-fired power generation cost range | 40-146 | |

According to the IRENA PPA (Power Purchase Agreement) and auction database, even if the auction price and the LCEO calculation are not directly comparable[30], projects for onshore wind and solar PV to be commissioned in 2020 have costs that continue to fall; very low auction prices for solar PV in Dubai, Mexico, Peru, Chile, Abu Dhabi and

[30] Comparisons between LCOE and auction price is challenging because each country and technology has different resource potentials, financing conditions, and auction designs. There is also a limited availability of information on contract-winning projects. It makes it difficult to state with certainty that these tender-determined prices are becoming the standard benchmarks for renewable generation costs (IEA News, 2019). For a more detailed discussion of the challenges of comparing PPA and auction data to LCOE calculations, please see IRENA, 2019b and Apostoleris et al., 2018.

Saudi Arabia (25 €/MWh) can be reached in national contexts where installed costs and operations and maintenance (O&M) are low, the solar resource is excellent and financing costs are low (IRENA, 2019a).

In **Figure 4-14**, the future EU electricity prices are presented according to the scenarios examined in the frame of the long-term strategy.

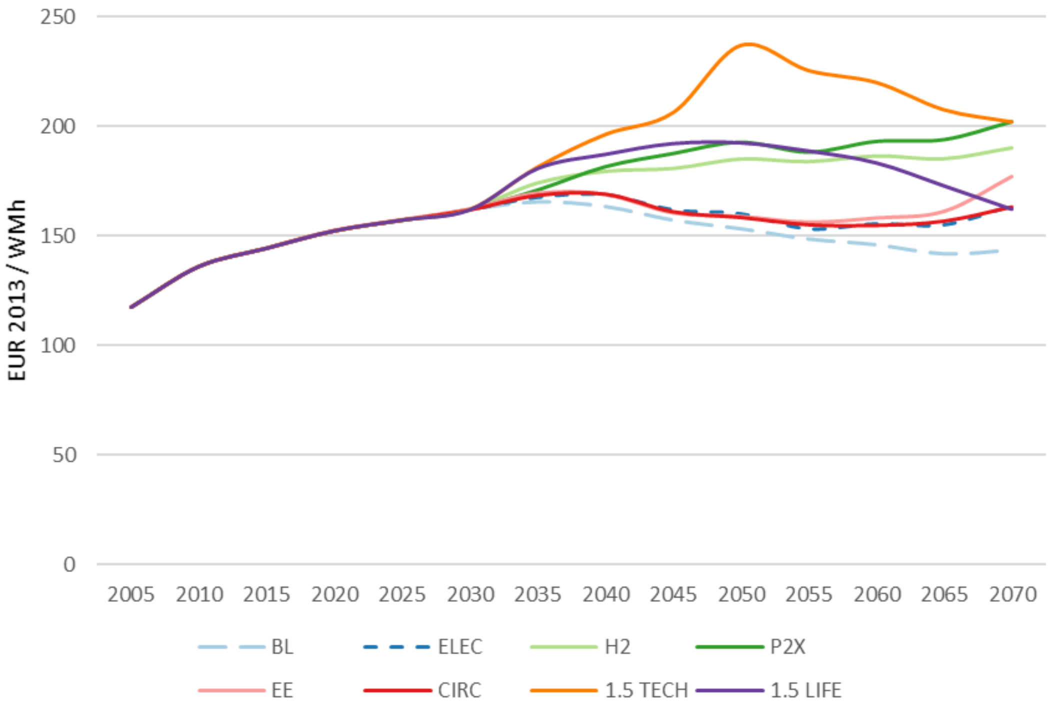



**Figure 4-14. Future EU electricity prices under all scenarios**
**Source: on (EC, 2018b)**

### 4.1.6 POTENTIAL CAPACITY AND ACTUAL PRODUCTION

A growing electrification of the economy is occurring in Europe and in the rest of the world. At the global scale, electrification displays different paces, is promoted by different drivers, and faces different socio-political and techno-economic issues depending on the world's areas, economies and policies. In Europe, the Commission states that "electrification is crucial to achieve carbon neutrality by 2050" and it anticipates that "the deployment of renewable energy will drive a large-scale electrification of the energy system, be it at the level of end-users – such as energy use in industry, buildings or transport – or to produce carbon-free fuels and feedstock for industry. The power sector will thus become a central element for the transformation of other economic sectors" (EC, 2018a; EC, 2018b).

The power sector is an essential piece of the global decarbonisation puzzle. The main reason lies in the extraordinary technological diversity within the sector: since the first electrification wave of the advanced economies some 150 years ago, the technological options to generate electricity at different scales has become more and more diversified and now offers the most widespread portfolio. Another reason for the power sector to play a crucial role in achieving substantial GHG mitigation is its strong and relatively quick reaction to climate policies. The level of technology substitution that this sector can exhibit results in among the fastest and cheapest decarbonisation options across human activities. This is made possible by the easy substitution of fuels to produce electricity.[31]

In the frame of the in-depth analysis accompanying the long-term strategy of the EU for a climate-neutral economy, eight different scenarios considering differentiated portfolios of decarbonisation options and different performances in terms of GHG emissions reductions were developed and assessed. According to the decarbonisation scenarios of the in-depth analysis, more than 80% of electricity will be coming from renewable energy sources (increasingly located off-shore) by 2050 (EC, 2018b). In 2015, the net installed electricity capacity was 985 GW whereas in 2050 is expected to be between 1700 GW to 2800 GW. As far as transport is concerned, the study confirms that electricity will gradually play a more important role: the consumption of electricity as fuel is expected to be in the range of 31.4 to 55.8 Mtoe (depending on the scenario) in 2050. It should be noted here that the respective value in 2015 was 4.8 Mtoe.

## 4.2 HYDROGEN

### 4.2.1 DEFINITIONS AND GENERAL DESCRIPTION

Hydrogen is a flexible energy carrier that can be produced from any regionally prevalent primary energy source. Moreover, it can be effectively transformed into any form of energy for diverse end-use applications. It is particularly well suited for use in fuel cells that efficiently use hydrogen to generate electricity.

The main processes for hydrogen production can be classified in three categories:

a) thermal processes such as steam methane reforming (SMR), catalytic decomposition of natural gas, partial oxidation of heavy oil, coal gasification, thermochemical water decomposition

b) electrolytic processes such as water electrolysis,

c) photolytic processes including photochemical, photo electrochemical, and photo biological processes.

The most widespread hydrogen production process is steam reforming of natural gas (essentially methane). In this process, the catalysed combination of methane and water at high temperature produces a mixture of carbon monoxide and hydrogen (known as “syngas”). The water gas shift (“CO-shift”) reaction then combines CO with water to form $CO_2$ and hydrogen. The process is technically and commercially well-established. Natural gas is a widely available and relatively cheap feedstock and advanced infrastructure is already in place for its extraction, transport and storage. Furthermore, SMR can use other hydrocarbons such as gasoline and methanol in its process.

As far as electrolysis is concerned, electricity is the primary energy source for producing hydrogen. Electrolysis uses electricity to split the water molecule. This is a well-established technology both at large and small scale. Interest in large-scale hydrogen production may result in improvements in terms of efficiency and cost. One particularly promising development route is high-pressure electrolysers (higher production pressure means less compression energy for storage). The use of electricity as the energy vector to produce hydrogen opens the door to the use of a large variety of primary energy sources including fossil and biomass but also wind energy and of course nuclear (JEC,2014).

[31] Source: POLES-JRC 2018.

### 4.2.2 WELL-TO-TANK GREENHOUSE GAS (GHG) EMISSIONS

Hydrogen itself contains no carbon; when used in a fuel cell or burned in a heat engine, water or water vapour is the only exhaust. When burned in a heat engine, NOx can also be produced if lean combustion is used to increase fuel efficiency, and in case a NOx after treatment is used, N2O might also result, producing a further GW impact. However, hydrogen can have a very significant carbon footprint. Its GHG emissions are determined by the primary energy source and the process used for hydrogen production, and must be taken into account when quantifying climate benefits.

**Table 4-2** presents the estimations for the Well-to-Tank GHG emissions for four thermal production pathways. The results are presented in terms of energy in the fuel. It should be noted that WTT GHG include emissions from the following processes: Production & conditioning at source, transformation at source, transportation to market, transformation near market and conditioning & distribution. Natural gas on-site reforming and the use of a 4,000 km pipeline has been selected as the most feasible option emitting 113 $gCO_2eq$/MJ fuel whereas the option with the minimum $CO_2$ emissions (on site SMR of biogas from wet manure) presents a negative value of -142.4g $CO_2eq$/MJ fuel.

**Table 4-2. GHG emissions (CO2eq) for different thermal production pathways for compressed hydrogen**
**Source: JEC-WTT, 2019**

| Thermal gasification path | WTT ($gCO_2$ eq/MJ fuel) |
|---|---|
| NG 4,000 km, on-site reforming[32] | 113 |
| Biogas from wet manure via onsite SMR | -142.4 |
| Biogas from sewage sludge | 41.6 |
| Farmed wood, liquid transport, cryo-compression | 17.8 |

Respectively, in **Table 4-3** similar figures are shown for the electrolysis pathways where the electricity used in the hydrogen production process comes from different sources. In the case of electrolysis, the WTT emissions range from 3.6 to 499.6 $gCO_2eq$/MJ.

[32] Natural gas supply from Middle East.

**Table 4-3. GHG emissions (CO2eq) for different electrolysis production pathways for compressed hydrogen**
**Source: JEC-WTT, 2019**

| **Electrolysis path** | **WTT (g$CO_2$ eq/MJ fuel)** |
|---|---|
| Electricity from EU-mix, on-site electrolysis | 175.2 |
| Electricity from EU-mix, central electrolysis pipeline transport | 174.8 |
| Wind electricity, central electrolysis, pipeline transport | 9.5 |
| Wind electricity, central reforming, hydrogen liquefaction, liquid hydrogen road transport to retail site, hydrogen cryo-compression in to vehicle tank | 3.6 |
| Coal EU-mix, conventional power plant, Central Electrolysis, Liquefaction, Road transport | 499.6 |
| Coal EU-mix, electrolysis on-site | 446.5 |
| Nuclear energy, on-site electrolysis | 6.2 |

To conclude, the emission figures (for thermal production, and for electrolysis) depend heavily on how the energy used for this process is produced.

### 4.2.3 WELL-TO-TANK ENERGY PERFORMANCE

The energy consumption for different hydrogen production pathways is shown below. **Figure 4-15** presents the consumption of energy for selected thermal production pathways. According to the JEC-WTT (2019), the production of hydrogen from natural gas gives an energy consumption of 2.02 MJ/MJ fuel whereas the production of hydrogen from biogas produced from sewage sludge 8.05 MJ/MJ fuel. As far as electrolysis is concerned (**Figure 4-16**), the WTT energy consumption ranges from 1.87 to 6.21 for the selected pathways.

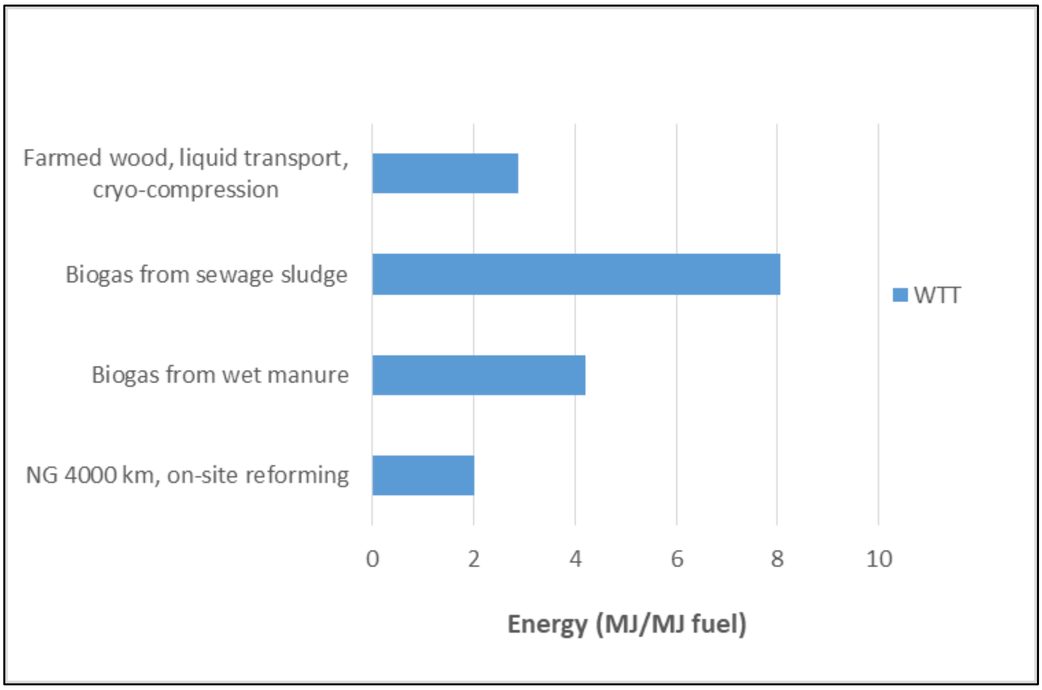



**Figure 4-15. WTT energy consumption from different thermal hydrogen production pathways; 2025+ estimates**
**Source: JEC-WTT, 2019**

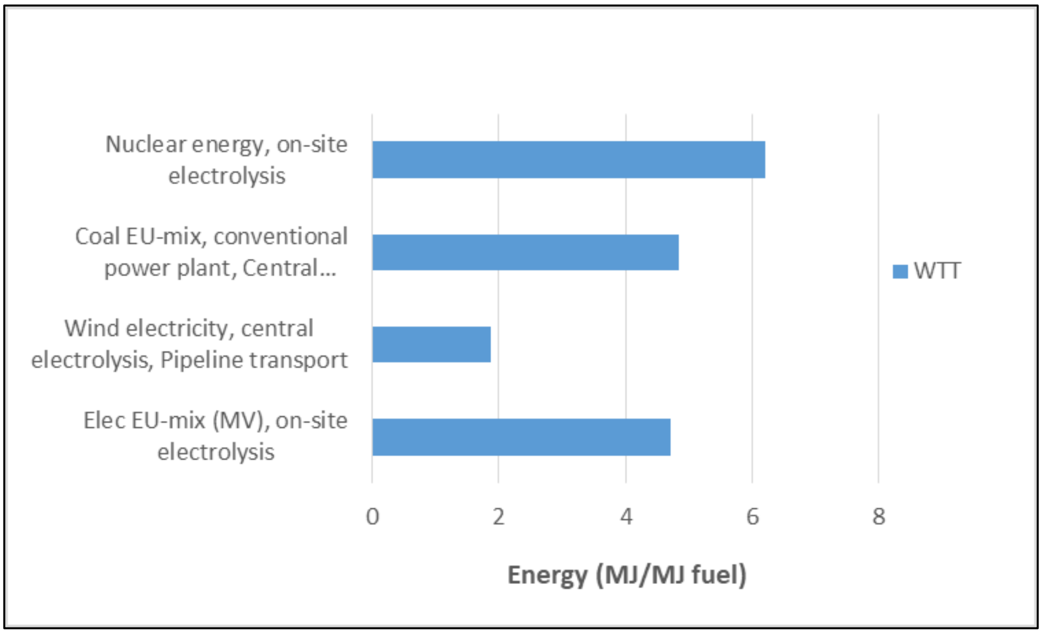



**Figure 4-16. WTT energy consumption from different hydrogen electrolysis production pathways; 2025+ estimates**
**Source: JEC-WTT, 2019**

### 4.2.4 MATURITY OF FUEL PRODUCTION

The basic advantage of hydrogen is that in principle it can be produced from virtually any primary energy source. Production pathways differ in terms of cost, GHG emissions, energy consumption, and technological maturity. While the exact split of production methods could differ among applications and depend on technology and cost developments, both electrolysis and steam methane reforming/auto thermal reforming with carbon capture and storage (SMR/ATR with CCS) will most likely play key roles in the future. Electrolysis could provide the sector coupling mechanism required for the integration of renewables. Electrolysers are usually available at small scale (< 1 MW) production, but given the fact that it is a modular technology, different modules can be combined in order to form alkaline systems of several MWs. The biggest commercial alkaline electrolyser module available is in the order of 3 MWs[33]. Both commercial alkaline electrolysis and SMR are considered as mature technologies (TRL 9, CRL 3) (FCH, 2019).

Currently, 48% of the world's hydrogen production is produced by using natural gas and 30% by using coal[34]. Steam reforming of heavier hydrocarbons is also possible but little applied, if at all, in practice because the process equipment is more complex and the potential feedstocks such as LPG or naphtha have a higher alternative value. Existing reformers are mostly large industrial plants but small scale prototypes have been developed. Syngas can also be produced by partial oxidation of a carbonaceous feedstock in the presence of water. This can be applied to a wide range of materials, in particular heavy feedstocks such as oil residues and coal, as well as biomass feeds such as wood. The front end of the process is essentially the same as for the manufacture of synthetic liquid fuels. The synthesis section is replaced by the CO-shift step. Small scale wood gasifiers for electricity production have been developed at the pilot plant stage and could conceivably be adapted for small scale hydrogen production. In these processes and particularly for heavy feedstocks, the bulk of the hydrogen comes from water, the carbon in the feed providing the energy required for splitting the water molecule. Reformers and gasifiers produce $CO_2$ at a single location and, when using oxygen rather than air, in a virtually pure form. Large-scale installations may offer a viable platform for possible $CO_2$ capture and sequestration projects.

Electrolysis represents a small part of the current hydrogen production (4%)[13]. However, in most countries hydrogen production with electrolysis has the potential to be competitive compared to the main alternative technology (SMR with Carbon capture and storage/usage (CCS/U)). Summarising the technology status of electrolysis, it is possible to affirm that alkaline electrolysis (AEL) represents the most mature technology, with the lowest specific investment and maintenance costs. There are manufacturers able to supply AEL with single-stack capacities up to 6 MW. In contrast, the development of proton exchange membrane electrolyser (PEMEL) has been driven very strongly by flexible energy storage application in recent years. PEMEL has entered the MW class and several pilot plants in the MW range up to 6 MW have recently been realised. One example is the development of a 6 MW PEMEL system installed at EnergiePark Mainz, while a 10 MW PEMEL will be installed at Shell’s refinery in Cologne (FCH JU project REFHYNE) (personal communication from Hydrogen Europe). Moreover, a 6 MW PEMEL will be used in the steel making process in Austria (FCH JU project H2FUTURE) (personal communication from Hydrogen Europe). PEMEL offers several advantages compared to AEL with regard to compact design (high current-densities), pressurised operation and flexibility (O’Connell *et al.*, 2018). **Table 4-4** summarises the state of the art on electrolysis.

[33] https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/

[34] http://www.airproducts.com/Industries/Energy/Power/Power-Generation/faqs.aspx

**Table 4-4. Summary of the state of art on electrolysis (own work based on Shell, 2017)**

| **Low temp versus/ high temp membranes** | **Temperature (°C)** | **Electrolyte** | **Efficiency (HHV or LHV)** | **Maturity level (Shell assessment)** |
|---|---|---|---|---|
| **Alkaline Electrolysis** | 60-80 | Potassium hydroxide | 65-82% | Used in industry for last 100 years |
| **Proton Exchange Membrane** | 60-80 | Solid state membrane | 65-78% | Commercially used for medium and small applications (less 300kW)<br><br>Some MW scale already available (Proton, Hydrogenics) |
| **Anion Exchange Membrane** | 60-80 | Polymer membrane | N/A | Commercially available for limited applications |
| **Solid Oxide Electrolysis – high temperature** | 700-900 | Oxide ceramic | 89% HHV | TRL7 |

Wind and photovoltaic electricity can be used to generate the power needed to produce hydrogen while, direct solar energy can also be used to produce hydrogen by thermal splitting of water, but the development of this process is still in its infancy. The Power to Gas concept has the possibility to convert hydrogen into synthetic methane ($CH_4$), via the reaction of the $H_2$ produced with $CO_2$, either as a waste product from biogas plants or from the atmosphere, but the required capture technologies are not yet a mature nor energy efficient option in the current state of development. According to an IEA study (IEA 2017), 1 GTCO2/y would require 300TWh electricity, 6.7 EJ of low temperature heat (possibly waste if available) and significant amounts of water. This Synthetic Natural Gas (SNG) has the same chemical composition as natural gas and biomethane. Additionally, hydrogen can be directly blended with natural gas. Technically, no serious problems are expected with up to 20% hydrogen blends by volume. However, the admissible limits for the blending of hydrogen to natural gas in Europe range from 0% to 12% (H2FCSUPERGEN, 2017).

Concerning the position of Europe, it is considered a technology leader in certain FCH application-areas (non-stationary) but other regions (e.g. Japan and the US) are developing quickly mainly with respect to infrastructures as a result of public intervention and support.

Technological progress has been made by European companies, especially in the transport sector, also due to a good support from projects developed jointly under the European R&D framework programme. The first Fuel Cell and Hydrogen Joint Undertaking (FCH JU) was created in 2008 to promote coordination and collaboration across Europe's FCH sector and accelerate the commercialisation of FCH technologies. This initiative has been extended under Horizon 2020 as FCH 2 JU. Up to now, 56 projects on hydrogen production have been funded with investments of 215 million euros from FCH JU and FCH 2 JU and other sources, including private and national/ regional funding in Horizon 2020 (FCH, 2019).

### 4.2.5 WELL-TO-TANK COSTS

Different ranges of transaction prices for hydrogen have been reported by Glenk and Reichelsteinm, 2019 (and confirmed by industry experts according to the same authors) in relation to the production scale and purity. Prices are in the range of 1.5–2.5 €/kg$H_2$ (corresponding to 13-21 €/GJ and 45-75 €/MWh[35]) for large-scale supply, up to 3.0–4.0 €/kg$H_2$ (25-33 €/GJ and 90-120 €/MWh using same conversion factors) for medium-scale and above 4.0 €/kg$H_2$ for small-scale supply. However, these prices appear to refer to hydrogen produced via reforming, whereas hydrogen produced via electrolysis would have higher prices.

Production costs of hydrogen produced from different technologies have been estimated by Bolat and Thiel (2014) considering 2012 as reference year. They concluded that biomass steam reforming (SR) and steam methane reforming (SMR) were the most cost-effective options for hydrogen production. Electrolysis (considering EU electricity price in 2012) and biomass gasification showed relatively high costs on the basis of their calculations. This is still true today; according to Hydrogen Europe, hydrogen produced by SMR is cheaper than hydrogen produced via water electrolysis.

Cost of hydrogen produced from power mainly depend on the price of electricity that may vary in function of local grid bottlenecks and renewable energy sources curtailment. Low-cost renewable electricity is currently available in various locations across Europe.

As the prices of renewable electricity decrease and the electrolyser technology[36] matures, the price of renewable hydrogen is expected to reduce. A recent study (Glenk and Reichelsteinm, 2019) models the perspective of an investor who considers a hybrid energy system that combines renewable power (from wind) with a power to hydrogen facility (efficiently sized) in Germany. The study shows that, under specific conditions, renewable hydrogen could already reach production costs of 3.23 €/kg$H_2$[37] and be considered competitive in niche applications, although not yet for industrial-scale.

According to Hydrogen Europe, the current production cost range of hydrogen is between below 5 to 10 €/kg$H_2$ at the nozzle, depending on where the hydrogen is produced and the volume. The main driver to the hydrogen production cost is the electricity or gas price; other key drivers include the proximity to a chemical industry[38], or to a wind farm[39] (personal communication by Hydrogen Europe, 2019).

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[35] The conversions are based on LHV for hydrogen: 120 MJ/kg and 0.03 kg/kWh (JEC WTT, 2014).

[36] A recent study from IRENA, 2018a provides an overview of the different electrolysers used for hydrogen production and their impact on the cost of hydrogen production.

[37] Glenk and Reichelsteinm, 2019: the model takes into account the advantage of real-time fluctuations in electricity prices and intermittent renewable power generation. The authors also assume that the current feed-in premium will be credited as an equivalent production premium (this premium is currently paid only for renewable electricity fed into the grid).

[38] For example, chlor-alkali where hydrogen is a by-product that can be vented, or refineries/ammonia plant where methane is cracked into hydrogen and $CO_2$ (personal communication by Hydrogen Europe, 2019).

[39] Renewable hydrogen using electrolysis, helps integrate more renewables into the system (personal communication by Hydrogen Europe, 2019).

### 4.2.6 POTENTIAL CAPACITY AND ACTUAL PRODUCTION

Hydrogen is already produced in significant quantities today mostly for industrial and refinery purposes. The global demand for hydrogen in 2015 was 325 TWh of which 65% represents the demand of the chemical industry (e.g. production of ammonia, polymers, resins) (IRENA, 2018a). Oil refineries are also large hydrogen consumers for hydrodesulphurisation of various streams such as gasoil and heavy oil conversion processes accounting for 25% of the global $H_2$ demand (IRENA, 2018a). However, for the use of hydrogen in fuel cells the hydrogen has to be purified to a high level, involving removal of impurities that could impact fuel cell performance. Hydrogen is stored in tanks under very high pressure (up to 700 bars). The installed capacity of thermal power plants is 400 GW. The current global capacity of electrolysers is around 8 GW. If we assume this is distributed by regions proportionally to hydrogen demand (EU demand is 7 out of 50 mtpa globally), EU should have close to 1 GW of installed capacity (Kanellopoulos & Blanco Reano, 2019).

It is hard to make accurate projections for the future capacity. In the case of hydrogen (as a fuel) many factors such as the deployment of the necessary hydrogen infrastructure and distribution of hydrogen also via the gas grid are involved. Therefore, different assumptions regarding the variables of each analysis result in different results. However, the importance of hydrogen as a fuel is reflected in the studies of international organisations which have developed different scenarios for the deployment of hydrogen. According to IRENA (2018b) the potential hydrogen demand in 2050 will be 8 EJ, dedicated mostly to feedstock uses in industry (6.8 EJ) with transport accounting for 0.9 EJ. However, a study for the Hydrogen Council (2017) concerning hydrogen's long-term potential, in the same time horizon predicts that 18 % of global final energy demand could be met by hydrogen, equal to about 78 EJ. In this case, hydrogen in transport would account for 22 EJ. As far as EU is concerned, increased deployment of hydrogen is identified as one of the scenarios assessed in the frame of the long-term strategy of the EU for a climate neutral economy (EC, 2018b). In the aforementioned scenario the hydrogen use in final energy demand in the EU in 2050 would account for 133 Mtoe whereas in the baseline scenario the respective value would be 6 Mtoe. According to the same study, the hydrogen consumption in transport in 2050 would range from 5.7 to 48.1 Mtoe in the different scenarios.

## 4.3 GASEOUS FUELS (NATURAL GAS AND BIOMETHANE)

### 4.3.1 DEFINITIONS AND GENERAL DESCRIPTION

The use of gaseous fuels, as an alternative to traditional gasoline and diesel in road transport sector, is already an option widely applied in several MSs, while other MSs have decided to limit investments for deploying gaseous fuel. Among this class of alternative fuels, Compressed Natural Gas (CNG) certainly represents the major player. In the medium term, Liquefied Natural Gas (LNG) is expected to significantly contribute. In several MSs, Liquefied Petroleum Gas (LPG), a light part of oil fractionation, is also distributed as car fuels.

CNG, LNG and LPG are today mainly obtained from fossil sources, nevertheless bio-derived alternatives may contribute to greening the transport sector, providing that sufficient feedstock is available.

CNG and LNG are the two technical solutions currently used in the transport sector, as they allow for a significant increase of vehicles operational ranges Therefore, biogas has to be upgraded and the resulting biomethane is compressed in order to be injected into the existing grid or liquefied to be transported. Biomethane can be distributed through the existing widely distributed EU gas grids. Hence biomethane is able to ensure reliability and flexibility to the energy system. As an example, Italy has a well spread gas infrastructure/grid of more than 32,000 km (SNAM, 2014) and numerous connections to other transnational grids; this asset can support biomethane penetration.

Biomethane, either compressed (bio-CNG) or liquefied (bio-LNG), is produced through biogas upgrading or via gasification followed by synthesis (GOBIGAS project). The quality of biomethane is established by the European standard EN 16723-1 for injection into the gas grid, and EN 16723-2 for use as bio-CNG or bio-LNG in road transport.

In the renewable energy and transport sector, biogas and biomethane represent effective strategies to move towards the 2020 targets set by the Renewable Energy Directive (2009/28/EC, RED) as amended by the so-called Indirect Land Use Change (ILUC) Directive (Directive 2015/1513, ILUC), and to the 2030 targets set in the Renewable Energy Directive - recast (2018/2001, RED II). Until 2020, biogas counts towards the target of 20% renewable share of the final energy consumption from renewable sources. The use of biomethane in transport until 2020 can contribute to the target of 10% share of energy from renewable resources in the transport, and to the goal to reduce the average GHG emissions from the production and use of fuels by 6% compared to a 2010 baseline as set in the Fuel Quality Directive (2009/30/EC, FQD).

Between 2021 and 2030, biogas and biomethane will count towards the 32% renewable energy share of the EU energy consumption and towards a sub-target of minimum 14% of the energy consumed in the transport sector (2018/2001, RED II). Specifically for the transport target, 3.5% must come from advanced biofuels produced from feedstocks listed in Part A of Annex IX that includes e.g. feedstock suitable for biomethane production, such as manure and sewage sludge, bio-waste from households and industry, agriculture and forestry residues, algae, and energy crops. Advanced biofuels will be double-counted towards both the 3.5% target and towards the 14% target. The RED II defines sustainability criteria for biofuels used in transport, as well as for solid and gaseous biomass fuels used for power, heating and cooling sectors. The sustainability criteria for the biofuels and bioenergy must be fulfilled to account towards the above-mentioned targets.

An interesting alternative to biogas upgrading is Synthetic Natural Gas (SNG). The scientific and industrial communities seem currently focusing on methanation reaction as a promising technology for the power-to-fuel applications. Nevertheless, the evaluation of its current TRL suggests to lower its potential contribution by 2030. On the other hand, the technology of SNG from biomass gasification, with the exception of the Ambigo (AMBIGO, 2018) project, lacks confidence as regards its profitably. The cancelling of the EU largest project (GoBiGas) can be considered as paradigmatic of the current state of play.

The use of gaseous fuels as an alternative to liquids can lead to advantages in terms of lower pollutant emissions for LDVs and HDVs. In the Blue Corridor project (LNG-BC, 2018) about 90% less emissions of particulate matter (PM) is reported when gas vehicles are used in comparison with their gasoline and diesel counterparts. On the other hand, ultrafine particle emissions can be higher than conventional diesel in natural gas HDVs, at least until newer vehicles of the Euro VI E (EC No 459/2012) standard, that accounts for ultrafine particles in real driving, come to the market.

Recent studies are highlighting that the use of CNG in internal combustion engines can cause an increase of particle emissions below 23 nanometre, which is the current cut-off limit for the measurement of PN (Particle Number) from vehicles. Concerns today exist for solid sub-23 nm PM, that current regulations do not measure (Giechaskiel et al., 2017a). A recent study from the same author (Giechaskiel et al., 2017b) has shown that for heavy-duty engines fuelled with CNG, 23 nm PM seem to increase compared to standard diesel engine.

This is confirmed by other authors (e.g. Distaso, 2018; Khalek, 2018, Hallquist, 2013) and EU funded projects (Downtoten[40], Sureal 23[41]), which measured a significant increase in the number of particles compared to diesel. Despite these studies suggest the need of further research, application of LNG in newly designed engines may limit these ultrafine particles emissions, but this has still to be proven.

According to recent studies (Quiros et al., 2017), HPDI technology has already a TTW reduction benefit of about 15%, in terms of GHG emission, when compared with diesel and further improvements could be achieved by 2030 (i.e. High Efficiency Spark Ignited (HESI)). The actual total GHG benefit however depends also on other factors like the fugitive methane emissions from combustion and tanks, which can drastically lower the TTW advantages of this alternative fuel.

The use of methane and biomethane in transport is not limited to road segment; natural gas use in the maritime and inland waterways systems is rapidly getting momentum. The International Maritime Organisation (IMO) has recently adopted a strategy aiming to at least halve total GHG emissions from shipping by 2050 when compared with 2008 levels, while, at the same time, pursuing efforts towards phasing them out entirely (IMO, 2018). Additionally, the limitations in the Sulphur Emission Control Areas (SECAs), which include most of European coastal waters, require to adopt alternative solutions to current fuels. The utilization of LNG in the maritime sector is expected to contribute to air quality (PM, SOx, NOx), but also regarding $CO_2$ emissions reductions. As reported in the "GHG Intensity of Natural Gas" study from NGVA Thinkstep (Thinkstep, 2019), the shifting from heavy fuel oil (HFO) and marine diesel oil (MDO) to LNG translates into a $CO_2$ emissions reduction by 30% and 26% respectively. On the other end, similarly to CNG, when methane leakages are considered, the real GHG saving of this option could be significantly reduced or even neglected (EC, 2016 and Lehtoranta, et al., 2019).

#### 4.3.2 WELL-TO-TANK GREENHOUSE GAS (GHG) EMISSIONS

In the JEC-WTT (2019) study, fossil derived gaseous fuels are used as benchmark for the performances of the alternative pathways. Organic fraction of municipal solid waste has been considered as a promising feedstock, as it allows for a relevant GHG saving. Another waste stream analysed is the manure, suitable for co-digestion, either in open or closed cycle for digestate. The use of food and feed derived feedstocks, such as maize, is expected to be reduced in the next decade, because of the limits set by RED II. SNG from waste wood also offers potential interesting GHG savings, when compared to the fossil options.

[40] http://www.downtoten.com/project

[41] http://sureal-23.cperi.certh.gr/

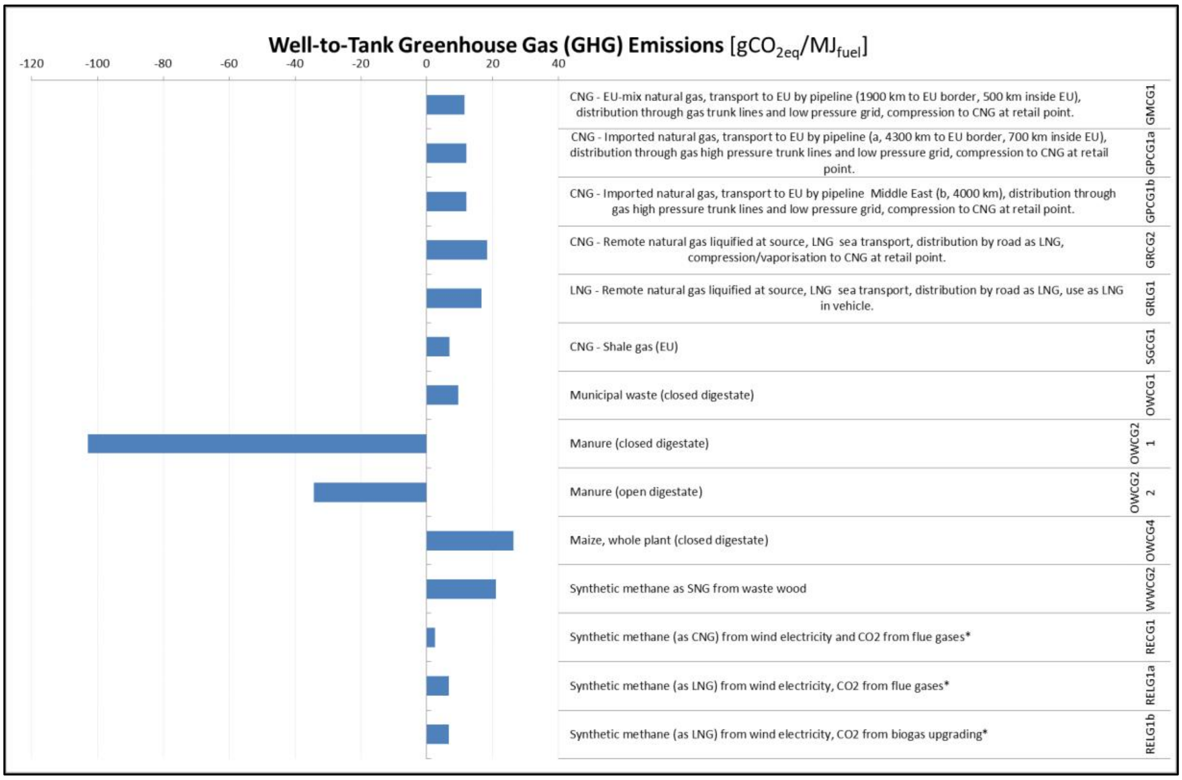


**Figure 4-17. Well-to-tank production emissions performances for selected pathways**
**(* These are e-fuels; more details on e-fuels can be found in section 4.4.3, p. 63)**
**Source: JEC-WTT, 2019**

### 4.3.3 WELL-TO-TANK ENERGY PERFORMANCE

The production of biomethane from biogas requires a significant amount of energy compared to fossil products. This energy demand is mainly due to the production or recovery of the feedstock, its pre-treatment and the upgrade from biogas to biomethane.

Despite the relevant energy demand, high greenhouse gas emission savings can be achieved for all the pathways considered.

SNG does not show significant advantages compared to the other alternative options.

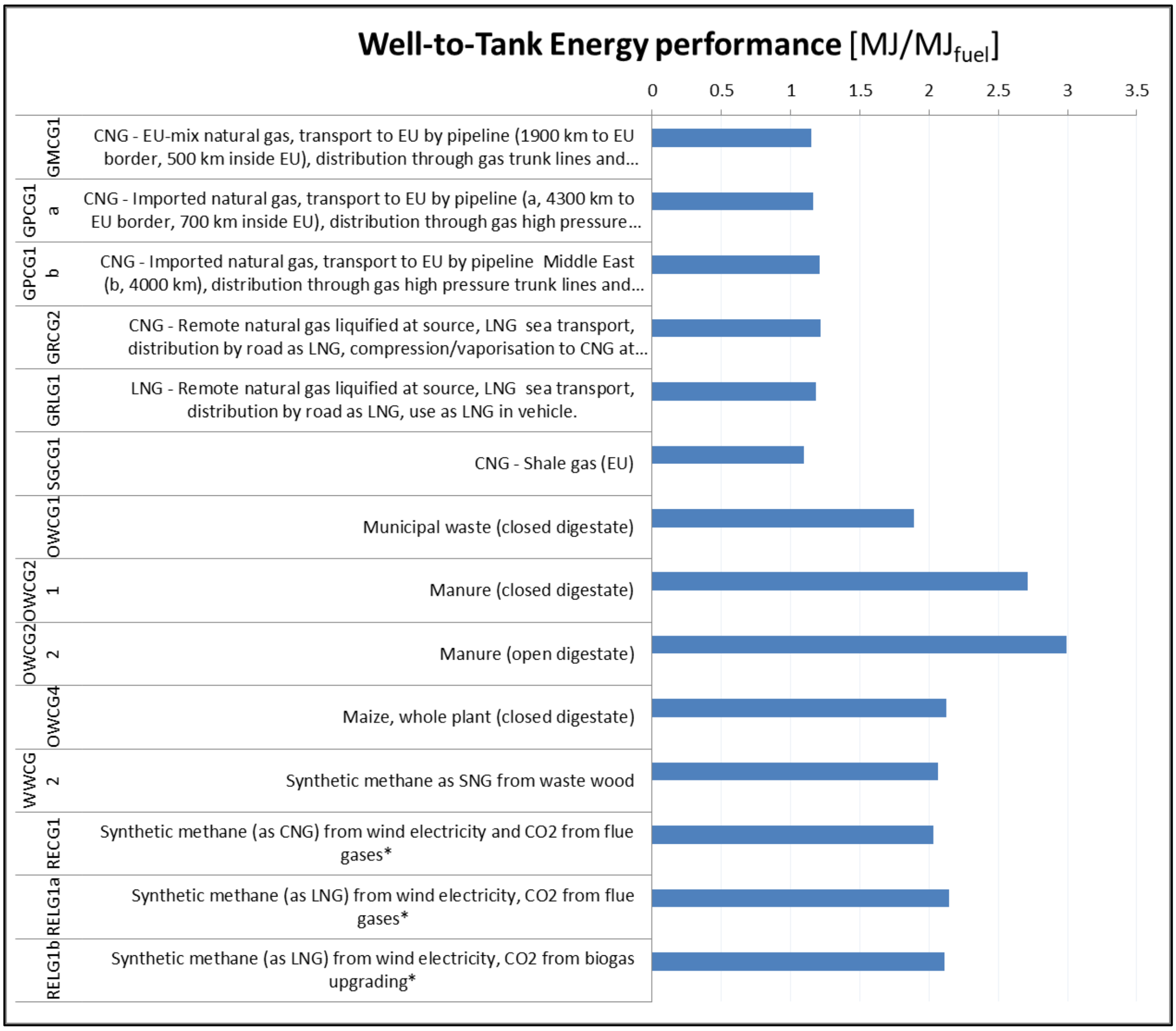


**Figure 4-18. Well-to-tank production energy performances for selected pathways (* These are e-fuels; more details on e-fuels can be found in section 4.4.3, p. 63)**
**Source: JEC-WTT, 2019**

### 4.3.4 MATURITY OF FUEL PRODUCTION

Biogas production from various feedstocks has proven to be a reliable, fully mature technology. Room for innovation is present by utilising advanced feedstock, e.g. organic fraction of municipal solid waste and lignocellulosic streams. Projects such as NER300 VerBIO[42] have shown the techno-economic feasibility of converting lignocellulosic materials into biogas.

Upgrading biomethane from biogas, by its cleaning and separation, has been demonstrated in a large number of plants, nevertheless the economics may improve by scaling-up the size of the initiatives.

Biomethane production from biogas can be defined already at a high TRL, for almost all feedstocks, whereas the CRL (ARENA, 2014) of the biomethane is not so homogeneous: costs for pre-treatment, yields, and other parameters are today limiting the deployment of several pathways, despite the technology appears almost mature.

[42] www.verbio.de

As mentioned in the introduction, the case of SNG is slightly different, as the technology has been proven at large scale but poor economics led to the stop of the most promising initiative/project GoBiGas (BioEnergy International, 2018).

### 4.3.5 WELL-TO-TANK COSTS

An EC report prepared by the Sub Group on Advanced Biofuels (EC SGAB, 2017) identified production costs of biomethane produced from biogas in the range of 40 to 120 €/MWh assuming a range of feedstock prices between 0 and 80 €/MWh. Biomethane produced from waste streams and via biogas could be considered competitive to fossil fuels in certain niche markets, where feedstock prices are assumed to be low (EC SGAB, 2017).

As a comparison, European wholesale price of fossil natural gas corresponds to about 18 €/MWh, in 2017 (converted from 6 USD/mmbtu; **Figure 4-19**) (EC, 2019). It should be noted here that MSs have different taxation policy concerning natural gas. Detailed data on the taxation can be found in the **Appendix to Chapter 4, p. 79**.

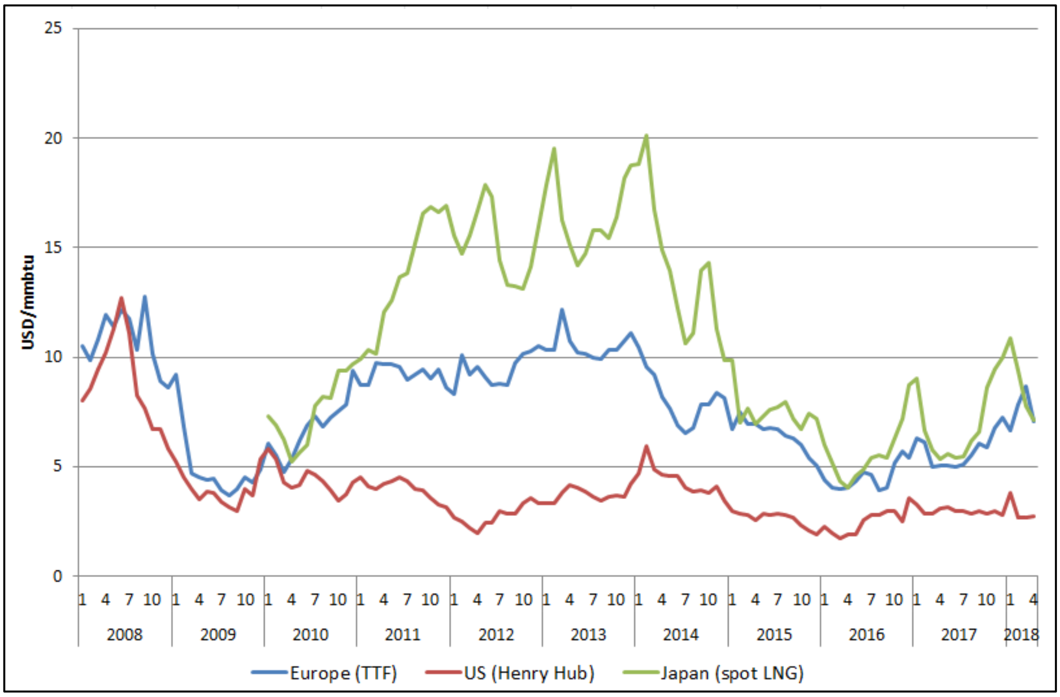


**Figure 4-19. European (US and Japanese) wholesale gas prices. Source: Platts, Thomson Reuters. Reprinted from EC (2019)**

Biomethane production costs have been found to be highly dependent not only on feedstock prices but also on the plant scale, varying from 80 €/MWh for a capacity of 500 $m^3$/y to 120 €/MWh for units with a capacity of around 80 $m^3$/y biomethane (**Figure 4-20**). These figures refer to a total cost of biomethane injection estimated on the basis of a survey performed with several plant operators in a Horizon 2020 project partner countries (France, Germany, UK, Austria) (EC Horizon 2020 project Biosurf, 2016).

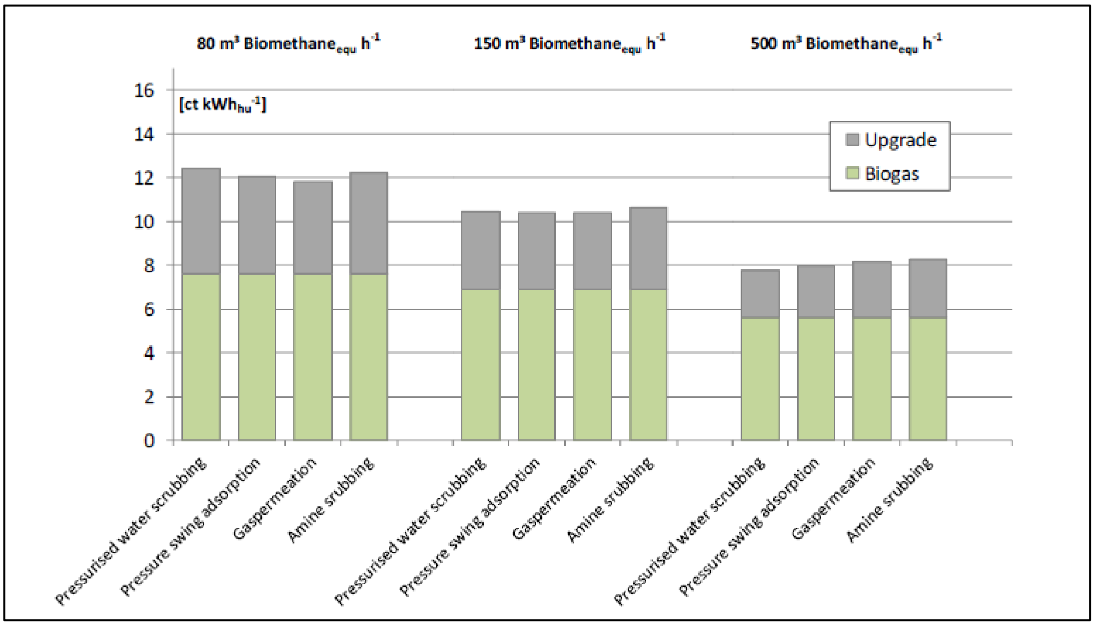


**Figure 4-20. Total production costs of biomethane production in relation to upgrading capacity and processing technique**
**Source: Reprinted from Biosurf, 2016**

Country-specific studies estimated biomethane production costs showing that, under the current market conditions, biomethane needs financial support to be competitive with natural gas; Enea (2017) calculated a range of costs between 80 and 95 €/MWh for France case depending on the different standard production types and related feedstocks, and concluded that the current feed-in tariffs make the sector profitable.

Estimates for biomethane production costs in 2030 were provided in another EC study (EC, 2017). The study considers different biogas deployment scenarios. Scenario 3 (see **Figure 4-21**) assumes for existing plants an increasing share of biogas converted to biomethane; the biomethane, meeting technical specifications, can be injected into the gas grid or converted to bio-CNG or bio-LNG. While scenario 4 assumes an accelerated deployment of the biogas/biomethane production and accelerated innovation rates. Production costs of biomethane were estimated to be higher than the 2014 average EU price for natural gas; in particular, bio-LNG costs are higher because of the extra investments needed for liquefaction.

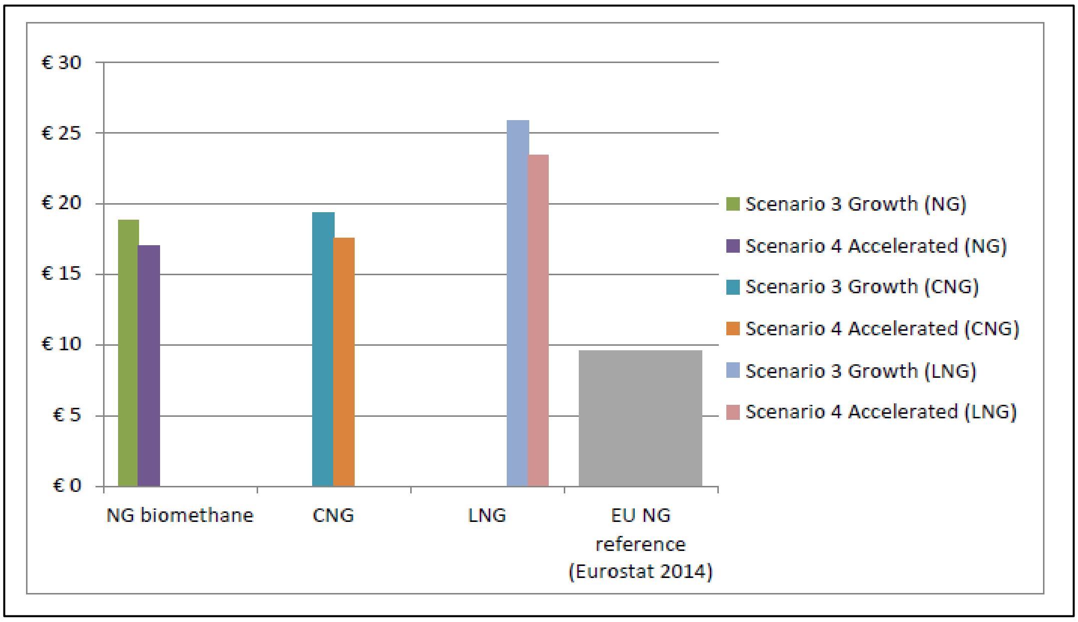


**Figure 4-21. Production costs of biomethane, bio-CNG and bio-LNG in 2030 of new capacity over period 2015-2030 in €/GJ**
**Source: Reprinted from EC, 2017**

### 4.3.6 POTENTIAL CAPACITY AND ACTUAL PRODUCTION

In Europe in 2017, the number of biogas plants has been estimated to over 17,783 for a total installed capacity of about 10 GW; biogas is upgraded in more than 500 plants in 15 countries (EBA, 2018). In comparison, in 2018 total EU natural gas production amounted to 120 billion $m^3/y$ (655 TWh), 8% less than in 2017 (131 billion $m^3/y$) (Market Observatory for Energy DG Energy, q4 2018). Currently, one of the world largest bio-LNG initiatives started the production in 2018 in Norway (LNG-BC, 2018). The biogas upgrading and liquefaction plant, installed close to a paper mill, is able to convert biogas from fishery waste and residual paper mill slurry into liquid bio-LNG fuel, with a capacity of 3,000 $Nm^3/h$ of raw biogas. Target for the initiative is the public transport sector.

The biomethane production is influenced by the biogas composition, which depends on the feedstock and the process used; the methane content ranges from 45 to 60% in the case of landfills gas up to 60-70% for organic waste digesters (Ullah Khan et al., 2017).

JRC has developed a database of the most relevant biomethane initiatives around Europe. The database has been created by collecting and structuring information from various sources, in particular from projects websites, datasets provided by associations, literature, etc. (Hoyer et al., 2016), (Angelidaki et al., 2018), (Deremince, 2017), (EBA, 2018), (RBN, 2018) and (DENA, 2018):results have been published in (Prussi et al., 2019).

Upgrading technologies are mainly based on three techniques: Pressure Swing Adsorption (PSA), Water Scrubbing (WSC) and Chemical Scrubbing (CSC). New biogas plants will likely be equipped with biogas separation units, which may allow costs reduction and a consolidation of the operation plants availability.

Biomethane production from biogas upgrade, based on the data available in JRC database, shows a technical nominal potential of 236,000 $m^3/h$ in the EU-28. In order to calculate the annual production potential, the biogas plant availability (in terms of operational h/y) is a key parameter: it has been proven to be very high and upgrading plants are showing technical availability up to the 96% (Bauer et al., 2013) and thus the annual potential energy output can be calculated considering 8,410 h/y. The resulting annual nominal potential for biomethane can be estimated to 1.9 billion $m^3$/y, equivalent to 71.7 PJ (calculated on higher heating value (HHV)).

These values are in good agreement with EBA (2018) in which the current nominal capacity for EU biomethane has been reported at 250,000 $m^3$/h and with values reported by Natural Gas Vehicles Association (NGVA): 1.94 billion $m^3$/y was reached in 2017.

Based on the calculated potential, a moderate scenario was defined for the market penetration uptake of biomethane in 2030. As presented in **Table 4-5**, biomethane is expected to grow rapidly, as the technologies have already been demonstrated at significant scale and the infrastructure for the product substantially developed; in the scenario proposed, the overall biomethane potential for EU in 2030 accounts for about 18 billion $m^3$/y.

**Table 4-5. Moderate scenario for biomethane from biogas**

| billion $m^3$/y | 2017 | 2020 | 2025 | 2030 |
|---|---|---|---|---|
| Biomethane | 1.9 | 9.0 | 15.5 | 18.0 |

This estimation results more conservative than those from other studies. For example, TU-Delft reported (van Grinsven, 2017) a 2030 production potential of biogas from waste and residues streams ranging from 33.6 – 46.9 billion $m^3$/y, representing 2-4% of the estimated total primary EU energy consumption.

NGVA (NGVA, 2018) estimates an even larger potential at 2030, in the range of 36–51 billion $m^3$/y. The study looks upon availability of sustainable feedstock and power-to-fuel medium term deployment as important parameters; this considers a larger use of animal manure. Moreover, NGVA (2018) considers a significant contribution from technologies which are alternative to fermentation, such as power-to-gas and SNG.

With a longer-term horizon, referring to 2050, Ecofys (van Melle et al., 2018) foresees a potential production in Europe of around 98 billion $m^3$/y. For reference, in 2018 in the EU, the natural gas consumption was 474 billion $m^3$/y, down by 1.8% compared to 2017, when it amounted to 483 billion $m^3$/y (Market Observatory for Energy DG Energy, q4 2018). With an estimated maximum production potential of up to one quarter of current natural gas consumption (including uses in other sectors, such as industry and heating), it is not clear how much biomethane would be available for the transport sector in the long term. Despite this consideration, the long-term climate strategy of the EU foresees specifically for the transport sector a consumption of natural gas between 0.8 to 15.2 Mtoe and a consumption of 0.3-7.4 Mtoe of biomethane depending in the different scenarios (EC, 2018b).

## 4.4 RENEWABLE LIQUID FUELS (INCLUDING CO-PROCESSING)

### 4.4.1 BIO-BASED FUELS

#### 4.4.1.1 DEFINITIONS AND GENERAL DESCRIPTION

This section deals with conventional ethanol, biodiesel as well as advanced biofuels pathways. According to the Future Transport Fuels Group of fuel production experts (FTF, 2011), the main advantages of liquid biofuels are their relatively high energy density and compatibility with existing vehicles and fuel distribution infrastructure, up to certain limits in concentration. Low blends do not need additional infrastructure. Higher blends typically require some adaptations of engine design and adaptations to existing infrastructures. The Group also noted the production of biofuels was limited by the land availability and sustainability considerations (FTF, 2011). For example, Fatty Acid Methyl Esters (FAME) biodiesel is typically blended with fossil diesel. It has physical properties close to those of fossil diesel, but not the same. It is also a non-toxic and biodegradable fuel (ETIP, 2018). Rapeseed, sunflower, soybean, palm oils, used cooking oil (UCO) and animal fat are the most common raw materials used for the production of FAME.

The strict definition of whether or not a biofuel is advanced can vary depending upon the source. Some entities describe a biofuel as advanced based on the *final fuel molecule* produced (by for e.g. considering hydrotreated vegetable oil (HVO) an advanced biofuel compared to FAME biodiesel, as HVO is "fungible" and can be blended into regular fossil diesel at higher blends). While others consider a biofuel is advanced based on the *feedstock* used (for e.g. FAME made from UCO may be considered advanced compared to FAME from rapeseed oil).

In the Renewable Energy Directive - recast (2018/2001, RED II) the term 'Advanced biofuels' refers to biofuels made from a specific list of feedstocks listed in Part A of Annex IX of the Directive. Advanced biofuels can be produced, e.g. from lignocellulosic feedstocks such as straw or bagasse, certain biomass fractions of wastes, or other organic residues; they typically produce comparatively low $CO_2$ emissions when compared to first generation biofuels, and tend to have zero or low ILUC impact. Advanced biofuel pathways are comprised of range of different biological and thermochemical processes for producing transport fuels.

**Figure 4-22** illustrates combinations of feedstocks and conversion technologies to produce advanced biofuels.

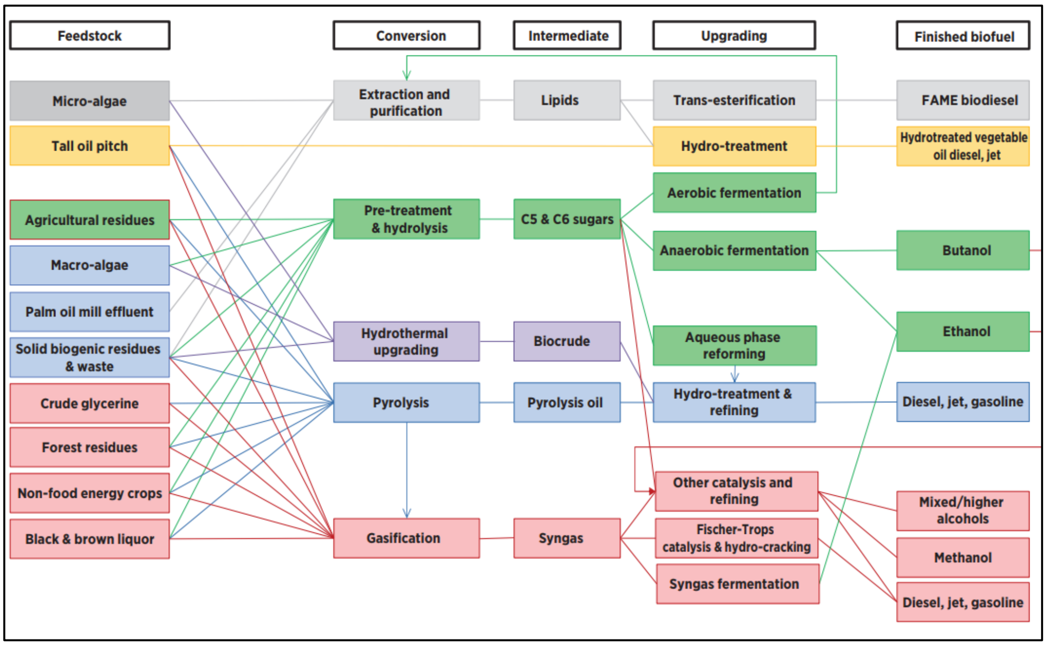


**Figure 4-22. Advanced biofuels pathways**
**Source: Reprinted from SGAB (2017)**

In addition to so called "stand-alone" biofuel processing plants, co-processing is when biomass (most typically a vegetable oil or animal fat) is turned into fuels in a common process with fossil fuels. In the EU vegetable oils are usually added to middle distillates (kerosene and diesel precursors which come from the distilling of crude oil) for a joint hydroprocessing. This uses hydrogen to remove the sulphur from the middle distillates and splits the vegetable oil into hydrocarbon chains (thus making HVO) and propane. Alternatively, vegetable oils can be co-processed with the heaviest liquid fraction from crude oil distillation, so-called vacuum gas oil (VGO), in a fluid catalytic cracker (FCC) but this is much less prevalent currently, and even less-so in the EU as FCC units are more common in the US where they are required to increase the production of gasoline. The dedicated production of HVO, making what are termed "paraffinic fuels," is included in **section 4.4.2, p. 58**. In addition, there is interest in using bio-oils made from biomass materials via pyrolysis or hydrothermal processes, but these remain in a developmental stage.

The new Renewable Energy Directive - recast (2018/2001, RED II)

The use of biofuels in the EU is driven by the Renewable Energy Directive (2009/28/EC, RED), most recently updated in 2018 (2018/2001, RED II). The RED II establishes that the Member States must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. Within the 14% transport sub-target, there is a dedicated target for advanced biofuels produced from feedstocks listed in Part A of Annex IX. These fuels must be supplied at a minimum of 0.2% of transport energy in 2022, 1% in 2025 and increasing to at least 3.5% by 2030. Advanced biofuels will be double-counted towards both the 3.5% target and towards the 14% target (ICCT, 2018) and (EU Science Hub, 2019). Biofuels produced from feedstocks listed in Part B of Annex IX will be capped at 1.7% in 2030 but will also be double counted towards the 14% target.

The RED II defines a series of sustainability and GHG emission criteria that bioliquids used in transport must comply with to be counted towards the overall 14% target and to be eligible for financial support by public authorities. Some of these criteria are the same as in the original RED, while others are new or reformulated. In particular, the RED II introduces sustainability for forestry feedstocks, and GHG criteria for solid and gaseous biomass fuels.

RED II, Annex V and VI

Default GHG emission values and calculation rules are provided in Annex V (for liquid biofuels) and Annex VI (for solid and gaseous biomass for power and heat production) of the RED II. The Commission can revise and update the default values of GHG emissions when technological developments make it necessary. Economic operators have the option to either use default GHG emission values provided in the RED II or to calculate actual values for their pathway. As shown in **Table 4-6**, the mandatory savings thresholds are getting progressively stricter for transport biofuels and electricity, heating and cooling.

**Table 4-6. GHG savings thresholds in the RED II**

| GHG savings thresholds in RED II | | | |
|---|---|---|---|
| Plant operation start date | Transport biofuels | Transport renewable fuels of non-biological origin | Electricity, heating and cooling |
| Before October 2015 | 50% | - | - |
| After October 2015 | 60% | - | - |
| After January 2021 | 65% | 70% | 70% |
| After January 2026 | 65% | 70% | 80% |

In addition to the minimum GHG savings noted in the **Table 4-6**, biofuels, bioliquids and biomass fuels from agricultural biomass must not be produced from raw materials coming from:

- High biodiversity land (as of January 2008), including: primary forests, areas designated for nature protection or for the protection of rare and endangered ecosystems or species, and highly biodiverse grasslands.
- High carbon stock land that changed use after 2008 from wetlands, continuously forested land or other forested areas with trees higher than five meters and canopy cover between 10% and 30%.
- Land that was peatland in January 2008.

<u>RED II, Annex IX</u>

However, biofuels and bioenergy produced from waste and residues as listed in Annex IX only need to comply with the GHG emission sustainability criterion.

The maximum contribution of biofuels produced from food and feed crops will be frozen at 2020 consumption levels plus an additional 1% with a maximum cap of 7% of road and rail transport fuel in each Member State. If the total share of conventional biofuels is less than 1% by 2020 in any Member State, the cap for those countries will still be 2% in 2030. Further, if the cap on food and feed crops in a Member State is less than 7%, the country may reduce the transport target by the same amount (for example, a country with a food and feed crop cap of 5% could set a transport target as low as 12%). "Intermediate crops" such as catch and-cover crops are exempt from this cap. Fuels produced from feedstocks with "high indirect land-use change-risk" will be limited by a more restrictive cap at the 2019 consumption level, and will then be phased out to 0% by 2030 unless specific batches are certified as "low indirect land-use change-risk." "Low indirect land-use change-risk" feedstocks include those that are produced on land that was not previously cultivated (ICCT, 2018).

The RED II also introduces new sustainability criteria for forestry feedstocks and mandates that: harvesting takes place with legal permits, it does not exceed the growth rate of the forest, and that forest regeneration takes place. In addition biofuels (& bioenergy) from forest materials must comply with requirements mirroring the principles in the EU Land Use, Land Use Change and Forestry Regulation (2018/841).

#### 4.4.1.2 WELL-TO-TANK GREENHOUSE GAS (GHG) EMISSIONS

It should be noted that the GHG intensity (GHGi) of the pathways (and also the energy balance), as described in the following section, can be affected by differences in processing, or in assumptions over what is the fate of any co-products. Co-products can arise from a biofuel process such as distiller's dried grains (DDGS) made when ethanol is produced from grains. For more detail on the processing and co-product options which can be involved with biofuel pathways, it is recommended to review the JEC-WTT (2019) from where this data were sourced. For the purposes of this report, the focus is on the most important biofuels currently dominating the EU market, along with considerations of key advanced (or non-food) biofuels which are either now on the market, or are considered close to come to the market and are therefore the subject of considerable R&D to develop them sufficiently and to get them to commercial production.

A further crucial point to note is that the following section describes *direct* emissions from the production of these biofuels. However, *indirect* emissions, or those likely to arise if you divert a feedstock from its current use to instead make fuels, are not included in these GHGi estimations. This effect, in which land outside the immediate fuel production system is required to make more feedstock to replace that needed in its first use, is called Indirect Land Use Change (ILUC). ILUC varies depending on feedstock, and the effect on emissions can be hugely significant for certain feedstocks, such as palm oil. A second area in which additional emissions to those described in the following graphs, that will likely become of concern in the near future, is the effect of intensive biofuel feedstock cultivation on soil carbon stocks. Depleting soil carbon in essence releases additional carbon into the atmosphere. Therefore, it is recommended when comparing the following biofuel GHGi to other fuel pathways, that likely additional emissions arising from these two important areas are considered if an overview assessment is carried out. The new RED II accounts for ILUC by setting a cap on the amount of biofuels which count towards MS renewable energy targets, which are produced from food and feed crops. In addition, it requires Member States to set a specific and gradually decreasing limit for biofuels, bioliquids and biomass fuels produced from food and feed crops for which a significant expansion of the production area into land with high-carbon stock is observed.

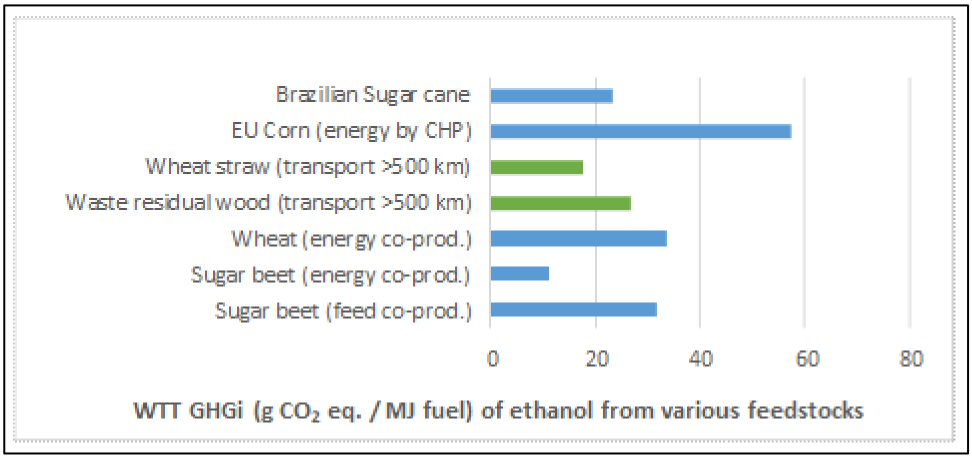


**Figure 4-23. Well-to-tank production emissions performances**
**Note: The green bars represent non-food or non-feed waste-type biodiesels.**
**Source: JEC-WTT,2019**

The WTT GHG emissions for the principal *first-generation* bioethanols in production in the EU are shown in **Figure 4-23**, along with (and highlighted in green) likely emissions for second generation (or advanced) bioethanol pathways. It must be noted the second generation bioethanols are not in production in the EU in any considerable volume.

It can be seen that options are available to lower the GHG emissions for pathways even when using the same starting feedstock. For example, sugar beet (by far the largest used feedstock for bioethanol in the EU (USDA, 2018) can have similar WTT GHG emissions compared to wheat ethanol, but using the beet pulp as fuel and slops for biogas production, both of which are used for co-generation of electricity and heat, helps lower emissions (JEC-WTT, 2019). Please see "Sugar beet (energy co-prod.)" in the previous graph. The GHG emissions balance for other ethanol pathways shows the advantage which advanced ethanol production *could* have: its emissions could be lower than the basic sugar beet and wheat pathways, although it is important to reiterate at time of writing there are still negligible levels of production of these fuels. Although it is not made in the EU and therefore not included above, sugar cane ethanol can also exhibit relatively low emissions (of about 25 g $CO_2$eq/MJ), and this biofuel is made successfully in large volumes most notably in Brazil. Maize ethanol has comparatively poorer GHG performance, with emissions of almost 60 g$CO_2$eq/MJ.

For biodiesels, in a similar tendency to that seen for ethanol, the fuels made from advanced feedstocks (in the case of advanced biodiesel this refers mainly to waste cooking oil and animal fat (tallow) feedstocks) tend to exhibit lower GHG emissions than those coming from crop-based feedstocks. The two principle biodiesel types made in the EU are included on the next graph, namely waste cooking oil and rapeseed oil, which together comprise two-thirds of the total EU feedstock use (USDA, 2018). With no emissions attributed to the *production* of waste feedstocks, the positive effect on emissions when using waste cooking oil can clearly be seen (JEC-WTT, 2019): WTT emissions of about 20% that of the rapeseed oil biodiesel.

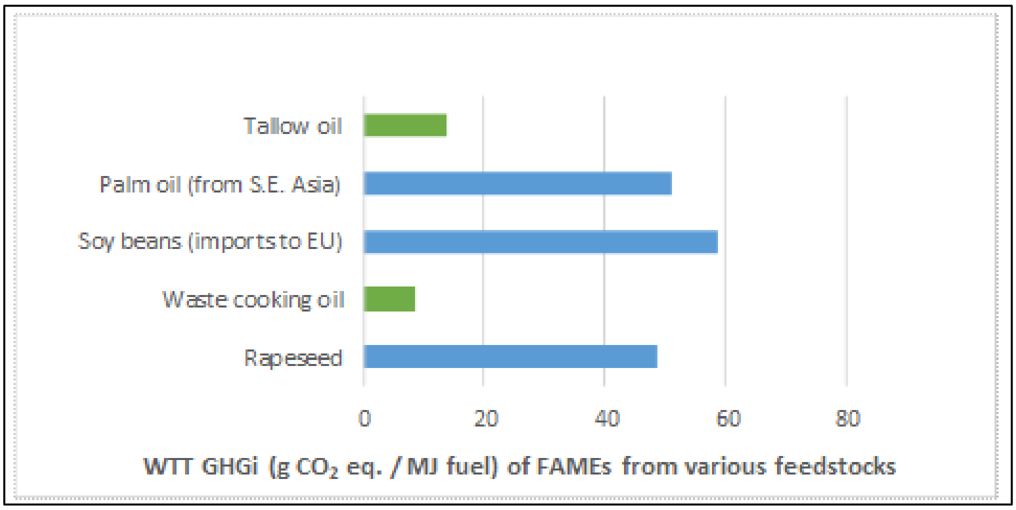


**Figure 4-24. Well-to-tank production emissions performances for selected biodiesel pathways**
**Note: The green bars represent non-food or non-feed waste-type biodiesels**
**Source: JEC-WTT,2019**

### 4.4.1.3 WELL-TO-TANK ENERGY PERFORMANCE

The WTT energy performance of the main bioethanols produced in the EU are shown in **Figure 4-25**Figure 4-25. The results range from just under 2 MJ expended to produce 1 MJ of final fuel for ethanol from sugar beet (and where the co-products are used as energy), to over 3.0 MJ expended for the waste residual wood pathway. Sugar cane ethanol, the principle bio-ethanol made in Brazil, expends just over 3 MJ of energy to make 1 MJ of final fuel (JEC-WTT, 2019). Another bioethanol option which could be of interest for the future is that coming from straw, which expends approximately 2.5 MJ per 1 MJ of final fuel.

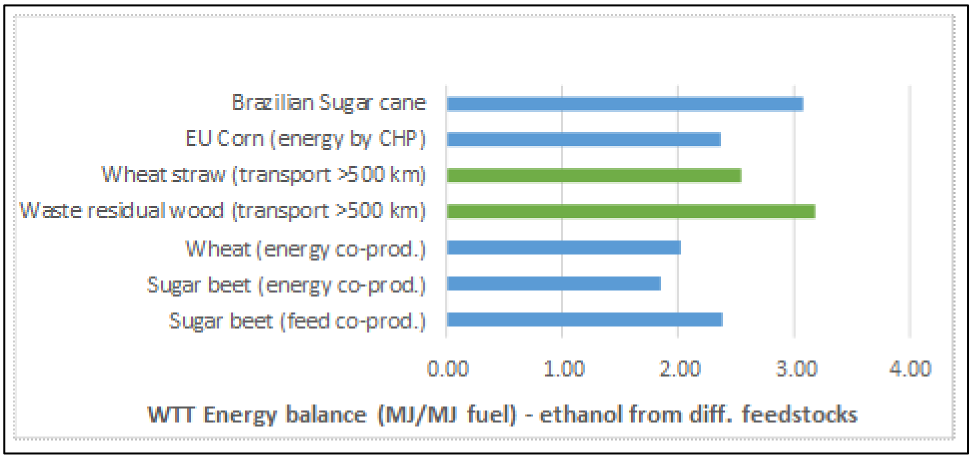


**Figure 4-25. Well-to-tank production energy performances for selected bioethanol pathways**
**Source: JEC-WTT,2019**

For biodiesels, the two main biodiesel feedstocks in the EU are waste cooking oil and rapeseed oil. The rapeseed oil pathway recycles glycerine and meal from the crushed rape seeds to make biogas. Nonetheless, a clear advantage can be seen for biodiesels made from the advanced feedstocks. Waste cooking oil biodiesel uses less than 1.25 MJ energy to make 1 MJ of final fuel, while the other principle EU-made biodiesel from rapeseed oil uses over 2 MJ to make 1 MJ of final fuel. Also shown in **Figure 4-26**, waste tallow (i.e. animal fat), which can principally only be used as a fuel due to strict animal by-product regulations in the EU, also shows a good overall energy balance. For comparison, and while made in comparatively significant volumes in the EU when considered alongside rapeseed and used cooking oil biodiesels, but soybean oil pathways require over 3.5 MJ of energy inputs to make 1 MJ of final fuel.

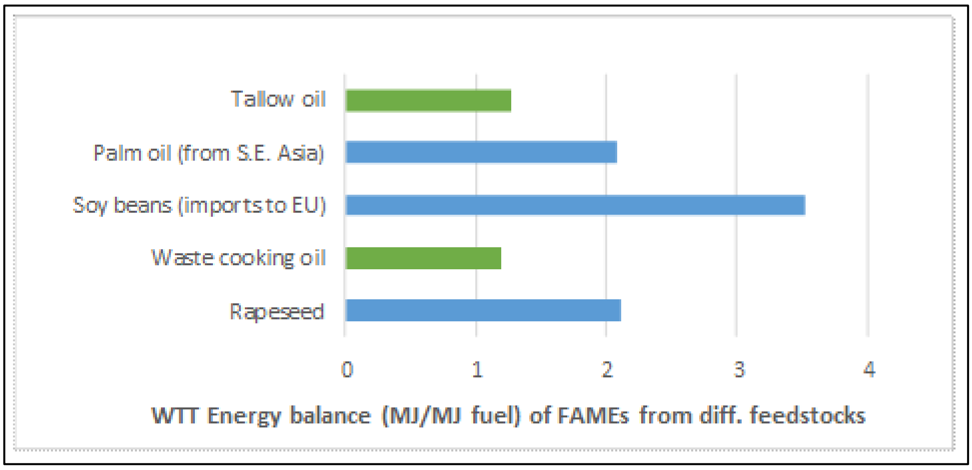


**Figure 4-26. Well-to-tank production energy performances for selected biodiesel pathways**
**Source: JEC-WTT, 2019**

#### 4.4.1.4 MATURITY OF FUEL PRODUCTION

Ethanol is a well-established substitute for gasoline in spark-ignition engines. As seen in **Figure 4-23** it can be produced from a variety of crops and other biomass resources. It has been used for many years in several parts of the world, occasionally neat, but more often in various blending ratios with conventional gasoline. The European EN228 gasoline specification allows blending of ethanol up to 10 vol%. Personal communication by Enerkem (2019) suggests most cars may also be able to use up to 20 vol% ethanol in gasoline, although the European Automobile Manufacturers Association (ACEA, 2018) expressed reservations on this regard, even for 10 vol% ethanol. Ethanol from first-generation feedstocks such as sugar cane or sugar beet can be considered a mature technology. However, ethanol from straw, so-called second generation ethanol, is still only produced in minor volumes. Personal communication from the European renewable ethanol association ePURE (2019) are positive toward the technology, suggesting cellulosic ethanol production is at TRL 8-9 and thus is now "ready for commercialisation". But they note production to-date remains marginal. Clariant (personal communication, 2019), a prominent company in the field of cellulosic ethanol production, having had a pilot plant running since 2009 and moving to large-scale commercial production, appear more reserved indicating that in the next 1 – 2 years the industry will be at TRL 8. Caution on future production estimates is certainly recommended for this technology for purely cellulosic feedstocks. Although it holds potential for the future, reports of relatively large-scale demonstration cellulosic ethanol facilities (4,000 tonnes/annum ethanol) being "fully operational" date back at least 10 years (ETIP Bioenergy, 2019), but production remains still negligible. ArtFuels (personal communication 2019) indicate a global production *capacity* of less than 1 million tonnes, and they expect a further boost in capacities from a "second wave of installations in a few years", especially in India. Their current capacity estimation appears on the high side of estimates, considering, for example, the approximately 0.05 million tonnes capacity in the EU presently (USDA, 2018).

Biodiesel is produced by reacting a vegetable oil with an alcohol, usually methanol, to give a so-called Fatty Acid Methyl Ester (FAME). This process splits the tri-glyceride molecule, separating glycerine as a co-product and producing a fuel which boils at around 350°C and is a suitable diesel fuel. FAME biodiesel can be used without problems in standard diesel engines in blends up to 7% with conventional diesel fuel as allowed by the EN590 diesel fuel specification (JEC-WTW, 2014), and higher blends such as B20 or B30 can be found in tightly controlled (captive) fleets. The technology can be considered fully mature (TRL 9), with production in the EU increasing from over 1,000,000 tonnes/year in 2004 to more than 12,000,000 tonnes/year by 2016 (EBB, 2019). Production of FAME from advanced or waste feedstocks (i.e. UCO and waste tallows) can also be considered technologically mature (TRL 9). The USDA (2019) estimate approximately 3,500,000 tonnes of these fuels were made in the EU in 2018. As an alternative, vegetable oils can be hydrotreated to remove double bonds and oxygen from the molecule, yielding a paraffinic fuel similar in properties to Fischer-Tropsch diesel (please see the synthetic and paraffinic fuels **section 4.4.2, p. 58**).

#### 4.4.1.5 WELL-TO-TANK COSTS

The WTT biofuel cost analysis quantified the production costs of the main conventional and advanced biofuels produced in Europe for the time period 2014-2016 (JEC-WTT, 2019). The production cost of conventional ethanol (produced from sugar beet, wheat and maize) is estimated to be in the range of 15-22 €/GJ (compared to 12 €/GJ of gasoline for the same time period). While biodiesel production cost is estimated to be around 16-21 €/GJ considering crops as feedstocks (rapeseed, sunflower, soya and palm oil) but also including wastes feedstocks (UCO and tallow oil) (in contrast with the 11 €/GJ of conventional diesel for the same time period). Those costs are consistent with market prices of biofuels: ethanol price is about 23 €/GJ (in 2014-2015), while for biodiesels, prices range from 20 to 24 €/GJ (average for 2014-2016, (JEC-WTT, 2019)).

Looking at the different cost components, the cost of feedstock plays the major role on the total production cost for first generation biofuel plants. This makes the economics of production heavily dependent on the feedstock price changes on the global markets (JEC-WTT, 2019).

Several recent studies investigated production costs of advanced biofuels technologies, including the (JEC-WTT, 2019) cost analysis mentioned above, the 2017 EC report by SGAB, a 2016 report from the International Renewable Energy Agency (IRENA), and a report from E4Tech published in December 2017 (prepared for ePURE and other stakeholders). The production costs of cellulosic ethanol are reported in those studies and their results are shown in **Table 4-7**. The different cost ranges depend on the different assumptions on the various components of the cost calculations related, in particular to the cost of feedstock, scale of the plants and capital cost[43]. The types of feedstocks that are used in advanced biofuel plants have usually regional prices and they are traded locally. Their price therefore depends on the local amount of production and their competing uses (E4Tech, 2017). The ranges of production costs of cellulosic ethanol found in the (EC SGAB, 2017) and (E4Tech, 2017) seem to be lower compared to the other two sources. But generally, the reported production costs for cellulosic ethanol appear to be substantially higher compared to conventional ethanol and biodiesel prices, and far from being competitive with fossil fuel.

[43] For further details on the specific assumptions and methodology used, please refer to the studies.

**Table 4-7. Production costs of cellulosic ethanol from various sources**

| €/GJ | JEC-WTT, 2019 | EC SGAB, 2017[1] | IRENA, 2016[2] | E4Tech, 2017 |
|---|---|---|---|---|
| Cellulosic ethanol from agricultural residues or woody biomass | 45-53<br>[cost of feedstock: 19-22 €/GJ fuel] | 24-43<br>[cost of feedstock: 8-16 €/GJ fuel[3]] | 31-55<br>[cost of feedstock: 15-27 €/GJ fuel] | 35-38<br>[cost of feedstock: 10 €/GJ fuel[4]] |

[1] Data extracted from Figure 18 of the EC SGAB report.
[2] Data from original source (reported for first commercial plants) converted from $ to € assuming 2015 exchange rate.
[3] Calculated using the typical biomass price reported in Figure 18 of the EC SGAB report (10-20 €/MWh) and assuming E4Tech's ethanol yield (E4Tech, 2017) and LHV of wheat straw from (JEC-WTT, 2014).
[4] Converted from original figure of 60 €/dry tonne and assuming average yield of ethanol to be 4.8 tonnes biomass/tonne ethanol reported in E4Tech, 2017.

Advanced biofuels technologies that are at earlier stage of commercialisation, such as cellulosic ethanol, are still facing significant technology challenges (low maturity of the technology) and showing significant capital and operational costs due to the complexity of the conversion processes. But they have potential for future costs reduction (JEC-WTT, 2019).

Regarding variable costs, a cellulosic ethanol producer reported that the cost of feedstock can be considered as the major contributing factor depending on its accessibility, transportation costs and also the alternative use (personal communication by Clariant, 2019). Enzymes are also a relevant cost component. An integrated process for enzyme production could result in a significant reduction of production costs and ensure independence from supply shortages and price volatility. According to Clariant, a number of factors can contribute to costs reduction in the future (up to 20-35% reduction over time) such as:

- Reduction of quantity as well as cost of consumables (e.g. chemicals, yeast, biocatalysts);
- Reduction cost of labour required for operation (i.e. more efficient and more automated plant over time) and/or costs associated with engineering and installation;
- Reduction of equipment costs (e.g. due to higher volumes of production, prefabrication, robotic welding);
- Increase of plant size;
- Yield improvement (e.g. debottlenecking, technology improvements).

It is noteworthy that the Commission assessed the costs of the transition from conventional biofuels to advanced biofuels in the framework of an impact assessment accompanying the RED II proposal. According to modelling results, average annual investments in bio-refineries for advanced biofuels (in addition to investments already necessary in the reference case) would range from 0.1 billion to 0.9 billion (annual averages in the period 2021-30)[44].

#### 4.4.1.6 POTENTIAL CAPACITY AND ACTUAL PRODUCTION

In the EU approximately 4.3 million tonnes of fuel ethanol was produced in 2018, from an EU production capacity of 5.4 million tonnes (see **Table 4-8**). In other words, the EU's fuel ethanol industry appears to be operating at just under 80% of their total capacity (USDA, 2018).

**Table 4-8. Production and capacity of main EU biofuels**
**Source: Source: (USDA, 2018)**
**HVO (highlighted in grey) is covered in the paraffinic fuel section 4.4.2, p. 58.**

| | Ethanol | FAME biodiesel | HVO |
|---|---|---|---|
| Current EU Production (million tonnes) | 4.3 | 9.7 | 2.2 |
| Current EU Capacity (million tonnes) | 5.4 | 18.7 | 3.9 |
| % Utilisation | 80% | 52% | 57% |

Regarding FAME biodiesel, approximately 9.7 million tonnes were produced in the EU in 2018. With a production capacity of about 18.7 million tonnes for FAME, the industry is operating at about 52% capacity (USDA, 2018), meaning there exists room for greater levels of production, if enough sustainable feedstock could be sourced. However concerns over the indirect effects of the use of large amounts of food and feed materials for biofuels led the EU to limit the amount of these feedstocks which can be used to make biofuels in the EU (2018/2001, RED II). Art Fuels (personal communication, 2019) predict growth in all biofuel production in particular outside of Europe. More detailed statistics on EU biofuel production and capacities is available directly from the industry associations (EBB, 2019, and ePURE, 2017). In the long term, the availability of sustainable feedstocks may represent a limiting factor to production expansion.

Biofuel consumption

Data on biofuels consumed in the EU (therefore also including the effect of biofuel trade in and out of the EU) is described in the annual Renewable Energy Progress Report by the EC. In 2016, the EU consumption of sustainable biofuels amounted to 13,840 ktoe. Of this, 11,083 ktoe (80%) was biodiesel and 2,620 ktoe (19%) bioethanol. Most (64%) biodiesel consumed in the EU in 2016 was produced from EU feedstocks, mainly rapeseed (38%), UCO (13%), animal fat (8%) and tall oil (2.5%). 19.6% came from Indonesian and Malaysian palm oil (respectively 13.3% and 6.3%). Ethanol consumed in the EU is made also mainly from EU feedstocks (65%), including wheat (25%), maize (22%), sugar beet (17%) and a minor amount (less than 1%) from cellulosic ethanol. Ethanol-based feedstock from outside the EU includes corn (16.4%), wheat (2.9%) and sugar cane (2.9%) from various parts. More info available in (Renewable Energy Progress Report, EC, 2019) (see also **section 5.3.1, p. 173**).

According to the long-term strategy of the EU for a climate neutral economy (EC, 2018b), consumption of liquid biofuels (including synthetic and paraffinic fuels

[44] Answer given by Mr Arias Cañete on behalf of the European Commission (Question reference: E-003160/2018).

discussed in the following section) in 2050 is expected to be in the range of 15.7 to 48.6 Mtoe in the baseline and different scenarios.

### 4.4.2 SYNTHETIC AND PARAFFINIC FUELS, INCLUDING HVO

#### 4.4.2.1 DEFINITIONS AND GENERAL DESCRIPTION

Synthetic fuel or synfuel is a liquid fuel, or sometimes gaseous fuel, obtained from syngas, a mixture of carbon monoxide and hydrogen, in which the syngas was derived from gasification of solid feedstocks such as coal (or biomass) or by reforming natural gas. Paraffinic fuels are made through the Fischer-Tropsch process from natural gas (GTL) (or from biomass, known as BTL), or through a hydrotreatment process from vegetable oils or animal fats (HVO). Bio-based fuels have been principally covered in the **section 4.4.1, p. 48**, but this section will include biofuels such as HVOs, Bio-DME, BTL and bio-methanol. These can also be classified as paraffinic or synthetic fuels due to their production processes. In addition, we discuss other synthetic and paraffinic fuels, which come from fossil feedstocks. In this respect, the sections of the report concerning biofuels and synthetic fuels could present some overlapping when addressing synthetic or paraffinic fuels produced from biomass.

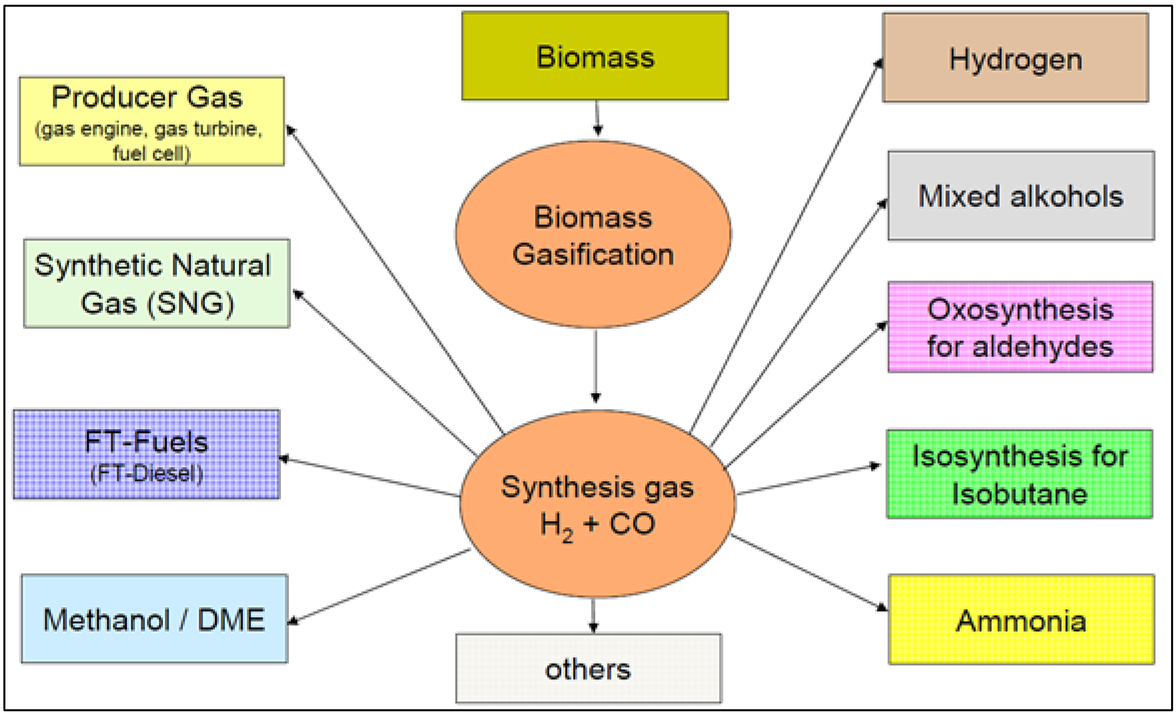


**Figure 4-27. Sample range of synthetic fuels**
**Note: The above schematic considers biomass as the feedstock, but the feedstocks could also be of fossil origin.**
**Source: Rauch, 2013**

More specifically, the other synthetic fuels considered are Fischer-Tropsch or syndiesel, dimethyl ether (DME), and methanol. The manufacturing of these synthetic fuels relies on steam reforming (which thus requires a water input to the process) or partial oxidation of a fossil hydrocarbon or organic feedstock to produce syngas, which is, in turn, converted into the desired fuel using the appropriate process. In other words, the fuel is reduced to smaller molecular components (CO, $H_2$) from which new products can be built (JEC-WTT, 2014).

Natural gas is the most likely feedstock for these processes because of its widespread availability, particularly as stranded (and therefore cheap) gas in remote locations and also because of the relative simplicity of the steam reforming and/or partial oxidation process compared to heavier feedstocks. Coal can also be used although the complexity and cost of the required plant are much higher. Both coal and gas lend themselves to large-scale facilities which are beneficial in terms of cost; however, they do not offer substantial emissions reduction. Cost considerations also mean that these facilities tend to be located near to the natural resource, to avoid or minimise shipping of raw materials. Biomass, most likely in the form of wood or perennial grasses, is also being actively considered as a source of such fuels (JEC-WTT, 2014). Finally, e-gas is also considered as a potential feedstock.

#### 4.4.2.2 WELL-TO-TANK GREENHOUSE GAS (GHG) EMISSIONS

The GHG intensities for a range of synthetic and paraffinic fuels follows. Using fossil feedstocks to make fuels produces higher emissions compared to using either residual wood (or indeed renewable electricity, at which point the fuel could be considered an e-fuel). Coal without carbon capture and storage (CCS), unsurprisingly, results in extremely high emissions of about 125g $CO_2$eq/MJ. When considering these results, it is worth noting three points:

(i) The WTT emissions of any of the following fuels which have been made from fossil feedstocks would incur further emissions during the combustion of the fuel of approximately 60-70 g$CO_2$eq/MJ depending on precisely which fuel.

(ii) This is not the case for fuels made using biomass feedstocks, as the plant they came from is assumed to have absorbed the same amount of $CO_2$ during its growth that is emitted during combustion.

(iii) And for reference, the fossil fuel comparator for regular fossil petrol and diesel in the RED II is 94 g$CO_2$eq/MJ, but this includes combustion emissions.

As shown in **Figure 4-28**, paraffinic fuels made from vegetable oils exhibit GHGi below the fossil fuel comparator, and the two fuels produced from the waste feedstocks (waste cooking oil, and residual wood) exhibits noticeably lower emissions compared to that from the new vegetable oil. General GHGi trends for the full range of vegetable oils and fats and animal fat feedstocks will follow closely those of FAME biodiesel (see **Figure 4-24**). It is noted these GHGi do not consider indirect effects or soil carbon effects for HVO's made using new vegetable oils.

For the other synthetic fuels, the GHG picture is more favourable for natural gas compared to coal as the energy involved is less carbon-intensive (the GTL process is in effect a carbon concentration process and a large fraction of the expended energy is in the form of hydrogen). It is however always worse or at best equal to that of fossil diesel, unless CCS is used.

Including combustion, GHG emissions for GTL are slightly higher than for conventional diesel. In the most favourable conditions (lower end of confidence range), where economic conditions allow the most efficient projected processing options to be used, their emissions have the potential to match those of diesel (JEC WTT v4a, 2014).

Using coal results in even higher GHG emissions. Without CCS, DME from coal has a higher GHGi than fossil diesel or DME from natural gas, reflecting both the higher energy inputs and the high C/H ratio of coal. For wood, GHG emissions are mainly incurred for wood growing and collection/transport, but in this case the wood pathway considered uses residual wood, helping the overall GHG emission remain very low (JEC WTT v4a, 2014).

CCS offers an opportunity for substantial reductions of $CO_2$ emissions. For GTL the reduction potential is in the order of 10% turning the product from having a similar GHGi to fossil diesel to slightly lower. For CTL, the reduction is much more dramatic (about 50%) because of the much larger amount of $CO_2$ emitted during the CTL process. With CCS, emissions for CTL are about 20% higher than for fossil diesel from crude oil. The CCS data were based on technical studies and are indicative, (JEC WTT v4a, 2014) notes as the processes develop, higher $CO_2$ recovery may be possible, although progress to-date remains limited. Interest in CTL with CCS remains high, especially in China, however a recent review of this technology indicates it remains unfeasible unless a high carbon price could be somehow ensured (Yao et al., 2019). For DME, it remains a fuel not in production in significant amounts when compared to for example HVO, but could theoretically be produced with low overall emissions if waste residual wood was used as the feedstock. Indeed, excess renewable electricity could be used also, thus making it an e-fuel (please see **section 4.4.3, p. 63** for more information on such e-fuels).

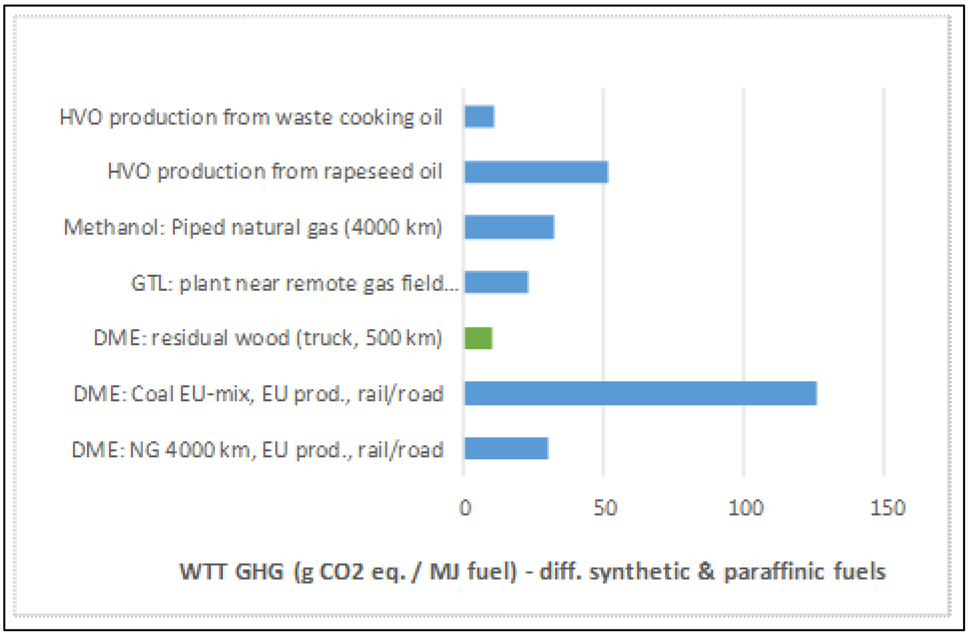


**Figure 4-28. Well-to-tank production emissions performances for various synthetic and paraffinic fuels**
**Source: JEC-WTT, 2019**

#### 4.4.2.3 WELL-TO-TANK ENERGY PERFORMANCE

Regarding WTT energy performance of synthetic pathways, it helps to consider the various pathways in broad groups. For DME pathways, the energy expended to make 1 MJ of final fuel ranges from about 1.7 MJ (using remote sources of natural gas) to almost 2 MJ (using coal, or coal to liquid). Waste wood to DME uses more energy than either of these fossil feedstocks (JEC-WTT, 2019). Similar trends would be seen if other final fuel molecules would be made from these feedstocks (for example, syndiesel or methanol pathways) (JEC-WTT v4a, 2014).

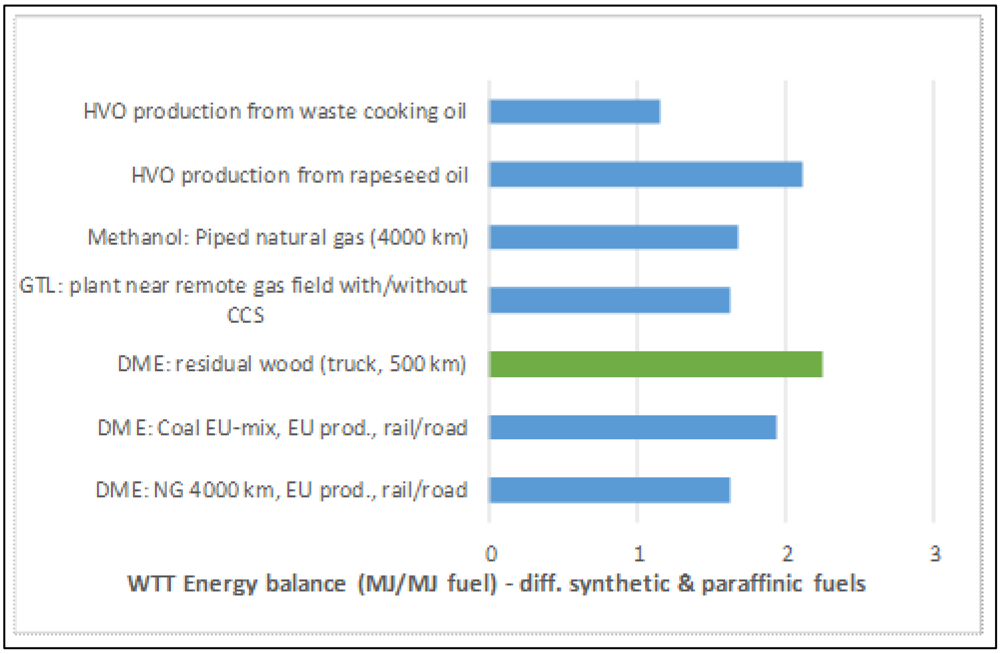


**Figure 4-29. Well-to-tank production energy performances for various synthetic and paraffinic fuels**
**Source: JEC-WTT, 2019**

#### 4.4.2.4 MATURITY OF FUEL PRODUCTION

GTL is technically well-established although the economics have, in the past, not been sufficiently favourable for large-scale development to occur. This has been changing more recently with a combination of technological advances and more favourable economics and a number of large-scale plants have been built. All such plants are located near a major gas field usually where the only alternative for bringing gas to market would be LNG. In such a situation in theory any captured $CO_2$ could be reinjected into the gas field (JEC WTW v4a, 2014).

Coal gasification is a well understood process that can be coupled to FT (Fischer-Tropsch) synthesis to deliver products very similar to GTL. But there are very few plants in operation today (JEC WTW v4a, 2014).

DME is synthesised from syngas and can therefore be produced from a range of feedstocks. The synthesis process is very similar to that of methanol and has a similar efficiency. The most likely feedstock in the short term is natural gas but coal or wood can also be envisaged. Should DME become a major fuel, future plants would be most likely to be similar to GTL plants i.e. large and located near a major gas field, however a dedicated distribution network and dedicated vehicles would be required (JEC WTW v4a, 2014). HVO pathways, at least from the feedstocks considered (please see **Figure 4-28**), represent fully mature pathways, although the search for other interesting waste-type lignocellulosic feedstocks which could be liquefied and hydrotreated into final fuels continues. Pathways attempting to use these comparatively less developed feedstocks certainly have a lower maturity level.

#### 4.4.2.5 WELL-TO-TANK COSTS

Production costs of synthetic fuels such as FT-diesel, methanol and dimethyl ether (DME) produced from woody biomass are estimated by the same studies as mentioned in **section 4.4.1.5, p. 55** (i.e. (JEC-WTT, 2019); (EC SGAB, 2017); (IRENA, 2016); (E4Tech, 2017)). The results are shown in **Table 4-9**. The different cost ranges depend on the different assumptions on the various components of the cost calculations related, in particular to the cost of feedstock, scale of the plants and capital cost[45]. As for cellulosic ethanol, the ranges of production costs found in the EC SGAB report appear to be lower compared to the other two sources. But generally, production costs are substantially higher than other biofuels and far from being competitive with fossil fuels.

**Table 4-9. Production costs of some synthetic fuels from various sources**

| €/GJ | JEC-WTT, 2019 | EC SGAB, 2017[1] | IRENA, 2016[2] |
|---|---|---|---|
| FT synthesis from woody biomass | 43-44<br>[cost of feedstock: 16 €/GJ fuel] | 25-38<br>[cost of feedstock: 6-12 €/GJ fuel[3]] | 28-48<br>[cost of feedstock:14-22 €/GJ fuel] |
| Methanol & Dimethyl Ether (DME) from woody biomass | 35-36<br>[cost of feedstock: 15 €/GJ fuel] | 19-25<br>[cost of feedstock: 5-11 €/GJ fuel[3]] | - |

[1] Data extracted from Figure 18 of the EC SGAB report.
[2] Data from original source (reported for first commercial plants) converted from $ to € assuming 2015 exchange rate.
[3] Both figures calculated using the typical biomass price reported in Figure 18 of the EC SGAB report (10-20 €/MWh) and assuming the yield of FT-diesel and DME reported in JEC-WTT, 2014.

Production cost for hydrotreated vegetable oil (HVO) pathways have been estimated in the (JEC-WTT, 2019) costs report and in the (EC SGAB, 2017) report. Both sources show similar ranges of production costs. (JEC-WTT, 2019) estimated for the time period 2014-2016 production costs in the range of 17 and 24 €/GJ considering vegetable oils (rapeseed, sunflower, soya and palm oil) but also including wastes feedstocks (UCO and tallow oil).

(EC SGAB, 2017) report costs between 14 and 25 €/GJ depending on the cost of feedstocks used for the fuel production.

Those costs are similar to the cost of conventional ethanol and biodiesel, but lower than production costs associated to other advanced biofuels technologies. They are still higher than fossil fuel prices (see **section 4.4.1.5, p. 55**).

#### 4.4.2.6 POTENTIAL CAPACITY AND ACTUAL PRODUCTION

HVOs have been produced industrially in the EU (and elsewhere) at the scale of millions of tonnes for many years; approximately 2.2 million tonnes of HVO were produced in the EU in 2018. Its production capacity is about 3.9 million tonnes, suggesting on average HVO plants are operating at 57% capacity (USDA, 2018). The production of other synthetic fuels via these pathways remains low, principally due to costs compared to the liquid fossil fuels predominantly used today. For example, the US' Energy Information Administration (EIA, 2017) note global production from GTL facilities averaged 0.2% of global liquids production, with more than 90% of this GTL production coming from just 4 facilities.

[45] For further details on the specific assumptions and methodology used, please refer to the studies.

One interesting area in which new production growth could be possible is in the use of HVO (or HEFA) in aviation. Current EU aviation fuel use is approximately 50 million tonnes/year. Flightpath 2020 had a non-binding target of 2 million tonnes in the EU for 2020, but very little renewable aviation fuel use is taking place in reality. As noted in the AFF (2018) report, there is today only a certain co-production of HEFA in one HVO installation World Energy and two gasification-based synthesised paraffinic kerosene (SPK) plants in construction with a combined capacity of the order of 0.1 million tonnes. Although there are many announcements for additional HVO capacity, none of these are dedicated HEFA producers. In Sweden it has been proposed to have a quota system with 1% SAF in 2021 and 30% in 2030 for all refuelling in Sweden. Other countries, e.g. Norway are also discussing similar systems, which would have an impact earlier than the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (see also **section 5.3.4 p. 181**). The availability of sustainable biomass feedstock may represent a limiting factor to production expansion in the long term.

### 4.4.3 RENEWABLE FUELS OF NON-BIOLOGICAL ORIGIN (REFUNOBIO)

#### 4.4.3.1 DEFINITIONS AND GENERAL DESCRIPTION

According to the RED II (2018/2001) renewable (liquid and gaseous transport) fuels of non-biological origin (ReFuNoBIO) refer to fuels used in the transport sector other than biofuels or biogas, which energy content is derived from renewable sources other than biomass. They are also called electrofuels (e-fuels), and can be gaseous and liquid fuels such as hydrogen (which is described in the **section 4.3, p 40**), methane, synthetic petrol, and diesel fuels generated from renewable electricity. The three main constituents of electrofuels or power-to-fuels (PtF) are electricity, $CO_2$ and water, producing a gaseous or liquid fuel. The fundamental technological steps for electrofuel production are (a) electrolysis, where water is broken down into hydrogen and oxygen by electrical energy, and (b) chemical fuel synthesis in which hydrogen is reacted with the carbon from carbon dioxide to produce more complex hydrocarbons (Cerulogy, 2017). Strong interest for electrofuels is noted by several industry players (personal communications from Fuels Europe, Hydrogen Europe, and Lufthansa, 2019). Ørsted (personal communication, 2019) note the price of the electricity is essential, while Lufthansa caution that a growth in electrofuels will likely mean "electrical energy generation capacity will have to be expanded considerably".

According to Lufthansa (personal communication, 2019) current prices (of electrofuels) are extremely high, estimated at some €6000 per tonne. However, Lufthansa expect this will come down "considerably" in the next couple of decades due to economies of scale. Production capacity currently is only lab scale, and such fuels are not expected to become available in larger scale prior to 2025. An estimate for 2030 may be around 500,000 tonnes in 2030. However, progress beyond that date may be considerable.

PtF can be completely renewable, and provide high GHG savings if the $H_2$ is produced from RES (renewable energy sources) electricity. PtF can also be produced using RES energy blended with some grid electricity, thus not entirely renewable electricity is used as an input, but such a situation may be necessary to allow the fuel facility to continue production during periods of low-renewable electricity availability. Also the carbon used as a feedstock for some processes can be derived by oxidation of biological carbon, or possibly fossil carbon, depending on where and how the fuel production facility is set up. Finally, the availability of water in the intended location or the energy needed to desalinise seawater needs to be considered and factored in.

#### 4.4.3.2 WELL-TO-TANK GREENHOUSE GAS (GHG) EMISSIONS

The GHGi of the electricity used in making a ReFuNoBIO typically forms the vast majority of the total emissions associated with that fuel. RED II (2018/2001) states the electricity should be renewable and ReFuNoBIOs cannot be counted as fully renewable if made when the renewable generation unit is not generating. Critically, the legislation notes the fuel producer should be adding to renewable deployment (or to the financing of renewable energy).

(Cerulogy, 2017) give a very useful approximation which enables a broad overview of the likely WTT GHG emissions of an electrofuel. They state that twice as much electrical energy is required as input to production of drop-in transport electrofuels as is delivered in fuel energy. This means that the GHGi of a transport electrofuel will be approximately twice the GHGi of the electricity used to produce it. There would likely be differences in overall emissions depending on the final fuel molecule produced and the degree of processing if any may be required for the water needed for electrolysis. But these are small compared to the effect the GHGi of the input electricity has on the final fuel emissions.

As stated above, in the event the fuel production facility is operating during times of insufficient renewable electricity, it will require some electricity from the grid. In such a situation, the GHGi of the electricity consumed in the country where the fuel production facility is situated therefore becomes of importance. Here, the vast range of GHGi of electricity consumed across different MS becomes an issue when trying to describe the GHGi of an electrofuel. For example, in 2013 the GHGi of electricity consumed in the EU ranged from a high of 260 $gCO_2eq/MJ$ in Poland to 13 $gCO_2eq/MJ$ in Sweden (Moro & Lonza, 2018). Using the approximation provided by Cerulogy above, indicates that the GHGi of electrofuels made in these MS could as a worst case scenario range (theoretically) from about 25 $gCO_2eq/MJ$ in Sweden to over 230 $gCO_2eq/MJ$ in the event grid electricity was used. Comparing these figures to the fossil fuel comparator for fossil fuels in the RED II of 94 $gCO_2eq/MJ$ shows the absolute need for electrofuels to use renewable electricity, or failing that, to use electricity from a grid with an inherently low GHGi and capacity to provide significant extra electricity without the need to switch on new generating facilities (see **Table 4-10**).

**Table 4-10. Approximate GHGi of grid-connected electrofuels facilities – assuming no extra electricity generation required**

| | GHGi of electricity CONSUMED ($gCO_2eq/kWh$ elec) | GHGi ($gCO_2eq/MJ$ elec) | Likely GHGi of electrofuel* ($gCO_2eq/MJ$ fuel) | RED II GHGi of fossil petrol and diesel ($gCO_2eq/MJ$) |
|---|---|---|---|---|
| Sweden | 45 | 13 | 25 | 94 |
| UK | 593 | 165 | 329 | 94 |
| Poland | 937 | 260 | 521 | 94 |
| EU Av. | 428 | 119 | 238 | 94 |

The promise of electrofuels is they could use curtailed grid electricity, or new renewable electricity capacity. If the electrofuels facility demand is so high that new electricity generation is required to maintain the grid (or indeed if the electrofuels facility is required to run when renewable electricity supply is too low to completely supply it), this must be considered. The new electricity generation could be assumed to be natural gas. Then the logic of going from a gas (natural gas) > to electricity > to a gas (hydrogen) > to a liquid must be considered, along with conversion losses. Electricity GHGi figures from (Moro & Lonza, 2018). * Calculated using (Cerulogy, 2017) guide. The GHGi of a transport electrofuel will be approximately twice the GHGi of the electricity feedstock.

In the event the electrofuels plant is grid-connected (even part of the time) and its connection causes the grid to require the generation of more electricity to meet the new larger demand, one would need to know the GHGi of this extra electricity production (also called the *marginal electricity production*) in that particular MS. If its natural gas then the GHGi of electricity made from this fuel would need to be included in the GHG calculations of the electrofuel. From an electricity demand perspective, switching on a biofuel plant is similar to switching on a few extra houses, but switching on an electrofuels plant is like switching on a city. Using grid electricity even in a MS with an apparently low *average* grid GHGi would likely be a significant issue, if the electrofuels plant causes new generation to come online.

Regarding the GHGi for these types of fuels, RED II requires the Commission to specify a methodology for assessing GHG emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels (which includes e-fuels) by 31 December 2021. As such, clear legislative rules for calculating the GHGi of these fuels do not yet exist yet, but are underway.

#### 4.4.3.3 WELL-TO-TANK ENERGY PERFORMANCE

The well-to-tank energy performance of electrofuels is not efficient. According to Cerulogy (2017), twice as much electrical energy is required as an input to produce drop-in transport electrofuels as is delivered in fuel energy. Transport and Environment (2017) stated that drop-in electrofuels deliver an overall efficiency of only 13% and they compared them to the direct supply of electricity for battery charging which delivers an overall 73% efficiency from electricity production to energy use in transport. The comparatively low efficiency results from losses arising from using the renewable electricity to make hydrogen, then the fuel synthesis step, and finally the combustion of said fuel in an Internal Combustion Engine (ICE).

In an absolute best-case-scenario (unlikely in practice), if the electrical input for the production of the electrofuels was fully from renewable electricity which would have been curtailed otherwise, the electrofuels production, while inefficient in itself, could still be seen as an efficient use of this electrical energy.

#### 4.4.3.4 MATURITY OF FUEL PRODUCTION

Interestingly, many of the technological steps required for liquid electrofuel production are already widely used in other industrial applications, while some parts of the power-to-fuel chain have lower TRLs. Despite the on-going activities, some authors (i.e. (Cerulogy, 2017)) consider that full process from electricity to synthetic fuel has never been demonstrated at commercial scale (although pilot scale facilities exist). Indeed, Total (personal communication, 2019) consider that electrofuels will still not be a mature solution by 2030, but that advanced biofuels currently still at the R&D stage, given positive circumstances, could be more viable at that stage. UPM (personal communication, 2019), suggest electrofuels production could start to grow from 2025 onwards.

#### 4.4.3.5 WELL-TO-TANK COSTS

A broad literature review on production costs of electrofuels has been performed by Brynolf et al. in 2017 and updated in 2018. The review has been based on primarily peer-reviewed literature published between 2010 and February 2016 including a total of 24 studies (Brynolf et al., 2018). Elecrofuels (and type of synthesis) included in their analysis are: methane (catalytic methanation), methanol (methanol synthesis), DME (direct DME synthesis), FT (Fischer-Tropsch synthesis) liquids, e.g. gasoline and diesel, gasoline (methanol synthesis and methanol-to-gasoline process). Estimates of production costs vary largely due to different assumptions and approaches among the different studies. However, the analysis performed by Brynolf et al., 2018 on the basis of data from literature resulted in more harmonised cost estimates for the different fuels, with base-case production costs of 200–280 €/MWh (55-78 €/GJ) in 2015 and 160–210 €/MWh (44-58 €/GJ) in 2030. Average data for the efficiencies and costs of electrolysers and fuel synthesis in the literature have been used for the base case.

**Figure 4-30** shows the estimated production cost ranges for low and high case for the different fuels, where the most optimistic and pessimistic values in the literature are used for the efficiencies and costs of electrolysers and fuel synthesis[46].

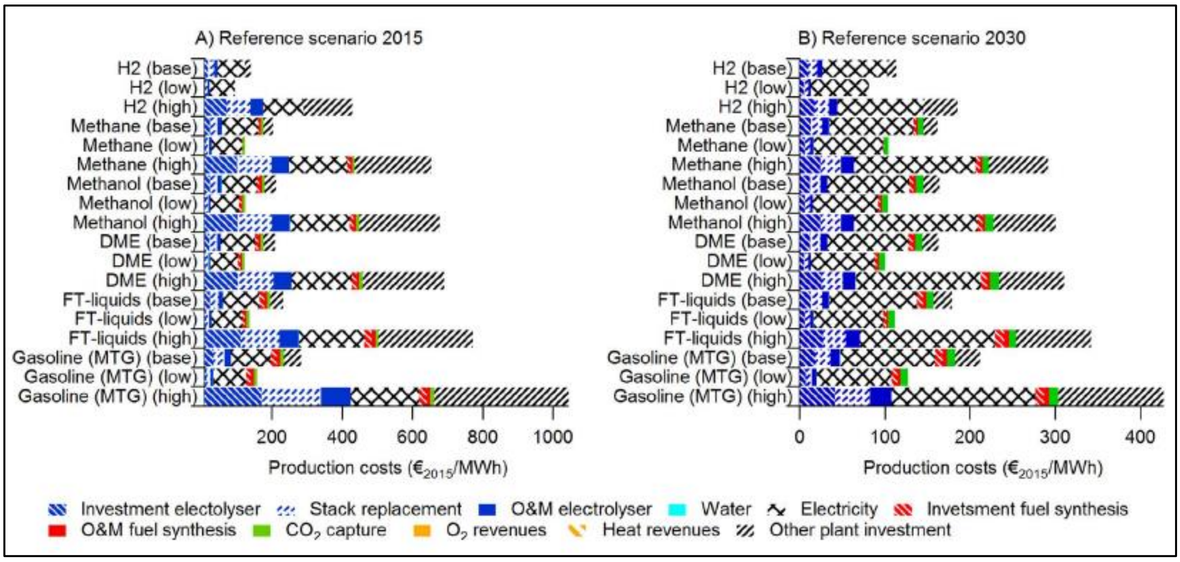


**Figure 4-30. Estimated production cost of e-fuels including low, base and high case in 2015 and 2030**
**Source: Reprinted from (Brynolf et al., 2018)**

The main parameters affecting the cost calculation are the capital cost of the electrolyser, as well as the stack life span and need for stack replacement, in combination with the electricity price; other factors, such as considering revenues from by-products as well as the scale of the electrofuels production plant, have been also marked as relevant factors. Brynolf et al. 2018 underline that the cost of electricity is handled differently in the considered studies: some of them use an average annual electricity price (representative for all hours of the year that the plant is in operation), while others couple the electricity price with the capacity factor, therefore linking the price to the annual electricity utilisation. Cost estimates reported by Brynolf et al. 2018 in the base-case are based on an electricity price of 50 €/MWh that could be considered rather low for near-term developments (Cerulogy 2017). However, the cost of electricity is different if electrofuels facilities are connected to the grid or directly connected to renewable power generation sites and disconnected from the grid (Cerulogy, 2017). Grid electricity price varies between geographical regions and with time of day and year, depending mainly on the type of generation technologies, transmission capacity and the flexibility of the load (Brynolf et al. 2018). The 2017 EU28 average grid electricity price (excluding all taxes) is between 58 €/MWh and 68 €/MWh for very large industrial consumer (Eurostat Band IG:

[46] (Brynolf et al., 2018) report ranges of CO2 capture costs for different CO2 sources from literature: between less than 20 €/tonne CO2 for bioethanol plant and biogas upgrading to more than 70 €/tonne CO2 from CO2 captured from the cement industry. Costs for air capture are not included since *"all air capture technologies are still at a very early stage of development and more research and development are needed in order to better understand future cost of air CO2 capture"* (p. 1896). However, studies reviewing techniques and cost for CO2 captured from air are mentioned. Production costs of 30 €/tonne CO2 for CO2 capture are assumed in their reference scenario.

consumption>150,000 MWh) and smaller industrial consumer (Eurostat Band ID: consumption from 2,000 to 19,999 MWh) respectively[47] (Eurostat data[48]). For facilities directly connected to the renewable power generations sites, the price of electricity depends on the capital and operational costs of power generation (see **section 4.1.5, p. 28** for renewable electricity prices).

A study performed by LBST and Dena (2017) reported much higher cost for electrofuels. They estimated the costs of supplying the final fuel for 2015 as being up to 4.50 €/litre diesel equivalent (corresponding to 451 €/MWh and 125 €/GJ using the LHV provided by the study[49]) (see **Figure 4-31**). LBST and Dena, 2017 assumed that the plants are connected to the high-voltage (110 kV) grid and electricity costs are about 110 €/MWh in 2015 (including transport and distribution) estimated on the basis of their own calculations on renewable electricity generation from onshore and offshore wind and PV systems in the EU. Target costs of approximately 1 € per litre diesel equivalent (corresponding to 100 €/MWh and 28 €/GJ) could be reached with imports from regions with very good solar and wind power conditions according to the same study (LBST and Dena, 2017).

Estimates to 2030 are also provided in a joint report by Prognos, Fraunhofer and DBFZ in 2018 where the production cost of electrofuels produced via Fischer-Tropsch synthesis has been estimated. The calculated generation costs are reported to be between 0.98 and 1.75 €/l of power to liquid (PtL) syncrude (corresponding to 29 and 51 €/GJ[50]) for 2030. Those estimates are calculated assuming electricity costs at cheaper and average-priced renewable energy sites (onshore wind farms and solar PV parks) in the MENA (Middle East North Africa) region and they are estimated to be 31 €/MWh and 64 €/MWh respectively (Prognos, Fraunhofer and DBFZ, 2018). However, in MENA water or concentrated $CO_2$ availability could be problematic.

From the literature, low electricity prices and/or substantial government policy support appear to be fundamental for electrofuels to be able to compete with fossil fuel or biofuels prices in the near future. However, as (Cerulogy, 2017) points out, the economics of electrofuel plants could be improved offering grid balancing services and operating for a smaller fraction of the year.

[47] A smaller industrial consumer is on the scale of a demonstration electrofuel plant (1 MW electrolysis capacity for 4,000 hours per year); a very large industrial consumer of electricity is considered to be a 100 MWH facility running for 8,000 hours a year (Cerulogy, 2017).

[48] Eurostat data, table nrg_pc_205_c.

[49] LHV = 35.88 MJ/l = 9.97 kWh/l.

[50] Using density of 0.78 and LHV if 44.0 MJ/kg of syndiesel from (JEC WTT, 2014).

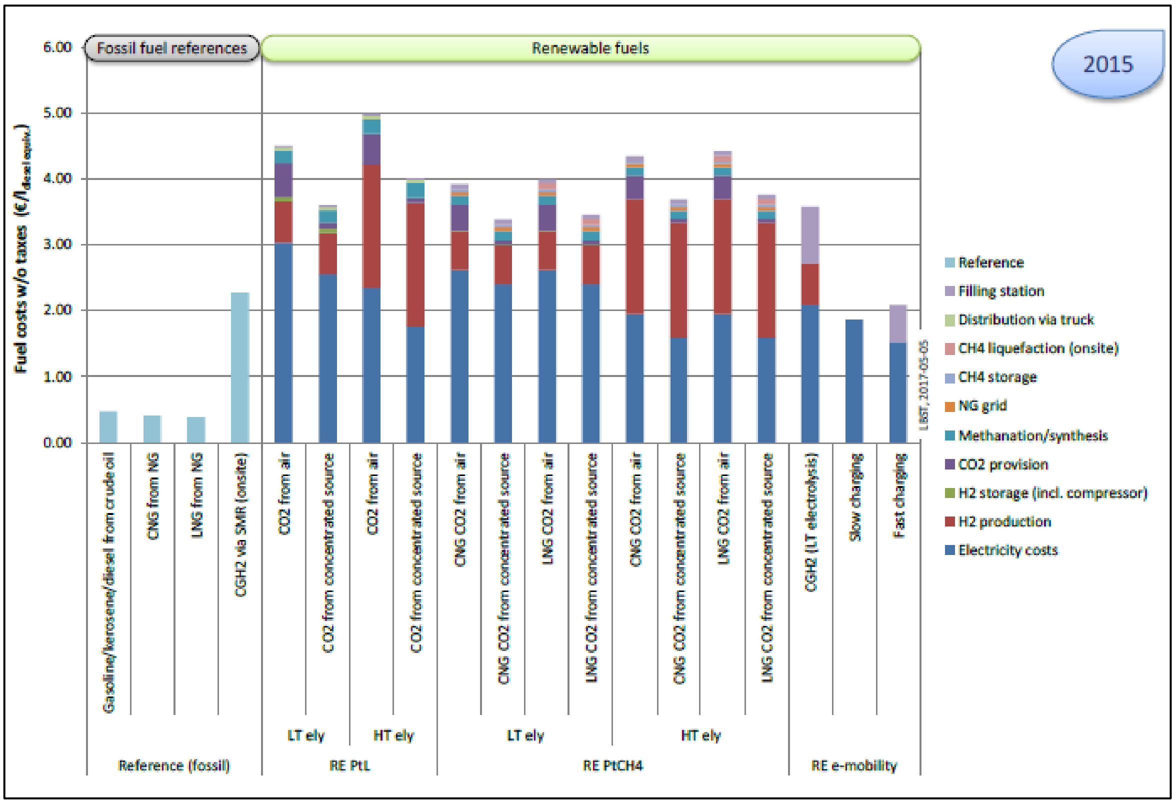


**Figure 4-31. Costs for supplying transportation fuels (expressed per litre of diesel equivalent) in 2015**
**Source: Reprinted from (LBST and Dena, 2017)**

#### 4.4.3.6 POTENTIAL CAPACITY AND ACTUAL PRODUCTION

Generally speaking, production scales are at the pilot plant level for these fuels, and therefore total production capacities remain very low (in the 100's of tonnes per annum) although the sector is expected to increase, especially for electrofuels as more variable renewable energy enters the grid. As an example, Audi with its partners, Ineratec GmbH and Energiedienst Holding AG, are planning to operate a new pilot plant which it is claimed will produce just over 300 tonnes of e-diesel per year[51]. So potential capacities are likely to remain small for the foreseeable future. And while precise figures on actual production are not available, given that the production capacity is in the low 100's of tonnes per annum, actual production will be below that, at most ~ 0.1 or 0.2 ktonnes/year.

At slightly larger scale are power-to-methane ($CH_4$) plants, which have a total annual production in the EU of approximately 2-3 ktonnes/year. These are (to-date) mostly situated in Germany and the majority currently use $CO_2$ captured from biogas upgrading. Considering new plants planned, under construction, or announced in the EU, the production capacity for these particular e-fuels will approximately double in the near future.

The long-term strategy of the EU (EC, 2018b) estimates the future consumption of e-liquids in the transport sector in 2050 to be in the range of 0 to 54.3 Mtoe depending on the considered scenario. E-gases are expected to contribute within a range of 0 to 16.3 Mtoe in the different scenarios.

[51] https://www.audi-mediacenter.com/en/audi-e-fuels-243

## 4.5 (NOTES ON) BIO-LPG (LIQUEFIED PETROLEUM GAS) POTENTIAL

LPG (Liquefied Petroleum Gas) is the generic acronym for C3 and C4 hydrocarbons (namely, propane and butane) that are gaseous under ambient conditions but can be stored and transported in liquid form at relatively mild pressures (up to about 2.5 MPa for propane). LPG is widely used for heating and cooking as well as petrochemicals. It is also a suitable fuel for spark ignition engines with a good octane rating. LPG is available as a road fuel in a number of European countries (JEC-WTW, 2014).

Origin of bio-LPG

Bio-LPG ($C_3H_8$) originates during the production of HVO fuels, following hydrogenation of the glycerol molecule in the vegetable oil.[52]

The carboxylic acid group (COOH) that remains (on the FFAs) must be removed to form straight-chain alkanes (such as methane, ethane, propane, butane). This is achieved by hydrotreating, where hydrogen alongside a hydrotreatment catalyst is added to the carbonyl group. At this point, three more reactions can take place, according to the selectivity of the process (Vásquez et al., 2017), namely hydrodeoxygenation, decarboxylation and decarbonylation. The rate of propane production will be lower for high (free) fatty acid materials such as palm fatty acid distillate (PFAD), due to the lower level of glycerol starting molecule.

Current production levels and likely potentials

An estimate of likely bio-LPG production potentials was provided by Atlantic Consulting in a report commissioned by the World LPG Association and AEGPL (the European LPG association) in 2018 (Atlantic Consulting, 2018) (see **Table 4-11**). They began with describing current global production levels, and note global production of bio-LPG is currently around 200 ktonnes/year, or just under 0.1% of all LPG production (Atlantic Consulting, 2018). Regarding the future, their "rough estimate ", based on new production capacities that they consider highly likely to come online is that production will increase by 100 ktonnes to 300 ktonnes in 2022. AEGPL (personal communication, 2019) noting (Atlantic Consulting, 2018) report suggest the bio-LPG potential could reach 2 million tonnes by 2030 (which would represent just over 8% of the total EU LPG production (AEGPL, 2016). However, Atlantic Consulting broadly estimate approximately 10% of HVO production is bio-propane. In order to have 2 million tonnes of bio-LPG production in 2030, it suggests that approximately 20 million tonnes of HVO would need to be made in the EU at that time which is unlikely. Or some of the other possible bio-LPG sources which may be possible in the future, as noted by AEGPL (personal Communication, 2019), and which are not yet in commercial production would need to be produced.

It is important to note that a large fraction of the bio-LPG made during HVO production is used in the HVO process as fuel for the process itself. Therefore, if it is removed and sold as bio-LPG, it will have to be replaced by another process fuel, most likely, natural gas. Generally speaking the GHGi of bio-LPG will follow the GHGi associated with the vegetable oil/animal fat feedstock from which it originates.

Atlantic Consulting further noted the biggest production trend regarding bio-LPG is that conventional oil refineries are co-processing bio-oils together with petroleum

[52] Fats or triglycerides are a glycerol ($C_3H_8O_3$) molecule bonded to 3 fatty acid chains. Hydrogenation first saturates any carbon-carbon double bonds in the fatty acids. E.g. hydrogenating a triglyceride containing three chains of fatty acids linoleic (C18:2) or ($C_{18}H_{32}O_2$), oleic (C18:1) or ($C_{18}H_{34}O_2$) and stearic (C18:0) or ($C_{18}H_{36}O_2$), would result in three chains of stearic acid. After saturation, more hydrogen causes the glycerol to break off, thus forming propane ($C_3H_8$), along with a chain of free fatty acids (FFAs).

intermediates at a blend of around 30% bio and 70% fossil, thus making bio-LPG. It results in a mixed stream of diesel/biodiesel and another, smaller stream of mostly bio-LPG. Co-processing can be done in existing hydrotreaters or hydrocrackers that undergo some modifications. At least one refiner is experimenting with co-processing bio-oil in a fluid catalytic cracker: again, bio-LPG comes out as a by-product to biodiesel (i.e. HVO production) (Atlantic Consulting, 2018).

**Table 4-11. Estimated global bio-LPG production in 2018**
**Source: Atlantic Consulting, 2018**

| Owner/Operator | Country | Is biopropane extracted? | Biopropane, kt/y[3] |
|---|---|---|---|
| **Americas** | | | |
| Petrobras | BR | No | NA |
| AltAir Fuels | USA | No | 7 |
| Renewable Energy Group | USA | Probably | 1.3 |
| Valero: Diamond Green Diesel | USA | Small quantities? | 10 |
| **Europe** | | | |
| Global Bioenergies | D | Biobutylene, yes | Biobutylene, 0.1 |
| CEPSA | ES | Maybe | NA |
| Repsol | ES | Probably starting in 2018 | NA |
| Total | F | Starting in 2018 | 30 |
| Eni | I | Yes | 20 |
| Irving Oil | IE | No | 3 |
| Neste Oil | NL, SF | Yes | 90 |
| GALP | P | Maybe | NA |
| PREEM[4] | SE | Yes | 15 |
| **Asia** | | | |
| Hitachi Zosen | JP | No | 0.0 |
| Neste Oil | Singapore | Yes | Included in the Neste total above |
| SUM | | | Estimated 200 |

## 4.6 (NOTES ON) BIO-METHANOL POTENTIAL

In recent years while turning natural gas into liquids such as methanol has become potentially viable particularly for remote locations, but actual project realisations remain few (JEC WTT v4a, 2014). Therefore, from both fossil and bio-feedstocks, it very much remains a niche fuel. Unlike ethanol, which in theory can be blended up to 10 vol% max in EN228 (European gasoline specification) petrol (gasoline), the limit for methanol in regular petrol is kept to 3 vol% - in reality this limit would be lower in the event there is ethanol already in the fuel blend, due to the limit on oxygenates in EN228.

There is currently only one biomethanol plant in the EU, in the Netherlands (BioMCN). It started production in 2010, has a capacity of 200 kT, and uses biogas feedstock. While it can be blended with gasoline (in low volumes), it can also be used for the production of bio-methyl tertiary butyl ether (bio-MTBE), bio-dimethyl ether (bio-DME), or synthetic biofuels. In 2017, BioMCN announced they would begin using $CO_2$, a by-product of biogas production, to produce an additional volume of 15 kT of biomethanol (USDA, 2018). In April 2019, the Canadian company Enerkem gave further details on their proposed waste-to-methanol factory in Rotterdam, and announced (Enerkem, 2019) their project will include Shell as a partner. The planned facility will have a production capacity of 220 kT per annum. While Enerkem describes the proposed factory's output as purely bio-methanol, it details their chosen feedstock will be non-recyclable mixed-waste materials which includes plastics, therefore it is likely a considerable fraction of their final methanol will in fact be of fossil origin.

There is a considerable amount of waste generated in the EU each year; approximately a 250 million tonnes of municipal solid waste was generated in 2017. Of this, bio-waste makes up the largest fraction; in 2013 the EEA estimated it to comprise on average 37% by weight (EEA, 2013). Therefore, if the Enerkem (or similar) technology is shown to work, there is a theoretically large potential for methanol, and indeed a smaller but still potentially significant percentage of bio-methanol could be produced from MSW.

### 4.7 (NOTES ON) AMMONIA

While hydrogen is a possible enabler of a low carbon economy, it faces (amongst others) issues around its storage and distribution. Indirect storage media such as ammonia (or indeed methanol) are other options, as are their possible direct use as fuel. Ammonia is carbon free and has an established and flexible transportation network, and it is seen by some researchers as possibly providing a next generation system for energy transportation, storage and use (Valera-Medina et al., 2018). Ammonia is also one of the most commonly produced industrial chemicals and is used in a diversified set of industrial sectors. It has been estimated the EU has an ammonia production capacity of 21 million tonnes. In the EU virtually all ammonia is produced by using natural gas as a feedstock. In global terms, about 80% of total ammonia production is consumed by the fertiliser industry (CEPS, 2014).

Ammonia can be seen as having favourable properties for use as an transport fuel, namely good storage properties and its mature production and distribution infrastructure. However, the sustainability of ammonia is questionable due to the environmental impact from conventional production technology, and the need for a secondary hydrocarbon fuel to promote combustion when used in internal combustion engines. Combustion in heavy-duty engines may be more straight-forward, with ship engine builders M.A.N. describing only "minor modifications" being needed to burn ammonia[53]. Care would have to be applied with respect to its handling, as it is both caustic and hazardous in concentrated form. Researchers conducting a life cycle analysis of an ammonia-fuel system found the most significant parameter was end-user vehicle fuel economy. Therefore, they recommended improving vehicle technology to enable the use of ammonia (Angeles et al., 2018). With regards to an alternative method of producing the ammonia, the researchers found a cyanobacteria-based process was optimal (Angeles et al., 2018). Concerning the production cost of ammonia, this is tightly linked to the production cost of hydrogen but ammonia bears much cheaper transport and storage costs (Osman and Sgouridis, 2018).

[53] http://nh3fuelassociation.org/2018/12/07/ship-operation-using-lpg-and-ammonia-as-fuel-on-man-bw-dual-fuel-me-lgip-engines/

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## 4.9 APPENDIX TO CHAPTER 4

### *ELECTRICITY*

| | | Electricity | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | For business use | | | | For non-business use | | | |
| | | CN 2716 | | | | CN 2716 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 0,5 EUR per MWh (Annex I of Directive 2003/96/EC) | | | | 1,0 EUR per MWh (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % |
| AT | EUR | | | 15 | 20 | | | 15 | 20 |
| BE | EUR | 1.9261 EUR/MWh (excise) + 3.4439 EUR/MWh (federal contribution) | | 5.37 | 21 | 1.9261 EUR/MWh (excise) + 3.4439 EUR/MWh (federal contribution | | 5.37 | 21 |
| BG | BGN | | 2 | 1.0226 | 20 | According Bulgarian Excise Duties and Tax Warehouses Act: Article 34a. (2) The excise rate for electricity falling within CN code 2716 for consumers of electricity for household purposes shall be BGN 0 per MWh. | 0 | 0 | 20 |
| CY | EUR | Levy (Article 4(2), Directive 2003/96/EC) | | 10 | 19 | Levy (Article 4(2), Directive 2003/96/EC) | | 10 | 19 |
| CZ | CZK | | 28.3 | 1.0984 | 21 | | 28.3 | 1.0984 | 21 |
| DE | EUR | | | 15.37 | 19 | Standard rate | | 20.5 | 19 |
| DK | DKK | | 4 | 0.5365 | 25 | | 884 | 118.567 | 25 |
| EE | EUR | | | 4.47 | 20 | | | 4.47 | 20 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| EL | EUR | 2.5 EUR for counsumers of high voltage | | 5 | 13 | 2.2 EUR for households | | 5 | 13 |
| ES | EUR | Tax on Electricity is an ad valorem (%) tax. The basis of assessment is the taxable amount that had been determined for the purposes of value added tax and the rate is 5.11269632% of it. The tax rate provided was the effective one in the first half of 2018. | | 5.1 | 21 | Tax on Electricity is an ad valorem (%) tax. The basis of assessment is the taxable amount that had been determined for the purposes of value added tax and the rate is 5.11269632% of it. The tax rate provided was the effective one in the first half of 2018. | | 9.6 | 21 |
| FI | EUR | Industrial use, mining, data centers, agriculture | | 7.03 | 24 | | | 22.53 | 24 |
| FR | EUR | classical VAT | | 22.5 | 20 | classical VAT | | 22.5 | 20 |
| HR | HRK | | 3.75 | 0.5045 | 25 | | 7.5 | 1.009 | 25 |
| HU | HUF | | 310.5 | 0.9612 | 27 | Electricity used by households is exempted, see Article 15(1)(h) of Council Directive 2003/96/EC. | 310.5 | 0.9612 | 27 |
| IE | EUR | | | 0.5 | 13.5 | | | 1 | 13.5 |
| IT | EUR | For monthly consumptions until 200,000 kWh. | | 12.5 | 22 | | | 22.7 | 10 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| SE | SEK | Business use = Electricity in the manu facturing process in industry, shoreside electricity and electricity used in datacenters | 5 | 0.484 | 25 | | 347 | 33.5915 | 25 |
| | | | | | 25 | Tax level in the northern parts of Sweden | 251 | 24.2982 | 25 |
| SI | EUR | to 10,000 MWH/year; excise duty 3.05 per MWh; 0,8 per MWh surcharge on energy end-use efficiency on electricity. Surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration onPay is paid on connection. | | 3.85 | 22 | to 10,000 MWH/year; excise duty 3.05 per MWh; 0,8 per MWh surcharge on energy end-use efficiency on electricity. Surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration onPay is paid on connection. | | 3.85 | 22 |
| | | | | | 22 | over 10,000 MWH/year; excise duty 3.05 per MWh; 0,8 per MWh surcharge on energy end-use efficiency on electricity. Surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration onPay is paid on connection. | | 2.6 | 22 |
| SK | EUR | | | 1.32 | 20 | | | 1.32 | 20 |

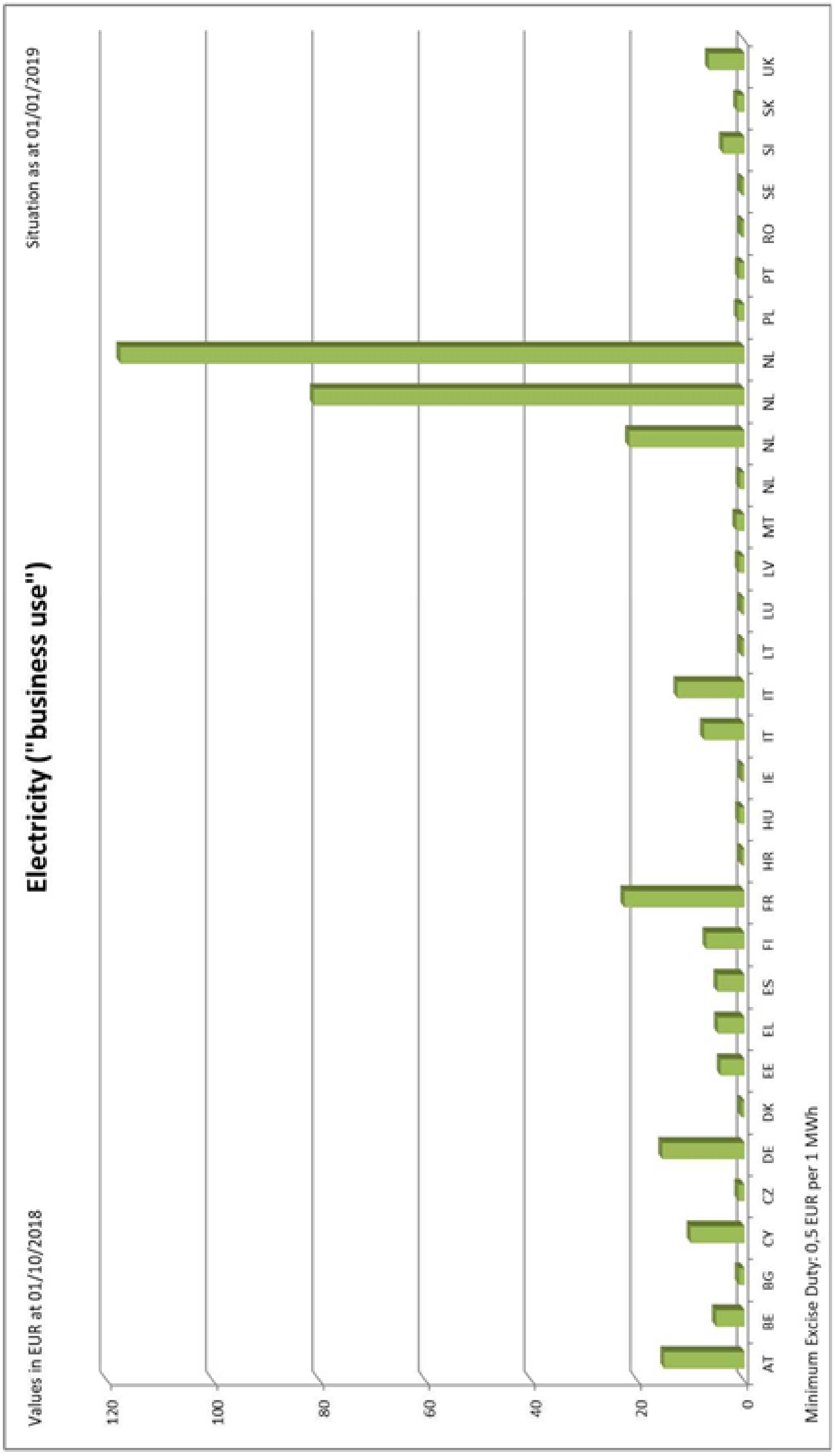
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | For monthly consumptions upper 200,000 kWh and until 1,200,000 kWh if monthly consumptions don't exceed 1,200,000 kWh. If monthly consumptions exceed 1,200,000 kWh, the monthly amount is 4,820 EUR for the consumptions upper 200,000 kWh, regardless of the real consumptions. | | 7.5 | 22 | | | | 22 |
| LT | EUR | | | 0.52 | 21 | | | 1.01 | 21 |
| LU | EUR | | | 0.5 | 8 | | | 1 | 8 |
| LV | EUR | | | 1.01 | 21 | | | 1.01 | 21 |
| MT | EUR | | | 1.5 | 5 | | | 1.5 | 5 |
| NL | EUR | 0-10,000 kWh | | 117.53 | 21 | 0-10,000 kWh | | 117.53 | 21 |
| | | <10,000-50,000 kWh | | 81.17 | 21 | <10,000-50,000 kWh | | 81.17 | 21 |
| | | <50,000-10,000,000 kWh | | 21.61 | 21 | <50,000-10,000,000 kWh | | 21.61 | 21 |
| | | >10,000,000 kWh | | 0.86 | 21 | >10,000,000 kWh | | 1.47 | 21 |
| PL | PLN | | 5 | 1.1683 | 23 | | 5 | 1.1683 | 23 |
| PT | EUR | | | 1 | 23 | | | 1 | 23 |
| RO | RON | | 2.44 | 0.5235 | 19 | | 4.89 | 1.0492 | 19 |

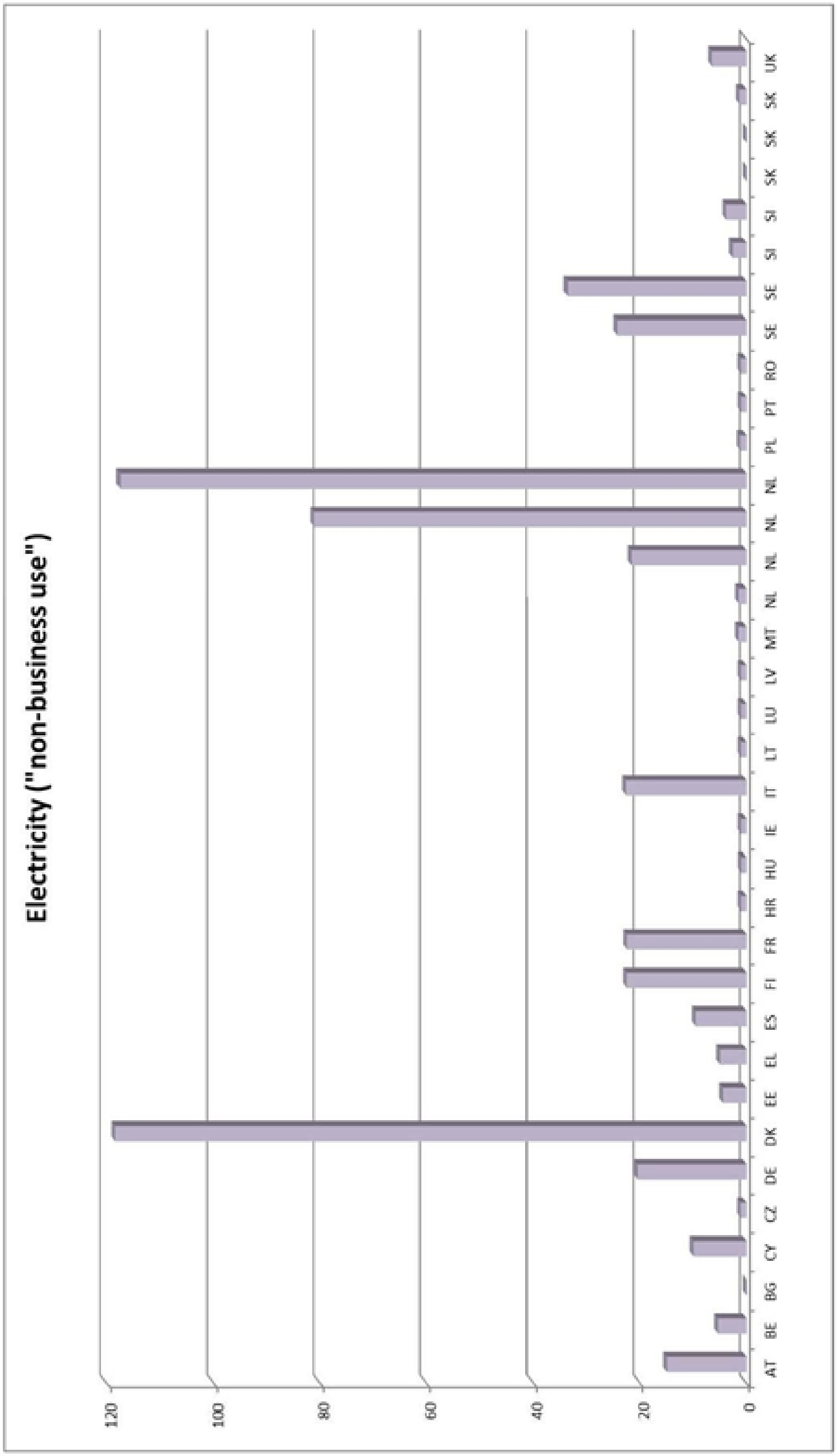
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 20 | Exemptions: used principally for the purposes of chemical reduction and in electrolytic and metallurgical processes; used in mineralogical processes; used for the manufacture of a product, when the cost of electricity accounts for more than 50% of the average own costs; used for the production of electricity and for maintaining the ability of the electricity generation facility to produce electricity; produced from a renewable source ... (exemptions continue in following cell) | | 0 | 20 |
| | | | | 20 | ... generated in a facility for combined power and heat generation, if supplied directly to the final electricity consumer; used for combined power and heat generation; used for the transportation of persons and cargo by rail, underground, tram, trolleybus, electric bus or funicular; generated aboard a ship used for the transportation of persons or cargo, where such transportation is carried out as part of commercial activities; used by a final household electricity customer | | 0 | 20 |
| UK | GBP | 5.83 | 6.5448 | 20 | Indicative rate only as this use is not taxable | 5.83 | 6.5448 | 20 |

### *Electricity*

| Per MWh | | Electricity reduced rates applied in specific sectors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CN 2716 | | | | | | | | |
| Reduced tax rates applied according to Directive 2003/96/EC | | If Article 15(3) is used for agricultural, horticultural or piscicultural works, and in forestry | | | Article 15(1)(e): reduced rate applied for railways | | | Article 15(1)(e): reduced rate applied for metro, tram and trolley bus | | |
| MS | National Currency | Excise duty Nat Curr | Excise duty EUR | VAT % | Excise duty Nat Curr | Excise duty EUR | VAT % | Excise duty Nat Curr | Excise duty EUR | VAT % |
| AT | EUR | n/a | | 20 | n/a | | 20 | n/a | | 20 |
| BE | EUR | | 0 | 21 | exemption | 0 | 21 | n/a | 5.37 | 21 |
| CZ | CZK | 28.3 | 1.0984 | 21 | 0 | 0 | 21 | 0 | 0 | 21 |
| DE | EUR | | 15.37 | 19 | | 11.42 | 19 | | 11.42 | 19 |
| DK | DKK | 4 | 0.5365 | 25 | 4 | 0.5365 | 25 | 4 | 0.5365 | 25 |
| EL | EUR | | 0 | 13 | | | 24 | | | 24 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ES | EUR | Tax on Electricity is an ad valorem (%) tax. The basis of assessment is the taxable amount that had been determined for the purposes of value added tax and the rate is 5.11269632% of it. The tax rate provided was the effective one in the first half of 2018. | | 5.1 | 21 | Tax on Electricity is an ad valorem (%) tax. The basis of assessment is the taxable amount that had been determined for the purposes of value added tax and the rate is 5.11269632% of it. The tax rate provided was the effective one in the first half of 2018. | | 5.1 | 21 | Tax on Electricity is an ad valorem (%) tax. The basis of assessment is the taxable amount that had been determined for the purposes of value added tax and the rate is 5.11269632% of it. The tax rate provided was the effective one in the first half of 2018. | | 5.1 | 21 |
| FI | EUR | | | 7.03 | 24 | | | 0 | 24 | | | 0 | 24 |
| FR | EUR | n.a. | | | 20 | | | 0.5 | 20 | | | 0.5 | 20 |
| HU | HUF | | 310.5 | 0.9612 | 27 | | 310.5 | 0.9612 | 27 | | 310.5 | 0.9612 | 27 |
| IT | EUR | | | | 22 | Exemption. | | | 22 | Exemption. | | | 22 |
| LT | EUR | n.a. | | | 21 | n.a. | | | 21 | n.a. | | | 21 |
| LU | EUR | n/a | | | 17 | n/a | | | 17 | n/a | | | 17 |
| LV | EUR | | | | 21 | | | 0 | 21 | | | 0 | 21 |
| MT | EUR | na | | | 18 | na | | | 18 | na | | | 18 |
| RO | RON | | 2.44 | 0.5235 | 19 | | 2.44 | 0.5235 | 19 | | 2.44 | 0.5235 | 19 |
| SE | SEK | | 5 | 0.484 | 25 | | 0 | 0 | 25 | | 0 | 0 | 25 |
| SK | EUR | | | 1.32 | 20 | | | 0 | 20 | | | 0 | 20 |
| UK | GBP | not applicale | | | 20 | | 0 | 0 | 20 | | 0 | 0 | 20 |


Electricity ("business use")
Values in EUR at 01/10/2018
Situation as at 01/01/2019
0
20
40
60
80
100
120
AT BE BG CY CZ DE DK EE EL ES FI FR HR HU IE IT IT LT LU LV MT NL NL NL NL PL PT RO SE SI SK UK
Minimum Excise Duty: 0,5 EUR per 1 MWh


Electricity ("non-business use")
120
100
80
60
40
20
0
AT BE BG CY CZ DE DK EE EL ES FI FR HR HU IE IT LT LU LV MT NL NL NL NL PL PT RO SE SE SI SI SK SK SK UK

## NATURAL GAS

| | | Natural Gas | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | Heating fuel for business use | | | Heating fuel for non-business use | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00<br>2,6 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | CN 2711 1100, CN 2711 21 00<br>0,15 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | CN 2711 1100, CN 2711 21 00<br>0,3 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | |
| MS | Nat Curr | Excise duty NatCurr | Excise duty EUR | VAT % | Excise duty NatCurr | Excise duty EUR | VAT % | Excise duty NatCurr | Excise duty EUR | VAT % |
| AT | EUR | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | 1.66 | 20 | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | 1.66 | 20 | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | 1.66 | 20 |
| BE | EUR | article 15(1)(i) is used | 0 | 21 | "for business which are parties to agreements or which take part in tradable permit schemes or equivalent arrangements that lead to the achievement | 0.3079 | 21 | 0.2772 EUR/MWh (excise) + 0.1579 EUR/MWh (federal contribution) | 0.4351 | 21 |

| | | Natural Gas | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | | Heating fuel for business use | | | | Heating fuel for non-business use | | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00 2,6 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00 0,15 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00 0,3 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | | |
| MS | Nat Curr | Excise duty | | | VAT % | Excise duty | | | VAT % | Excise duty | | | VAT % | |
| | | | NatCurr | EUR | | | NatCurr | EUR | | | NatCurr | EUR | | |
| | | | | | | of environmental protection objectives or to improvements in energy efficiency *0.15 EUR/MWh (excise) + 0.1579 EUR/MWh (federal contribution) | | | | | | | | |
| | | | | | 21 | 0.2772 EUR/MWh (excise) + 0.1579 EUR/MWh (federal contribution) | | 0.4351 | 21 | | | | 21 | |
| BG | BGN | Article 15(1)(i) | 0.85 | 0.4346 | 20 | | 0.6 | 0.3068 | 20 | | 0 | 0 | 20 | |
| CY | EUR | | | 2.6 | 19 | | | 2.6 | 19 | | | 2.6 | 19 | |

| | | Natural Gas | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | | Heating fuel for business use | | | | Heating fuel for non-business use | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00<br>2,6 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,15 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,3 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| CZ | CZK | | 38 | 1.4749 | 21 | | 8.5 | 0.3299 | 21 | | 8.5 | 0.3299 | 21 |
| DE | EUR | 1 MWh = 3.6 GJ | | 3.86 | 19 | 1 MWh = 3.6 GJ | | 1.14 | 19 | 1 MWh = 3.6 GJ | | 1.53 | 19 |
| DK | DKK | Energy tax (78.12 DKK) + CO2 tax (10.07 DKK) | 88.19 | 11.8285 | 25 | Energy tax (56.64 DKK) + CO2 tax (10.07 DKK) | 66.71 | 8.9475 | 25 | Energy tax (56.64 DKK) + CO2 tax (10.07 DKK) | 66.71 | 8.9475 | 25 |
| EE | EUR | | | 1.26 | 20 | 63.31€ per 1,000 m3 | | 1.67 | 20 | 63.31€ per 1,000 m3 | | 1.67 | 20 |
| EL | EUR | | | 0 | 13 | yearly consumption: 0-36,000 GJ | | 1.5 | 13 | | | 0.3 | 13 |
| | | | | | 13 | yearly consumption: 36,000-360,000 GJ | | 0.45 | 13 | | | | 13 |
| | | | | | 13 | yearly consumption: 360,001-1,800,000 GJ | | 0.4 | 13 | | | | 13 |
| | | | | | 13 | yearly consumption: 1,800,001-3,600,000 GJ | | 0.35 | 13 | | | | 13 |

| | | Natural Gas | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | Heating fuel for business use | | | Heating fuel for non-business use | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00 | | | CN 2711 1100, CN 2711 21 00 | | | CN 2711 1100, CN 2711 21 00 | | |
| | | 2,6 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | 0,15 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | 0,3 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | |
| MS | Nat Curr | Excise duty | | VAT % | Excise duty | | VAT % | Excise duty | | VAT % |
| | | NatCurr | EUR | | NatCurr | EUR | | NatCurr | EUR | |
| | | | | 13 | yearly consumption: over 3,600,000 GJ | 0.3 | 24 | | | 24 |
| ES | EUR | | 1.15 | 21 | | 0.15 | 21 | | 0.65 | 21 |
| FI | EUR | | 5.74 | 24 | | 5.74 | 24 | | 5.74 | 24 |
| FR | EUR | The national rate is 5.80€ per 100 m3. Conversion into GJ: 5.80/3.8 = 1.53€ VAT is applied to the already charged price, where the price of each product is valued at an inclusive value that changes each trimester. For this product it is | 1.53 | 20 | The national rate is 8.45€ per MWH. Conversion into GJ: 8.45/3.6 = 2.35€ classical VAT | 2.35 | 20 | The national rate is 5.88€ per MWH. Conversion into GJ: 8.45/3.6 = 2.35€ classical VAT | 2.35 | 20 |

| | | Natural Gas | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | | Heating fuel for business use | | | | Heating fuel for non-business use | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00<br>2,6 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,15 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,3 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| | | fixed at : 4.5€/m3 | | | | | | | | | | | |
| HR | HRK | | 0 | 0 | 25 | | 1.12 | 0.1507 | 25 | | 2.25 | 0.3027 | 25 |
| HU | HUF | The national rate is HUF 28.00 per nm3 for natural gas used as propellant. | 823.53 | 2.5493 | 27 | | 93.5 | 0.2894 | 27 | Natural gas used by households is exempted, see Article 15(1)(h) of Council Directive 2003/96/EC. | 93.5 | 0.2894 | 27 |
| IE | EUR | Carbon Component €1.03 Non-Carbon Component €1.57 | | 2.6 | 23 | | | 1.03 | 13.5 | | | 1.03 | 13.5 |
| IT | EUR | The rate is indicative as Article 15(1)(i) applies in this particular use. | | 0.09 | 22 | The rate is approximate The national rate is Euro:0.012496 per m3. | | 0.34 | 22 | The rate is approximate The national rate is Euro: 0.044 per m3 for annual consumptions until 120 m3. | | 1.19 | 10 |

| | | Natural Gas | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | Heating fuel for business use | | | Heating fuel for non-business use | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00 | | | CN 2711 1100, CN 2711 21 00 | | | CN 2711 1100, CN 2711 21 00 | | |
| | | 2,6 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | 0,15 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | 0,3 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | |
| MS | Nat Curr | Excise duty | | VAT % | Excise duty | | VAT % | Excise duty | | VAT % |
| | | NatCurr | EUR | | NatCurr | EUR | | NatCurr | EUR | |
| | | | | 22 | | | 22 | The rate is approximate The national rate is Euro: 0.175 per m3 for annual consumptions above 120 m3 and until 480 m3. | 4.73 | 10 |
| | | | | 22 | | | 22 | The rate is approximate The national rate is Euro: 0.170 for annual consumptions above 480 m3 and until 1,560 m3. | 4.59 | 22 |
| | | | | 22 | | | 22 | The rate is approximate The national rate is Euro: 0.186 for annual consumptions above 1,560 m3. | 5.03 | 22 |

| | | Natural Gas | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | | Heating fuel for business use | | | | Heating fuel for non-business use | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00<br>2,6 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,15 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,3 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| LT | EUR | | | 6.56 | 21 | | | 0.15 | 21 | | | 0.3 | 21 |
| LU | EUR | art. 15, i) | | 0 | 8 | cat. B | | 0.54 | 8 | cat. A | | 1.08 | 8 |
| | | | | | 8 | cat. C2 | | 0.3 | 6 | | | | 6 |
| | | | | | 8 | cat. C1 | | 0.05 | 6 | | | | 6 |
| LV | EUR | | | 2.68 | 21 | | | 0.15 | 21 | | | 0.46 | 21 |
| MT | EUR | na | | | 18 | | | 0.64 | 18 | | | 0.64 | 18 |
| NL | EUR | | | 4.68 | 21 | 0-170,000 m3 | | 9.82 | 21 | 0-170,000 m3 | | 9.82 | 21 |
| | | | | | 21 | 170,000-1,000,000 m3 | | 2.32 | 21 | 170,000-1,000,000 m3 | | 2.32 | 21 |
| | | | | | 21 | 1,000,000-10,000,000m3 | | 0.65 | 21 | 1,000,000-10,000,000m3 | | 0.65 | 21 |

| | | Natural Gas | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | | Heating fuel for business use | | | | Heating fuel for non-business use | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00<br>2,6 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,15 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,3 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | | | VAT % | Excise duty | | | VAT % | Excise duty | | | VAT % |
| | | | NatCurr | EUR | | | NatCurr | EUR | | | NatCurr | EUR | |
| | | | | | 21 | 10,000,000m3 | | 0.45 | 21 | >10,000,000 m3 | | 0.45 | 21 |
| PL | PLN | for CN27111100 832.27 PLN per 1,000 kg (includes fuel tax ) | 19.38 | 4.5285 | 23 | | 1.28 | 0.2991 | 23 | | 1.28 | 0.2991 | 23 |
| | | for CN27112100 (includes fuel tax ) | 14.36 | 3.3555 | 23 | | | | 23 | | | | 23 |
| PT | EUR | ISP=1.15 CO2=0.71 | | 1.86 | 23 | ISP=1.15 CO2=0.71 | | 1.86 | 23 | ISP=0.307 CO2=0.71 | | 1.02 | 23 |
| RO | RON | | 12.71 | 2.7272 | 19 | | 0.84 | 0.1602 | 19 | | 1.57 | 0.3369 | 19 |
| SE | SEK | Energy tax (0 SEK) + CO2 tax (62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 | 62.9 | 6.0891 | 25 | Reduced Energy tax (7.4 SEK). Business use = Heating purposes in the manu facturing process in industry + No CO2 tax is | 7.4 | 0.7164 | 25 | Energy tax (24.5 SEK) + CO2 tax (62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 | 87.4 | 8.4608 | 25 |

| | | Natural Gas | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Propellant** | | | | **Heating fuel for business use** | | | | **Heating fuel for non-business use** | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00 | | | | CN 2711 1100, CN 2711 21 00 | | | | CN 2711 1100, CN 2711 21 00 | | | |
| | | 2,6 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | | 0,15 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | | 0,3 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| | | GJ/1 000 m3 is used. | | | | applied in the manu facturing process in industry within the Emission Trading Scheme Reduced energy tax. | | | | 000 m3 is used. | | | |
| | | | | | 25 | Reduced Energy tax (7.4 SEK). Business use = Heating purposes in the manu facturing process in industry + CO2 tax(62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 000 m3 is used. | 70.3 | 6.6054 | 25 | | | | 25 |

| | | Natural Gas | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | | Heating fuel for business use | | | | Heating fuel for non-business use | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00<br>2,6 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,15 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | | CN 2711 1100, CN 2711 21 00<br>0,3 EUR per gigajoule.<br>(Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | | | VAT % | Excise duty | | | VAT % | Excise duty | | | VAT % |
| | | | NatCurr | EUR | | | NatCurr | EUR | | | NatCurr | EUR | |
| SI | EUR | Excise duty 2.37 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | | 3.74 | 22 | Excise duty 0.48 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | | 1.85 | 22 | Excise duty 0.48 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | | 1.85 | 22 |
| SK | EUR | | | 2.6 | 20 | | | 0.37 | 20 | | | 0.37 | 20 |

| | | Natural Gas | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Propellant | | | Heating fuel for business use | | | Heating fuel for non-business use | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | CN 2711 1100, CN 2711 21 00 | | | CN 2711 1100, CN 2711 21 00 | | | CN 2711 1100, CN 2711 21 00 | | | |
| | | 2,6 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | 0,15 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | 0,3 EUR per gigajoule. (Annex I of Directive 2003/96/EC) | | | |
| MS | Nat Curr | Excise duty | | VAT % | Excise duty | | VAT % | Excise duty | | | VAT % |
| | | *NatCurr* | EUR | | NatCurr | EUR | | | NatCurr | EUR | |
| UK | GBP | 5.67 | 6.3652 | 20 | 0.5623 | 0.6312 | 20 | Indicative rate only as this use is not taxable. non-business use is exempt | 0.5623 | 0.6312 | 20 |

### Natural Gas

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Article 8(2)(b): stationary motors | | | | Article 8(2)(c): plant and machinery used in construction, civil engineering and public works | | | | Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway | | | |
| | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | | | VAT % | Excise duty | | | VAT % | Excise duty | | | VAT % |
| | | | NatCurr | EUR | | | NatCurr | EUR | | | NatCurr | EUR | |
| AT | EUR | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | | 1.66 | 20 | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | | 1.66 | 20 | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | | 1.66 | 20 |
| BE | EUR | | | 0 | 21 | | | 0 | 21 | | | 0 | 21 |
| BG | BGN | | 0.85 | 0.4346 | 20 | | 0.85 | 0.4346 | 20 | | 0.85 | 0.4346 | 20 |
| CY | EUR | | | 2.6 | 19 | | | 2.6 | 19 | | | 2.6 | 19 |
| CZ | CZK | | 8.5 | 0.3299 | 21 | | 8.5 | 0.3299 | 21 | | 8.5 | 0.3299 | 21 |

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Article 8(2)(b): stationary motors** | | | | **Article 8(2)(c): plant and machinery used in construction, civil engineering and public works** | | | | **Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway** | | | |
| | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| DE | EUR | 1 MWh = 3.6 GJ if used in a plant with an efficiency of at least 60 % | | 1.53 | 19 | 1 MWh = 3.6 GJ Standard rate | | 3.86 | 19 | 1 MWh = 3.6 GJ if used for the transfer of freight in seaports | | 1.53 | 19 |
| DK | DKK | Energy tax (78.12 DKK) + CO2 tax (10.07 DKK) | 88.19 | 11.8285 | 25 | Energy tax (78.12 DKK) + CO2 tax (10.07 DKK) | 88.19 | 11.8285 | 25 | Energy tax (78.12 DKK) + CO2 tax (10.07 DKK) | 88.19 | 11.8285 | 25 |
| EE | EUR | 47.32€ per 1,000 m3 | | 1.26 | 20 | 47.32€ per 1,000 m3 | | 1.26 | 20 | 47.32€ per 1,000 m3 | | 1.26 | 20 |
| | | Liquefied natural gas (LNG), 66€ per 1,000 kg | | 1.37 | 20 | Liquefied natural gas (LNG), 66€ per 1,000 kg | | 1.37 | 20 | Liquefied natural gas (LNG), 66€ per 1,000 kg | | 1.37 | 20 |
| EL | EUR | | | 1.5 | 13 | | | 1.5 | 13 | | | 0 | 13 |
| ES | EUR | | | 0.65 | 21 | | | 1.15 | 21 | | | 1.15 | 21 |
| FI | EUR | | | 5.74 | 24 | | | 5.74 | 24 | | | 5.74 | 24 |
| FR | EUR | The national rate is 5.80€ per 100 m3. Conversion into GJ: | | 1.53 | 20 | n.a. | | 1.53 | 20 | n.a. | | 1.53 | 20 |

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Article 8(2)(b): stationary motors** | | | | **Article 8(2)(c): plant and machinery used in construction, civil engineering and public works** | | | | **Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway** | | | |
| | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| | | 5.80/3.8 = 1.53€ Idem for VAT | | | | | | | | | | | |
| HR | HRK | | 0 | 0 | 25 | | 0 | 0 | 25 | | 0 | 0 | 25 |
| HU | HUF | | 93.5 | 0.2894 | 27 | | 93.5 | 0.2894 | 27 | | 93.5 | 0.2894 | 27 |
| IE | EUR | | | 1.03 | 23 | | | 1.03 | 23 | | | 1.03 | 23 |
| IT | EUR | The rate is approximate. The national rate is Euro 11.73 per 1,000 m3. | | 0.32 | 22 | The rate is indicative as the product is not used in this particular use. | | 0.32 | 22 | The rate is indicative as the product is not used in this particular use. | | 0.32 | 22 |
| LT | EUR | | | 6.56 | 21 | | | 6.56 | 21 | | | 6.56 | 21 |
| LU | EUR | cat. A | | 1.08 | 8 | cat. A | | 1.08 | 8 | idem propellant | | 0 | 8 |
| | | cat. B | | 0.54 | 8 | cat.B | | 0.54 | 8 | | | | 8 |

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Article 8(2)(b): stationary motors** | | | | **Article 8(2)(c): plant and machinery used in construction, civil engineering and public works** | | | | **Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway** | | | |
| | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| | | cat. C1 (chemical reduction, metallurgical and mineral process) | | 0.05 | 8 | cat.C1 | | 0.05 | 8 | | | | 8 |
| | | cat. C2 | | 0.3 | 8 | cat. c2 | | 0.3 | 8 | | | | 8 |
| | | cat. D = production of electricity | | 0 | 8 | cat. D | | 0 | 8 | | | | 8 |
| LV | EUR | | | 2.68 | 21 | | | 2.68 | 21 | | | 2.68 | 21 |
| MT | EUR | na | | | 18 | na | | | 18 | na | | | 18 |
| NL | EUR | LNG Conversion:1000 kg = 45.16 Gj | | 7.62 | 21 | LNG Conversion:1000 kg = 45.16 Gj | | 7.62 | 21 | LNG Conversion:1000 kg = 45.16 Gj | | 7.62 | 21 |
| | | CNG | | 4.68 | 21 | CNG | | 4.68 | 21 | CNG | | 4.68 | 21 |
| PL | PLN | for CN27111100 832.27 PLN per 1,000 kg (includes fuel tax | 19.38 | 4.5285 | 23 | for CN27111100 832.27 PLN per 1,000 kg (includes fuel tax | 19.38 | 4.5285 | 23 | for CN27111100 832.27 PLN per 1,000 kg (includes fuel tax | 19.38 | 4.5285 | 23 |

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Article 8(2)(b): stationary motors | | | | Article 8(2)(c): plant and machinery used in construction, civil engineering and public works | | | | Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway | | | |
| | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % | Excise duty | NatCurr | EUR | VAT % |
| | | for CN27112100 (includes fuel tax ) | 14.36 | 3.3555 | 23 | for CN27112100 (includes fuel tax ) | 14.36 | 3.3555 | 23 | for CN27112100 (includes fuel tax ) | 14.36 | 3.3555 | 23 |
| PT | EUR | ISP=1.15 CO2=0.71 | | 1.86 | 23 | ISP=1.15 CO2=0.71 | | 1.86 | 23 | ISP=1.15 CO2=0.71 | | 1.86 | 23 |
| RO | RON | | 12.71 | 2.7272 | 19 | | 12.71 | 2.7272 | 19 | | 12.71 | 2.7272 | 19 |
| SE | SEK | Reduced Energy tax in the manu facturing process in industry and in agriculture,horticultural and piscicultural works and in forestry (7.4 SEK) + No CO2 tax is applied in the manu facturing process in industry within the Emission Trading Scheme. | 7.4 | 0.7164 | 25 | Energy tax (24.5 SEK) + CO2 tax (62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 000 m3 is used. | 87.4 | 8.4608 | 25 | Energy tax (0 SEK) + CO2 tax (62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 000 m3 is used. | 62.9 | 6.0891 | 25 |
| | | Reduced energy tax in the manu facturing process in industry and in agriculture, horticultural and piscicultural works and in forestry (7.4 SEK) + | 70.3 | 6.8054 | 25 | | | | 25 | | | | 25 |

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Article 8(2)(b): stationary motors** | | | **Article 8(2)(c): plant and machinery used in construction, civil engineering and public works** | | | **Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway** | | |
| | | CN 2710 1941 to 2710 1949 | | | CN 2710 1941 to 2710 1949 | | | CN 2710 1941 to 2710 1949 | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | |
| MS | National Currency | Excise duty NatCurr | Excise duty EUR | VAT % | Excise duty NatCurr | Excise duty EUR | VAT % | Excise duty NatCurr | Excise duty EUR | VAT % |
| | | CO2 tax (62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 000 m3 is used. | | | | | | | | |
| SI | EUR | Excise duty 2.37 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | 3.74 | 22 | Excise duty 2.37 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | 3.74 | 22 | Excise duty 2.37 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | 3.74 | 22 |
| SK | EUR | | 2.6 | 20 | | 2.6 | 20 | | 2.6 | 20 |

| | | Natural Gas - Industrial/Commercial use (Art.8, except for agriculture) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Article 8(2)(b): stationary motors** | | | | **Article 8(2)(c): plant and machinery used in construction, civil engineering and public works** | | | | **Article 8(2)(d): vehicles intended for use off the public roadway or which have not been granted authorisation for use mainly on the public roadway** | | | |
| | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | | CN 2710 1941 to 2710 1949 | | | |
| Minimum excise duty adopted by the Council on 27-10-2003 (Dir. 2003/96/EC) | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | | 21 EUR per 1000 litres. (Annex I of Directive 2003/96/EC) | | | |
| MS | National Currency | Excise duty | | | VAT % | Excise duty | | | VAT % | Excise duty | | | VAT % |
| | | | NatCurr | EUR | | | NatCurr | EUR | | | NatCurr | EUR | |
| UK | GBP | Indicative rate only as this use is not taxable | 5.67 | 6.3652 | 20 | Indicative rate only as this use is not taxable | 5.67 | 6.3652 | 20 | Indicative rate only as this use is not taxable | 5.67 | 6.3652 | 20 |

## *Natural Gas*

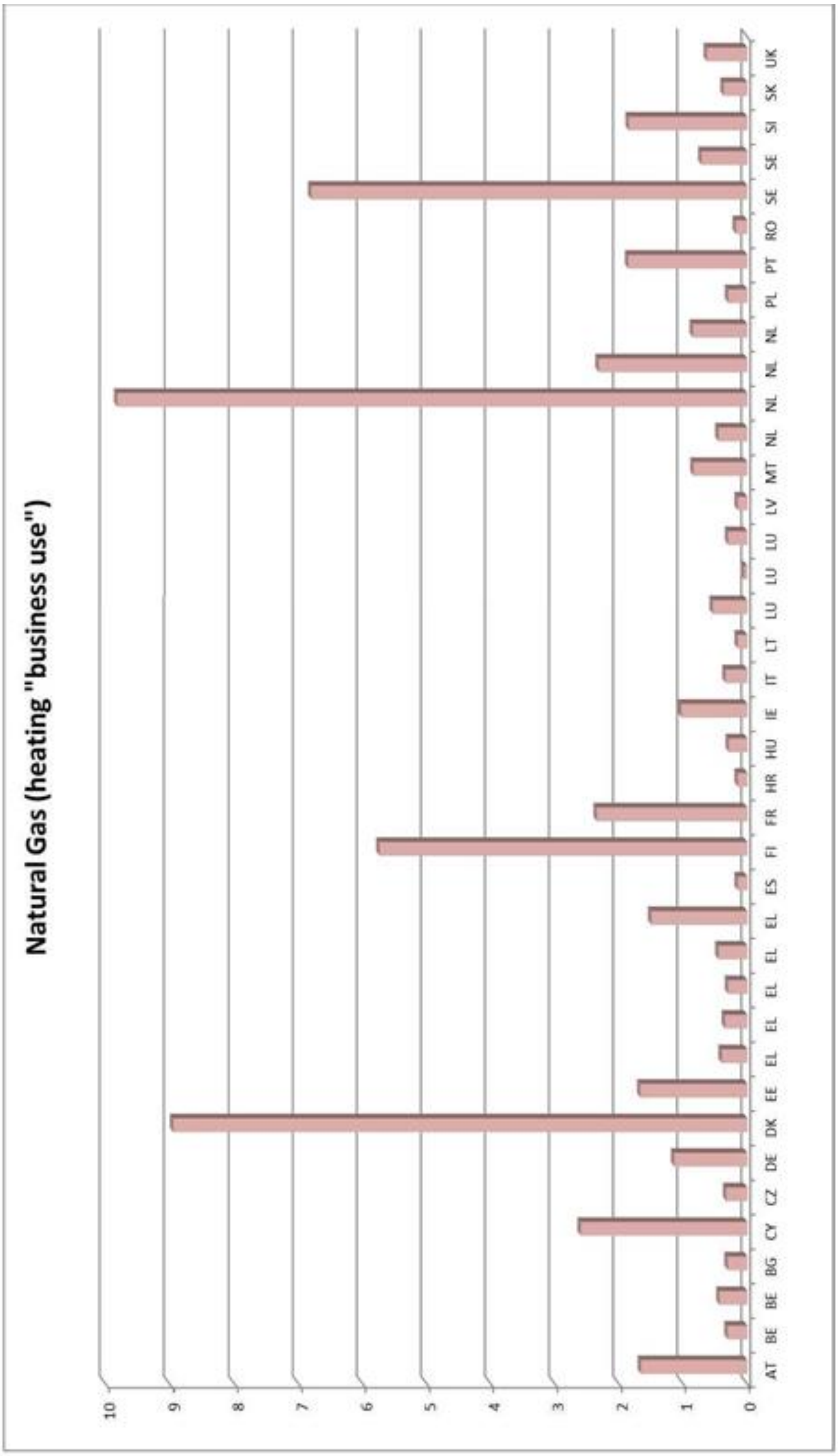
| Per gigajoule | | Natural gas reduced rates applied in specific sectors | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CN 2711 1100, CN 2711 21 00 | | | | | | | | | | | | | | | |
| Reduced tax rates applied according to Directive 2003/96/EC | | **Article 8(2)(a): motor fuel for agricultural, horticultural or piscicultural works, and in forestry** | | | | **If Article 15(3) is used for agricultural, horticultural or piscicultural works, and in forestry** | | | | **Article 5: differentiated rates for local public passenger transport (including taxis), waste collection, armed forces and public administration, disabled people, ambulances** | | | | **If Article 15(1)(i) is used for natural gas used as propellant** | | | |
| MS | National Currency | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % |
| AT | EUR | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | | 1.66 | 20 | n/a | | | 20 | n/a | | | 20 | See Council Directive 2003/96/EC. The tax rate of National Gas Tax (tax on the supply and consumption of natural gas) is based on volume (0,066 EUR per nm3) | | 1.66 | 20 |
| BE | EUR | article 15 (3) is used | | 0 | 21 | | | 0 | 21 | n/a (the differentiated rate is only applicable for gasoil used bij local public passenger transport (inlcuding taxis) | | 0 | 21 | | | 0 | 21 |
| BG | BGN | | 0.85 | 0.4346 | 20 | | | | 20 | | | | 20 | | 0.85 | 0.4346 | 20 |
| CY | EUR | | | 2.6 | 19 | | | 2.6 | 19 | | | 2.6 | 19 | | | 2.6 | 19 |
| CZ | CZK | | 38 | 1.4749 | 21 | | 38 | 1.4749 | 21 | | 38 | 1.4749 | 21 | | 38 | 1.4749 | 21 |

| gajoule | Natural gas reduced rates applied in specific sectors | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CN 2711 1100, CN 2711 21 00 | | | | | | | | | | | | | | |
| ced tax applied ding to ctive 96/EC | Article 8(2)(a): motor fuel for agricultural, horticultural or piscicultural works, and in forestry | | | | If Article 15(3) is used for agricultural, horticultural or piscicultural works, and in forestry | | | | Article 5: differentiated rates for local public passenger transport (including taxis), waste collection, armed forces and public administration, disabled people, ambulances | | | | If Article 15(1)(i) is used for natur used as propellant | | |
| National Currency | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR |
| EUR | 1 MWh = 3.6 GJ Standard rate | | 3.86 | 19 | 1 MWh = 3.6 GJ | | 1.14 | 19 | 1 MWh = 3.6 GJ if used for local public passenger transport | | 3.58 | 19 | 1 MWh = 3.6 GJ | | 3.86 |
| DKK | Reduced Energy tax (1.38 DKK) + CO2 tax (10.07 DKK) | 11.45 | 1.5357 | 25 | Reduced Energy tax (1.00 DKK) + CO2 tax (10.07 DKK) | 11.09 | 1.4875 | 25 | N.a. | | | 25 | N.a. | | |
| EUR | 47.32€ per 1,000 m3 | | 1.26 | 20 | | | | 20 | | | | 20 | | | |
| | Liquefied natural gas (LNG), 66€ per 1,000 kg | | 1.37 | 20 | | | | 20 | | | | 20 | | | |
| EUR | | | 1.5 | 13 | | | | 24 | | | | 24 | | | 0 |
| EUR | | | 1.15 | 21 | | | 1.15 | 21 | | | 1.15 | 21 | | | 1.15 |
| EUR | | | 5.74 | 24 | | | 5.74 | 24 | | | 5.74 | 24 | | | 5.74 |
| EUR | n.a. | | 1.53 | 20 | refund of tax in order to obtain 0.119€/MWH, ie 0.03€/GJ VAT is applied to the already charged priced, where the price of each product is valued at | | 0.03 | 20 | n.a. | | | 20 | | | |

| gajoule | Natural gas reduced rates applied in specific sectors | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CN 2711 1100, CN 2711 21 00 | | | | | | | | | | | | | | |
| ced tax applied ding to ctive 96/EC | Article 8(2)(a): motor fuel for agricultural, horticultural or piscicultural works, and in forestry | | | | If Article 15(3) is used for agricultural, horticultural or piscicultural works, and in forestry | | | | Article 5: differentiated rates for local public passenger transport (including taxis), waste collection, armed forces and public administration, disabled people, ambulances | | | | If Article 15(1)(i) is used for natur used as propellant | | |
| National Currency | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR |
| EUR | 1 MWh = 3.6 GJ Standard rate | | 3.86 | 19 | 1 MWh = 3.6 GJ | | 1.14 | 19 | 1 MWh = 3.6 GJ if used for local public passenger transport | | 3.58 | 19 | 1 MWh = 3.6 GJ | | 3.86 |
| DKK | Reduced Energy tax (1.38 DKK) + CO2 tax (10.07 DKK) | 11.45 | 1.5357 | 25 | Reduced Energy tax (1.00 DKK) + CO2 tax (10.07 DKK) | 11.09 | 1.4875 | 25 | N.a. | | | 25 | N.a. | | |
| EUR | 47.32€ per 1,000 m3 | | 1.26 | 20 | | | | 20 | | | | 20 | | | |
| | Liquefied natural gas (LNG), 66€ per 1,000 kg | | 1.37 | 20 | | | | 20 | | | | 20 | | | |
| EUR | | | 1.5 | 13 | | | | 24 | | | | 24 | | | 0 |
| EUR | | | 1.15 | 21 | | | 1.15 | 21 | | | 1.15 | 21 | | | 1.15 |
| EUR | | | 5.74 | 24 | | | 5.74 | 24 | | | 5.74 | 24 | | | 5.74 |
| EUR | n.a. | | 1.53 | 20 | refund of tax in order to obtain 0.119€/MWH, ie 0.03€/GJ VAT is applied to the already charged priced, where the price of each product is valued at | | 0.03 | 20 | n.a. | | | 20 | | | |

| Per gigajoule | | Natural gas reduced rates applied in specific sectors | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CN 2711 1100, CN 2711 21 00 | | | | | | | | | | | | | | |
| Reduced tax rates applied according to Directive 2003/96/EC | | **Article 8(2)(a): motor fuel for agricultural, horticultural or piscicultural works, and in forestry** | | | | **If Article 15(3) is used for agricultural, horticultural or piscicultural works, and in forestry** | | | | **Article 5: differentiated rates for local public passenger transport (including taxis), waste collection, armed forces and public administration, disabled people, ambulances** | | | **If Article 15(1)(i) is used for natural gas used as propellant** | | | |
| MS | National Currency | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % |
| | | for CN27111100 832.27 PLN per 1,000 kg (includes fuel tax | 19.38 | 4.5285 | 23 | | | | 23 | | | 23 | | | | 23 |
| PT | EUR | ISP=1.15 CO2=0.71 | | 1.86 | 23 | | | | 23 | | | 23 | | | | 23 |
| RO | RON | | 12.71 | 2.7272 | 19 | | 12.71 | 2.7272 | 19 | 12.71 | 2.7272 | 19 | | 12.71 | 2.7272 | 19 |
| SE | SEK | Energy tax (0 SEK) + CO2 tax (62.9 SEK). The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 000 m3 is used. | 62.9 | 6.0891 | 25 | Reduced energy tax (7.4 SEK) + CO2 tax (62.9 SEK) = Heating purposes. The national tax rates are expressed in 1 000 m3. Conversion factor 40 GJ/1 000 m3 is used. | 70.3 | 6.8054 | 25 | | | 25 | | | | 25 |
| SI | EUR | Excise duty 2.37 per gigajoule, surcharge on energy end-use efficiency 0.22 per gigajoule, surcharge for the promotion of electricity generation from | | 3.74 | 22 | | | | 22 | | | 22 | | | | 22 |

| Per gigajoule | | Natural gas reduced rates applied in specific sectors CN 2711 1100, CN 2711 21 00 | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reduced tax rates applied according to Directive 2003/96/EC | | **Article 8(2)(a): motor fuel for agricultural, horticultural or piscicultural works, and in forestry** | | | | **If Article 15(3) is used for agricultural, horticultural or piscicultural works, and in forestry** | | | | **Article 5: differentiated rates for local public passenger transport (including taxis), waste collection, armed forces and public administration, disabled people, ambulances** | | | | **If Article 15(1)(i) is used for natural gas used as propellant** | | | |
| MS | National Currency | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % | Excise duty | Nat Curr | EUR | VAT % |
| | | renewable energy sources and high-efficiency cogeneration 0.28 per gigajoule, 0.87 per gigajoule CO2-tax. | | | | | | | | | | | | | | | |
| SK | EUR | | | 2.6 | 20 | | | 2.6 | 20 | | | 2.6 | 20 | | | 2.6 | 20 |
| UK | GBP | Indicative rate only as this use is not taxable | 5.67 | 6.3652 | 20 | not applicable | | | 20 | not applicable | | | 20 | | 0.549 | 0.6163 | 20 |


Natural Gas (heating "business use")
0
1
2
3
4
5
6
7
8
9
10
AT
BE
BE
BG
CY
CZ
DE
DK
EE
EL
EL
EL
EL
EL
ES
FI
FR
HR
HU
IE
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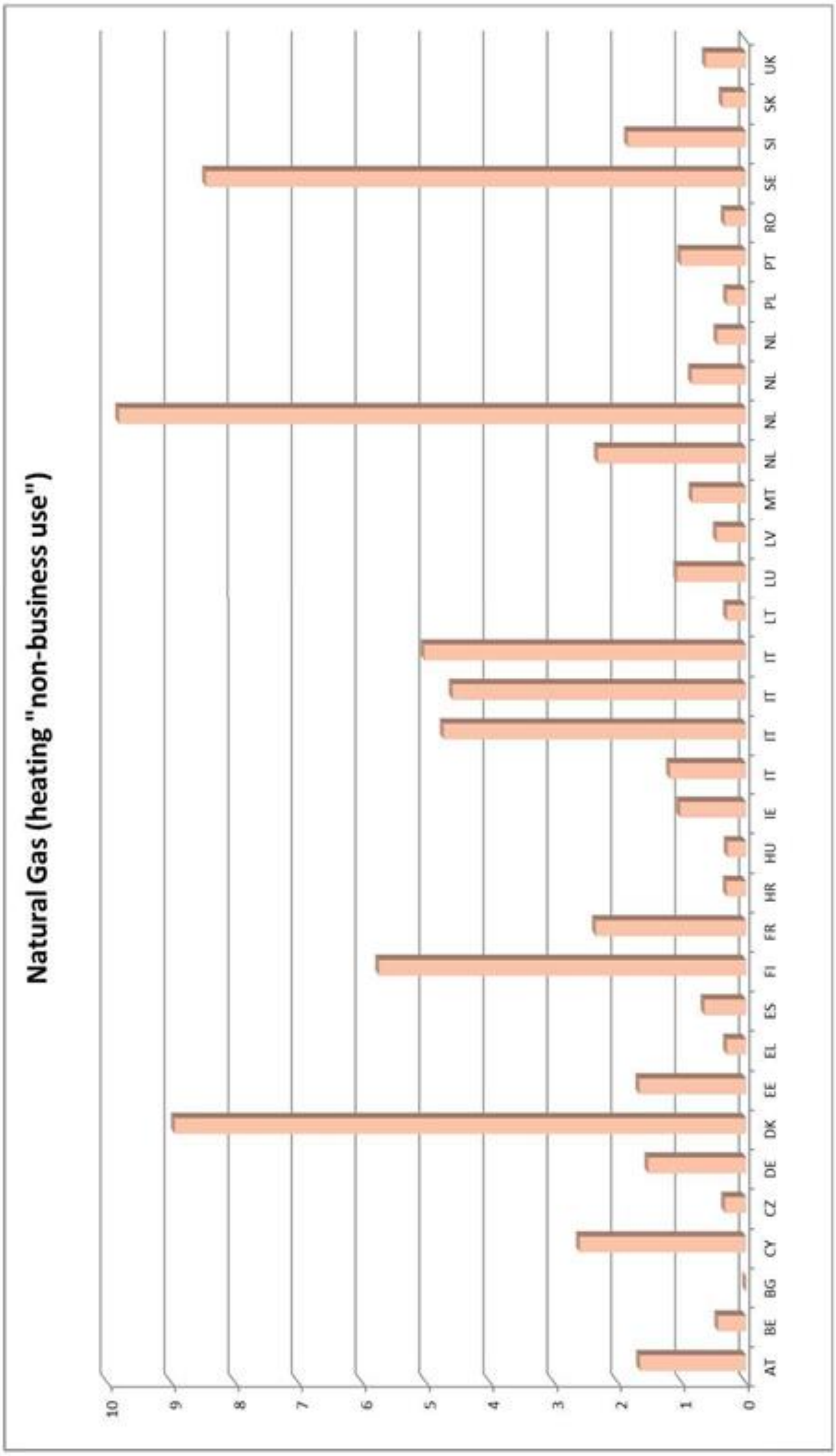
PT
RO
SE
SE
SI
SK
UK


Natural Gas (heating "non-business use")
0
1
2
3
4
5
6
7
8
9
10
AT
BE
BG
CY
CZ
DE
DK
EE
EL
ES
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# 5 MARKET DEVELOPMENT FOR TRANSPORT SYSTEMS AND INFRASTRUCTURE

Alternative fuels have to compete with conventional fuels in each of the different transport systems.

Almost 97 million vehicles were sold worldwide in 2017, of which ca. 22% in Europe (OICA, 2017). The vast majority of these vehicles are powered by petrol or diesel fuel.

- In 2018, 15.2 million new cars were registered in the EU (ACEA, 2019b), with 257 million cars in use in 2016 (ACEA, 2018b). Evidence of the alternative fuels (ethanol 85 (E85), electricity, hydrogen, LPG and natural gas) available in the EU car market can be found in (EEA, 2018b). In the first quarter of 2019, 8.5% of the new cars registered in the EU were powered by alternative energy sources (ACEA, 2019a).

- In 2018, 2.1 million new LCVs were registered in the EU (ACEA, 2019b), with 31.6 million LCVs in use in 2016 (ACEA, 2018b). Evidence of the alternative fuels available in the EU LCV market can be found in (EEA, 2018c).

- In 2016, there were 745,492 buses in use in the EU (ACEA, 2018), most of them running on diesel.

- In 2016, the stock of HCVs (>3.5t) in the EU was 6.3 million vehicles (ACEA, 2018), most of them powered by diesel. Around 95% of the European (EU+EFTA) market for new truck sales in that year was served by five manufacturers: Volkswagen (MAN (15%) and Scania (13%)), Daimler (21%), Volvo (Volvo Trucks (14%) and Renault Trucks (7%)), DAF (13%) and Iveco (12%) (EEA, 2018a).

In the EU car market, a recent trend is worth pointing out. **Figure 5-1** shows the number of new cars sold in the EU28 by segment in the last five years. As can be seen, the SUV segment has gained importance over time. In addition, the chart shows the percentage of SUV sales. The line shows an upwards trend, with SUVs reaching a market share of almost 35% in 2018. A decade ago, the share was only 8% (ACEA, 2018a). Since the energy requirements of heavier SUVs are greater than those of smaller cars, the figure is useful to assess the prospects of certain alternative powertrains in the EU car market (see also **section 5.1.1, p. 119**).

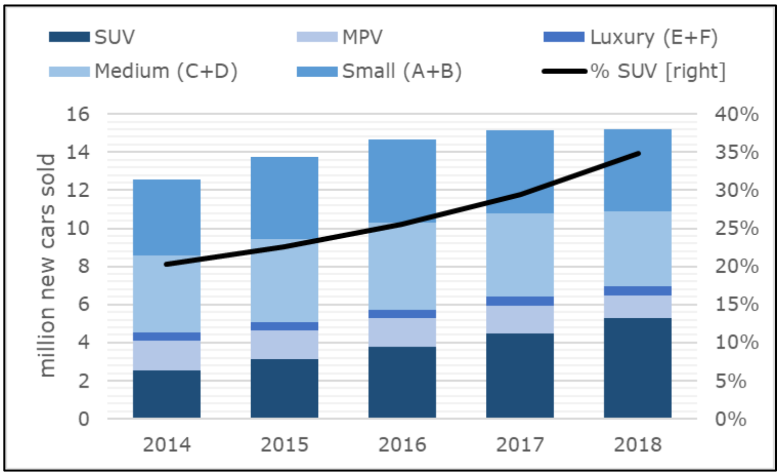



**Figure 5-1. EU28 new car sales by segment and SUV share**
**Note: MPV = 'multi purpose vehicle' and SUV = sports utility vehicle**
**Source: own work based on (ACEA, 2018a)**

In 2016, there were 65,567 locomotives and railcars in use in the EU28 (Eurostat, 2019). Almost 21% of the energy used in trains currently comes from renewable energy sources (CER, 2019). The deployment of alternative fuels and technologies in the rail transport system is needed for one out of five trains operating in non-electrified lines. Where further electrification of the rail network is uneconomical, trains powered by alternative fuels are an option to reduce $CO_2$ emissions (S2R, 2018).

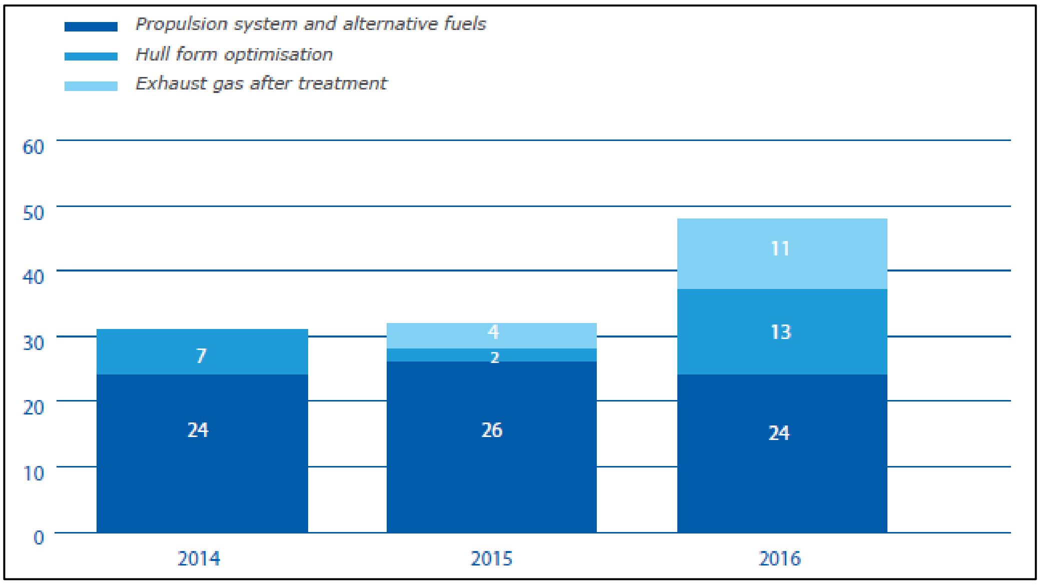



**Figure 5-2. Number of new inland waterway vessels, by type of greening measure**
**Source: CCNR, 2018**

The Danube and the Rhine are considered the two main inland waterways in the EU. Whereas freight shipping in the Danube represented less than 10% of total European inland waterway cargo volume in 2017 (DC, 2018), in the Rhine it accounted for over 66% (OEIN, 2019). With dry cargo (bulk such as coal or metallurgic products and container freight transport) as the main segment, ca. 2,600 and 7,300 dry cargo vessels operated in the Danube and Rhine countries in 2015, respectively (CCNR, 2018). **Figure 5-2** reflects the adoption of different greening strategies for the acquisition of new vessels over the period 2014-2016.

Concerning maritime vessels, in 2018 there were 94,159 propelled sea-going merchant ships of ≥100 gross tonnes (excluding inland waterway vessels) in operation worldwide, of which 50,732 were propelled sea-going merchant vessels of ≥1,000 gross tonnes (UNCTAD, 2019). In Europe, the share of vessel types (≥100 gross tonnes) in that year was as follows: 11% oil tankers, 9% bulk carriers, 20% general cargo, 6% container ships and 55% other types of ships (UNCTAD, 2019). For tankers, bulk carries and container vessels, respectively, (LR/UMAS, 2017) considers the following weight as representative: 110,000 deadweight tonnage (dwt), 53,000 dwt and 9,000 twenty-foot equivalent units (TEU) (much less weight can be generally carried by cruise (3,000 dwt) and roll-on/roll-off passenger (RoPax) (2,250 dwt)). Most of those fleets have traditionally been powered by the cheaper high-sulphur heavy fuel oil (HFO). To meet the more stringent sulphur limits, (low-sulphur) marine gas oil ((LS)MGO) and ultra-low sulphur fuel oil (ULSFO) are available. In view of the regulated sulphur limits, (McKinsey, 2018) expects MGO to become the most successful alternative to HFO, at least in the near term. In a scenario exercise, (CEDelft, 2016) estimated that the refinery capacity is adequate to meet the demand for low-sulphur marine fuels. According to (EGCSA, 2018), there were 983 vessels with an on-board exhaust cleaning system (scrubber) installed or on order in May 2018, with most of them being open loop retrofits. Notwithstanding, (Reuters, 2019d) recently reported that European ports have started to restrict or ban open loop scrubbers. Beyond fuel-switching and retrofitting strategies, vessel technologies based on alternative fuels are also available in the market.

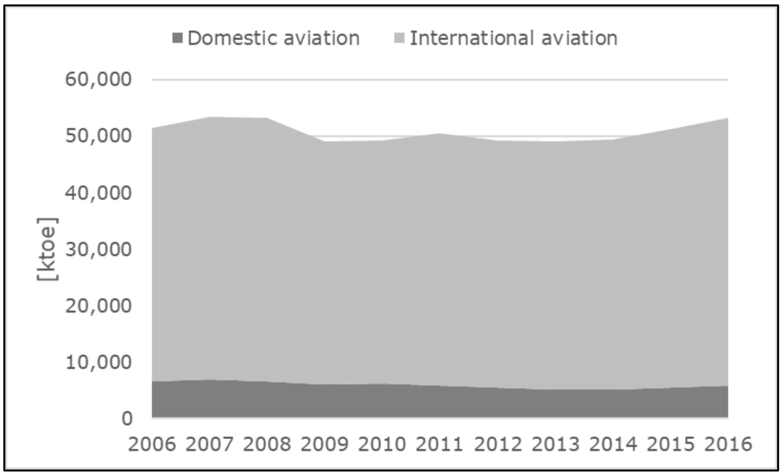



**Figure 5-3. Kerosene type jet fuel (without bio components) use by EU28 aviation**
**Source: Eurostat, 2019**

Over 1,600 billion passenger-km were flown by commercial flights departing from the EU and EFTA countries in 2017, a 60% increase compared to 2005 that has not fully translated into higher total fuel use thanks in part to efficiency improvements (EASA, 2019a). The stock of commercial aircraft in the EU28 has increased slightly from 6,515 in 2015 to 6,700 in 2016 (Eurostat, 2019). By the end of 2017, the stock of civil aircraft in the EU had 6,829 units, of which ca. 62% were passenger aircraft (EC, 2018e). **Figure 5-3** shows jet fuel use in the EU28 by domestic and international aviation. To mitigate emissions in the air transport system, part of jet fuel demand will have to be substituted.

CORSIA will allow aeroplane operators to claim benefits for the use of CORSIA Eligible Fuels (CEF). While the overarching rules have been adopted by International Civil Aviation Organization (ICAO) in June 2018, the accompanying technical requirements will likely be formally adopted by the end of 2019. Under CORSIA, aeroplane operators can reduce their offsetting requirements if they can demonstrate certification of the SAF used, against a set of sustainability criteria. CORSIA rules provide that a limited number of Sustainability Certification Schemes will be eligible to assess the compliance of the SAF against the sustainability framework. CEF can be either SAFs (renewable or waste-derived) or a Lower Carbon Aviation Fuels (fossil-based). In all cases, these fuels have to comply with a set of sustainability criteria. Until now, three sustainability criteria have been agreed to apply during the CORSIA pilot phase. These will require CEF to achieve at least 10% of emissions savings compared to a baseline defined for conventional jet fuel, and will require the CEF not to be obtained from land converted after 1 January 2008 that was high carbon stock land (e.g. forest, wetland, peatland, etc.). Under CORSIA, SAFs are assigned total life cycle emission values, which are computed with a life cycle assessment methodology, and through modelling to define induced land use change values. The rules agreed so far to account for the use of CEFs have been designed for Sustainable Aviation Fuels. An important piece of work remains to be done by the Committee on Aviation Environmental Protection (CAEP) Fuels Task Group to define a methodology and a sustainability framework for the use of Lower Carbon Aviation Fuels. Until this methodology is agreed, only SAF will be eligible under CORSIA. While some of the agreed rules have been provisionally agreed to apply only during CORSIA's pilot phase (2021-2023), all of CORSIA's rules related to fuels will necessarily be completed by the start of CORSIA's first phase on 1st January 2024. At this stage, there is no certainty on whether CORSIA will have a positive impact on the uptake of fuels. Stakeholders' views are reflected in **section 5.3.4, p. 181**.

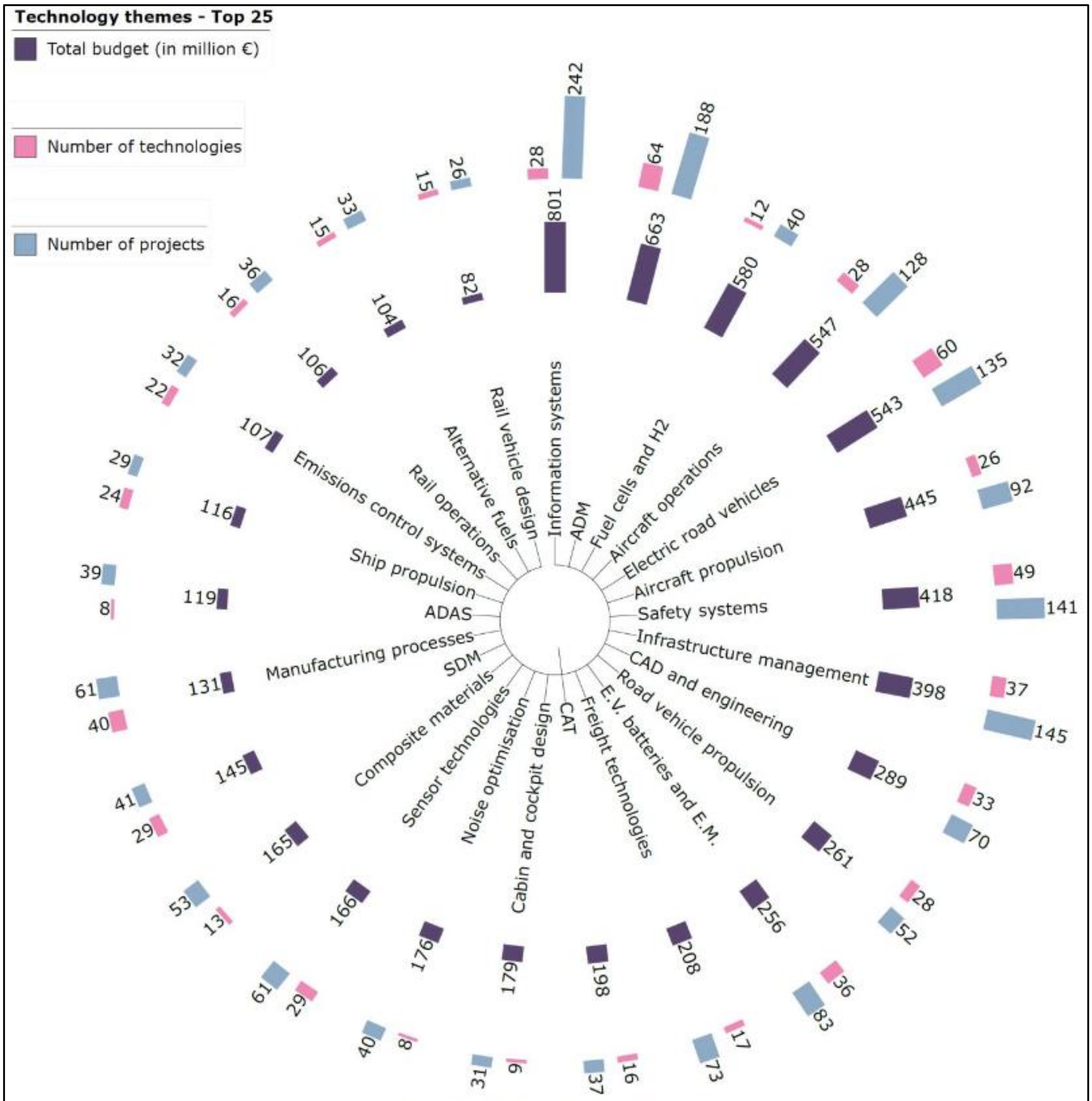
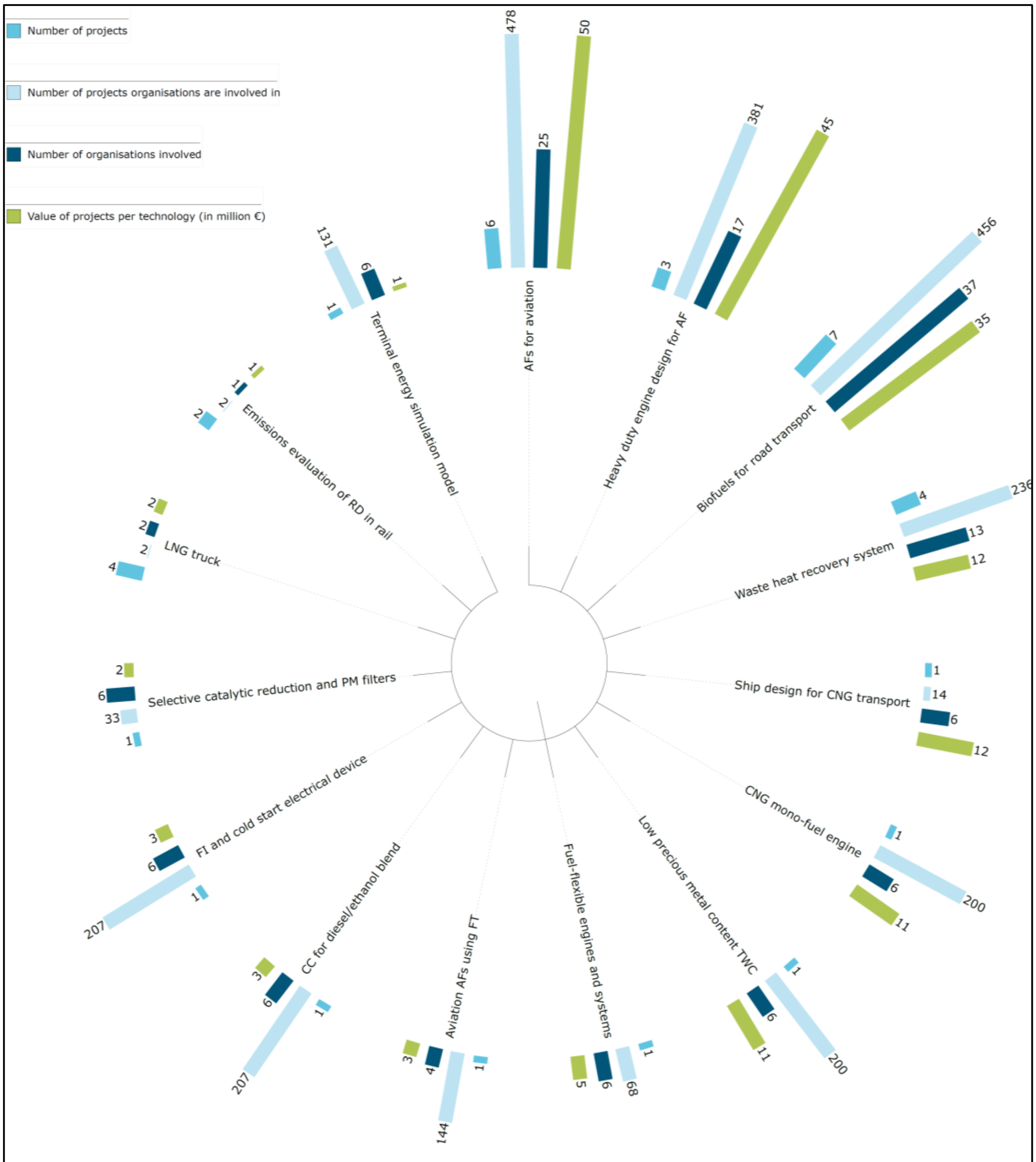



*Figure 1: Top 25 technology themes*

Abbreviations - ADM: Aircraft design and manufacturing; CAD: Computer-aided design; E.V.: Electric vehicle; E.M.: Energy management; CAT: Connected and automated vehicles; SDM: Ship design and manufacturing; ADAS: Advanced driver assistance systems

**Figure 5-4. Top 25 technology themes in Framework Programmes (2007-2020)**
**Source: JRC, 2019a**




Bars not in scale. Abbreviations: AF - Alternative Fuels; CC - Combustion Chamber; CNG - Compressed Natural Gas; FI – Fuel injection; FT - Fischer-Trop method; PF - Particulate Filter; RD - Renewable Diesel; TWC - Three-Way catalyst

**Figure 5-5. Top 15 technologies in Framework Programmes (2007-2020)**
**Source: JRC, 2019b**

Alternative fuels still play a relatively minor role in the EU transport systems. To increase the market share alternative fuels hold in these systems, there must be developments that make these fuels more attractive for both consumers and suppliers. This is possible through investment in research and innovation projects and deployment of infrastructure projects.

As can be seen in **Figure 5-4**, fuel cells and hydrogen have attracted €580 million of support for research and innovation, followed by electric road vehicles with €543 million, EV batteries and energy management with €256 million and alternative fuels with €104 million (see (JRC, 2019a)). The classification of these categories follows the Strategic Transport Research and Innovation Agenda (STRIA) roadmaps, and the TRIMIS NETTs analysis currently focuses on technologies researched in European Framework Programmes (FP), specifically FP7 (2007-2013) and Horizon 2020 (H2020) projects (2014-2020). For the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a budget of €1.33 billion is available (see **Box 7** in **section 5.2, p. 158**). Based on information from the STRIA roadmap on Alternative Fuels (thereby excluding electricity and hydrogen), **Figure 5-5** focuses on the top 15 alternative fuel transport technologies.

A summary of alternative fuel research in Europe, by parent programme, is provided in **Table 5-1**. In terms of research funding at the EU level, **Figure 5-6** shows daily funding under FP7 and H2020 by transport mode. **Figure 5-7** focuses on selected alternative fuels.

**Table 5-1. Alternative fuel research, by parent programme summary**
***European Research Area Net **Intelligent Energy Europe**
**Source: (JRC, 2019b)**

| *Parent programme* | *Total project value* | *Total EU contribution* | *Number of projects* |
|---|---|---|---|
| Horizon 2020 (2014-20) | € 378,432,226 | € 225,749,539 | 63 |
| FP7 (2007-2013) | € 318,986,109 | € 198,886,978 | 41 |
| ERA-NET* (2014-2020) | € 349,000 | € 349,000 | 2 |
| IEE** (2003-2013) | € 5,472,455 | € 4,445,460 | 5 |
| INTERREG (2014-2020) | € 21,286,887 | € 13,104,378 | 7 |
| LIFE (2014-2020) | € 17,367,557 | € 7,226,423 | 7 |

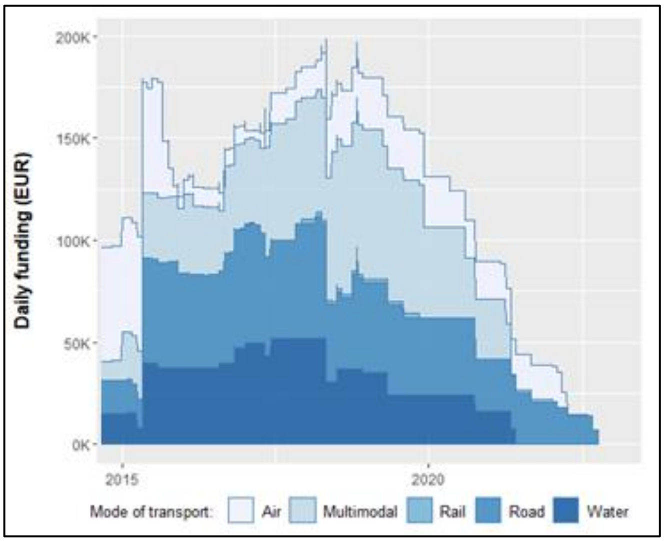



**Figure 5-6. Daily research funding by transport mode**
**Source: JRC, 2019b**

Concerning investment projects that support the deployment of alternative fuels infrastructure, **Table 5-2** shows the contribution of the Connecting Europe Facility (CEF).

**Table 5-2. Deployment of infrastructure actions**
**Source: (JRC, 2019b) (as of mid-2019**

| *Parent programme* | *Total project value* | *Total EU contribution* | *Number of actions* |
|---|---|---|---|
| CEF (2014-2020) | € 912,033,364 | € 284,669,659 | 52 |

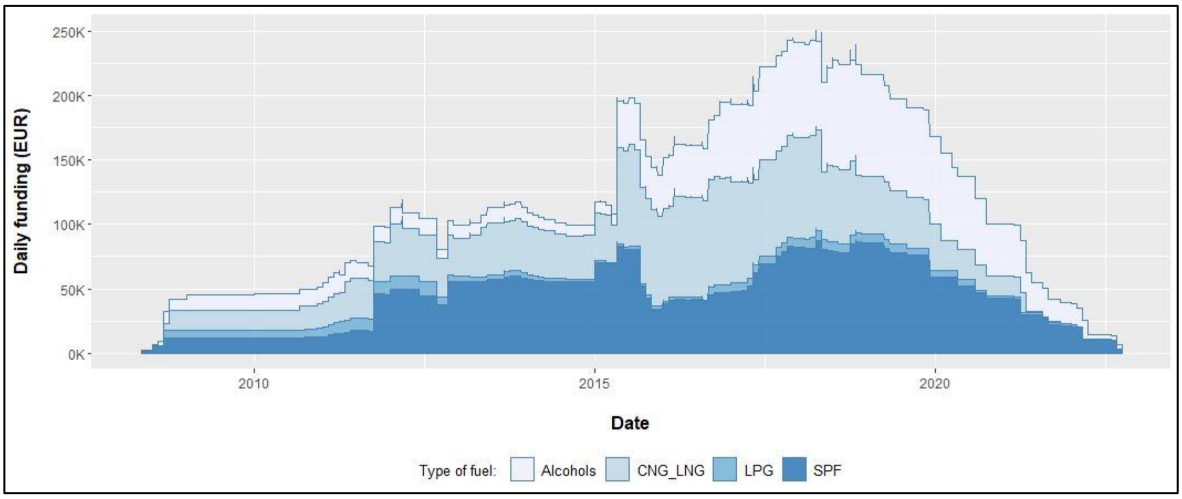



**Figure 5-7. Daily research funding by selected alternative fuel**
**Note: SPF refers to synthetic and paraffinic fuel**
**Source: JRC, 2019b**

## 5.1 ELECTRICITY

### 5.1.1 MATURITY OF TECHNOLOGY

The battery is the key component of an electric vehicle (EV), because its capacity, measured in kWh, influences the price, electric range, useful life and recharging time of the vehicle. Lithium-ion batteries (LIBs) remain the dominant technology in EVs (Iclodean, Varga, Burnete, Cimerdean, & Jurchiş, 2017). This technology is mature and diverse, as different cathode chemistries result in various types of LIBs (see **Figure 5-8**).

Three popular ones are LFP (particularly in buses), NCA (deployed in Tesla cars) and NMC (used by the majority of OEMs (Ruiz, 2018)). NMC is also preferred by PHEV manufacturers due to its longer lifetime (Zubi, Dufo-López, Carvalho, & Pasaoglu, 2018). According to the same authors, these three types of LIBs can be responsible for about 25% of the vehicle weight.

CLEPA expects 48-volt mild hybrid vehicles to play a role in the EU market in the future (personal communication). However, this type of vehicles and hybrid electric vehicles (HEVs) are beyond the scope of this report. Thus, lead-acid and nickel-metal hydride (Ni-MH) batteries are excluded from this analysis.

In 2017, (Olivetti, Ceder, Gaustad, & Fu, 2017) concluded that material availability is likely to be sufficient to meet the demand for LIBs in the next years, though the authors acknowledged that cobalt may pose a risk to LIBs in the near term.

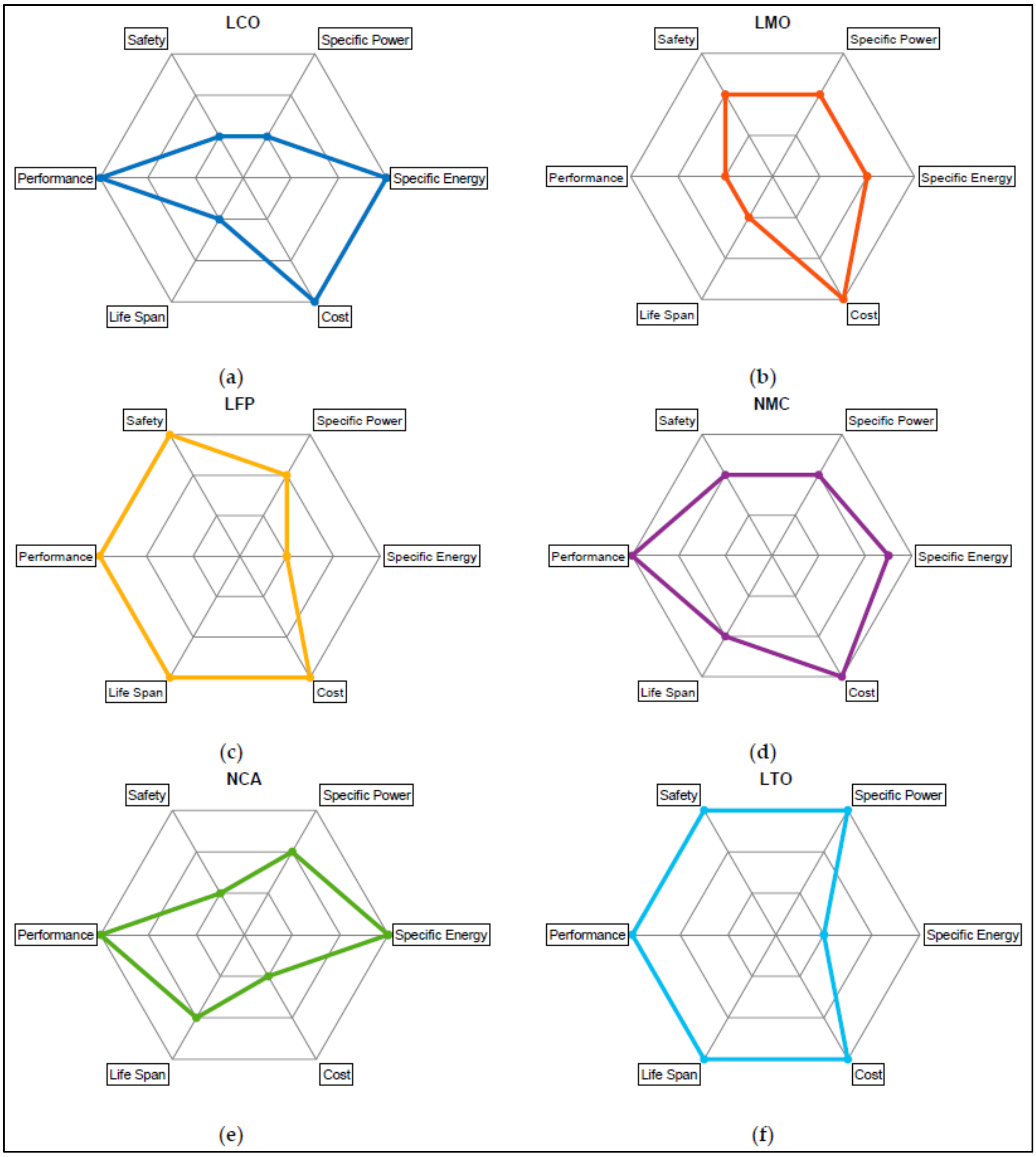



**Figure 5-8. Types of LIBs and their characteristics**
**Note: (a) Lithium Cobalt Oxide (LCO); (b) Lithium Manganese Oxide (LMO); (c) Lithium Iron Phosphate (LFP); (d) Nickel Manganese Cobalt (NMC); (e) Nickel Cobalt Aluminium (NCA); (f) Lithium Titanate (LTO).**
**Source: Saldaña, San Martín, Zamora, Asensio, & Oñederra, 2019**

Researchers continue to search for further improvements in battery performance. For instance, for LIBs (Yang et al., 2019) recently devised a method to recharge an EV in ten minutes for a range of 322-483 km. (Cavallo, Agostini, Genders, Abdelhamid, & Matic, 2019) demonstrated the use of a graphene sponge to improve degradation in a lithium-sulphur battery prototype.

Research in the automotive industry is ongoing on next-generation batteries (EUCAR, 2019). Over time, these technologies are expected to become mature, though uncertainty on the time horizon remains. (IEA, 2019c) expects NMC (8:1:1, 6:2:2, 5:3:2) and advanced NCA batteries to be increasingly used by 2025, thereby reducing the amount of cobalt needed in LIBs. (BU, 2019) lists five future batteries: Lithium-air, Solid-state Lithium, Lithium-sulphur, Lithium-metal and Sodium-iron. While Innolith asserts that the first three will likely not be commercially available before 2030 and plans to market a 1,000 Wh/kg battery in the next 4-5 years (BNEF, 2019c), some OEMs such as Renault, Toyota and Volkswagen seem to be more confident that solid-state batteries might be ready by 2025 (CarSales, 2019) (DE, 2019) (Toyota, 2019c) (VW, 2018b). OEM investments in solid-state and lithium-silicon technology firms underlie the strategic importance of these batteries (E&H, 2019). AVERE considers the silicon-based LIB (NMC (6:2:2) cathode and silicon alloy anode) to be the most likely battery by 2030 (personal communication).

In addition to the battery, the electric motor is another crucial component in EVs. Two technologies currently co-exist: induction and permanent magnet (PM). As can be seen in **Table 5-3**, the latter contains dysprosium (Dy) and neodymium (Nd), two rare earth elements considered as highly critical materials by (Moss, Tzimas, Willis, Arendorf, & Tercero Espinoza, 2013). Concerns over the future availability of raw materials for key EV components have been expressed by several stakeholders in personal communication (e.g. AEGPL, ALSTOM, ART FUELS). In 2017, the majority of EVs featured PM motors (Riba, López-Torres, Romeral, & Garcia, 2016), with the exception of Tesla and Renault. Tesla seems to have recently included PM in two-motor configurations (Reuters, 2018c) (Roskill, 2019). With regards to rare earth elements in electric motors, AVERE believes that various possibilities to replace or reduce them exist (personal communication). Tesla and Renault already have successful rare earth-free motors models, and by 2020, BMW plans to offer electric cars free of rare earth elements (BMW, 2019a).

**Table 5-3. Main materials in key EV components**
**Source: J. J. Gómez Vilchez, 2018 based on Moss et al., 2013**

| | | | Materials [kg] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *Al* | *Co* | *Cu* | *Dy* | *Graphite* | *Li* | *Mn* | *Nd* | *Ni* |
| **PHEV** | ***Motor*** | PM | - | - | - | 0.22 | - | - | - | 1.46 | - |
| | | Induction | - | - | 40.00 | - | - | - | - | - | - |
| | ***LIB*** | NMC | - | 2.38 | 8.39 | - | 9.07 | 0.79 | 2.20 | - | 2.46 |
| | | NCA | 0.23 | 1.44 | 11.41 | - | 12.33 | 1.06 | - | - | 7.97 |
| **BEV** | ***Motor*** | PM | - | - | - | 0.38 | - | - | - | 2.55 | - |
| | | Induction | - | - | 70.00 | - | - | - | - | - | - |
| | ***LIB*** | NMC | - | 13.91 | 49.13 | - | 53.08 | 4.64 | 12.88 | - | 14.43 |
| | | NCA | 1.35 | 8.44 | 66.82 | - | 72.19 | 6.23 | - | - | 46.65 |

With regards to electrification of the different transport modes, the EU Long-Term Strategy for GHG emissions reduction identified road transport as the mode in which electrification is more suitable (EC, 2018c).

**Box 1. Notes on the EU position on battery manufacturing**

This section briefly examines how well Europe is positioned in the markets for alternative fuels. With regards to the manufacturing of electric vehicle batteries, Asian players dominate the cells market (Lebedeva, Di Persio, & Brett, 2016). **Table 5-4** shows the estimated current and future electric vehicle cell and battery manufacturing capacity in the EU.

**Table 5-4. Battery manufacturing capacity in the EU, by location**
**Source: own work based on (Daimler, 2017) (Daimler, 2019f) (EC, 2019c) (Electrive, 2019a) (GSYuasa, 2018) (Hyperbat, 2019) (LGChem, 2019) (Nissan, n.d.) (Northvolt, 2019) (SamsungSDI, 2017) (SKI, 2018) (VW, 2019e) and (Tagesspiegel, 2019).**

| Location | Firm | Start | Production[a] | *Capacity[b]* |
|---|---|---|---|---|
| Berlin area (Germany) | Tesla | | | |
| Erfurt (Germany) | CATL | 2022 | 14 GWh/year | *60 GWh/year* |
| Kamenz (Germany) | Accumotive (Daimler) | 2012 | 2 GWh/year | |
| Salzgitter (Germany) | VW | 2023-2024 | 16 GWh/year | |
| Sindelfingen (Germany) | Daimler | | | |
| Untertürkheim (Germany) | Daimler | | | |
| Göd (Hungary) | Samsung SDI | 2018 | 2.5 GWh/year[c] | |
| Komárom (Hungary) | SK Innovation | 2020 | 7.5 GWh/year | |
| Miskolc (Hungary) | GS Yuasa | | | |
| Dolnośląskie (Poland) | LG Chem | | 4 GWh/year[c] | |
| Jawor (Poland) | Daimler | >2020 | | |
| Wrocław (Poland) | LG Chem | 2017 | 5 GWh/year[c] | *15 GWh/year* |
| Skellefteå (Sweden) | Northvolt | 2020 | 16 GWh/year | *32 GWh/year* |
| Coventry (UK) | Hyperbat | 2019 | 0.7 GWh/year[d] | |
| Sunderland (UK) | Envision | 2013 | 2 GWh/year | |
| *Europe (undetermined)* | *Saft / PSA* | | | |
| *Europe (undetermined)* | *BYD* | | | |

[a] Estimated current or initial annual production capacity. [b] Targeted full capacity after expansion plans. [c] Assuming 50 kWh/vehicle. [d] Assuming 65 kWh for the Aston Martin Rapide E

European LIB manufacturing capacity is expected to increase from ca. 3% to 8% of the world market by 2022 and may reach 105 GWh by 2028, with most of this capacity available in Germany, Poland and Sweden (personal communication by AVERE). In addition to information gaps, there is uncertainty with regards to new construction and expansion plans as well as to the extent to which capacity reflects *cell* manufacturing capacity. For instance, Samsung SDI will be sourcing *cells* to Webasto as well as to AKASOL (13 GWh of battery *cells* and *modules* over 2020-2027) for production of LIB *systems* in Europe (AKASOL, 2019) (Webasto, 2019). The table also excludes Samsung SDI's battery *systems* production site in Graz (Austria) as well as Northvolt's LIB *systems* production facility in Gdańsk (Poland), which is expected to ramp up manufacturing to 10,000 modules/year (Northvolt, 2019). BMW, Scania and VW are Northvolt's industrial partners. The TerraE plans for a 34 GWh battery cell production site have also been excluded from the table, as (Tagesspiegel, 2018) reported that this project has been cancelled. Europe's market share in LIB cell manufacturing is expected by (BNEF, 2019b) to increase from 4% (<13 GWh) in 2019 to 11% (133 GWh) in 2025. By 2030, the European ambition is to hold 30% of the market (JRC, 2019c). By 2040, (McKinsey, 2019) projects that the demand for batteries from EVs annually produced in Europe will approximate 1,200 GWh. It remains to be seen whether these plans, including the ones in **Table 5-4**, materialise or not. There is a risk that the EU continues to rely heavily on battery imports, at least in the near future. To mitigate that risk, initiatives have been made such as the prominent European Battery Alliance (EBA, 2019). (Steen, Lebedeva, Di Persio, & Boon-Brett, 2017) highlighted two necessary conditions for successful European LIB cell manufacturing: lowered risk for private investors and room for economies of scale exploitation.

**Figure 5-9** shows how battery capacity and e-range have evolved since 2015 for the small-sized Renault Zoe and the medium-sized Nissan Leaf passenger cars. Following increases in battery capacity and e-range, today there are model variants of these two BEVs that nearly achieve 400 km of e-range in the European car market. This range is way above the average daily distance driven by Europeans (Pasaoglu, 2012) and considered sufficient to increase user acceptance. A version of the Tesla Model S offers an e-range of 610 km based on the worldwide harmonised light vehicle test procedure (WLTP) (Tesla, 2019a). (VW, 2019d) asserts that if the eGolf's LIB were replaced with a solid-state battery, which is safer and offers greater fast recharging capability, its e-range would reach about 750 km, compared to the current e-range of 231 km.

In the SUV segment, three examples of upcoming electric SUVs are: Audi e-tron (95 kWh battery for a WLTP e-range of 411 km (ADAC, 2019a)), Jaguar I-Pace (90 kWh battery for a WLTP e-range of 480 km (ADAC, 2019c)) and Mercedes EQC (80 kWh battery for a WLTP e-range of 390 km (ADAC, 2019d)). In other words, an extra battery capacity of around 30 kWh is needed for vehicles in the SUV segment to achieve a similar e-range as lighter and more aerodynamic cars. In addition to their higher electricity consumption, the fact that SUVs require larger batteries has at least two important implications. First, in the event of battery supply constraints, a business decision will have to be made on which segment receives the battery orders. Second, SUV GHG emissions associated with battery manufacturing are expected to be considerable higher than those of cars requiring smaller battery capacities.

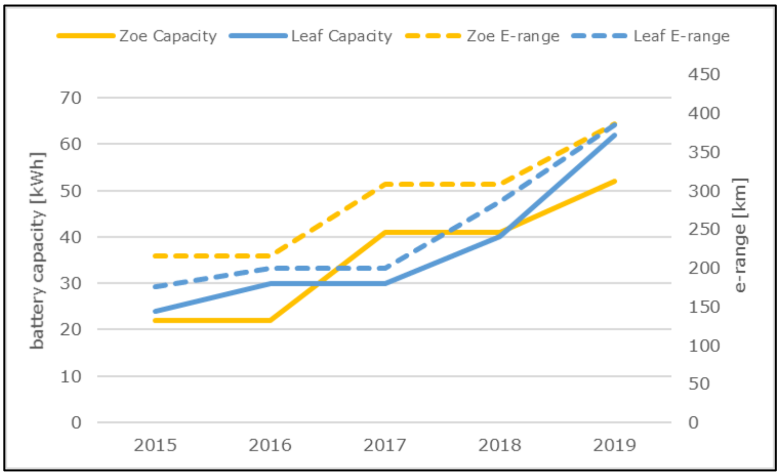



**Figure 5-9. BEV e-range and battery capacity**
**Source: own analysis based on (Nissan, 2019b) and (Renault, 2019c)**

E-range is dependent also on average speed. **Figure 5-10** shows the relationship between these two variables for the Zoe, under two battery capacities: 22 kWh and 41 kWh. As can be seen, when the average speed of the electric car is higher, the electric range decreases.

In terms of LCVs, several versions of the 40 kWh battery-powered electric Street scooter are available: 720 kg of payload (WORK version with a range of 101 km), 585 kg (WORK with a range of 205 km) and 905 kg (WORK L with a range of 187 km). In addition, a version with a 76 kWh battery (WOK XL) offers a payload of 1,150 kg and a range of up to 200 km (StreetScooter, 2019)[54]. (Daimler, 2019g) has announced an electric version of the Vito (eVito) with a 41 kWh battery capacity delivering a 150km e-range. A year later, the eSprinter with a payload of up to 900 kg will be introduced with a 55 kWh battery capacity, providing also an e-range of 150 km. IVECO has announced the Electric Daily, with an autonomy ranging from 90 to 130 km at full load.

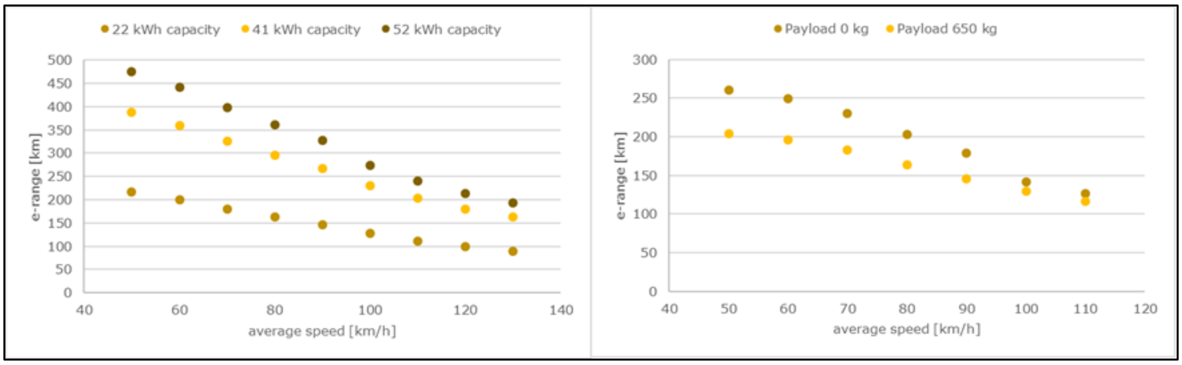



**Figure 5-10. E-range and average speed, by battery capacity (left) and payload (right) Source: own work based on the Zoe car (left) and the 33 kWh Kangoo Z.E. LCV (right) using respectively (Renault, 2019c) and (Renault, 2019b)**

In the 2015 report, electric buses were expected to reach market maturity soon. This expectation can today be considered confirmed. Depending on the charging strategy, differences in the bus battery capacity exist: on average, 75-100 kWh for opportunity charging and 250-300 kWh for overnight charging (personal communication by RATP). This can be seen, for a selection of electric buses, on **Table 5-5**. As with electric cars, the battery capacity affects the e-range. For instance, the eCitaro will have a 292 kWh battery capacity and an estimated e-range of 150 km (250 km under ideal conditions) (Daimler, 2019c). (Irizar, 2019) has recently announced that the new generation of its 'ie' electric bus will have a 350 kWh battery capacity and a range of approximately 250 km under standard weather conditions. There seems to be a trend in this sector to move from LFP to NMC (see e.g. Aptis in **Table 5-5**) and, in the near future, to solid-state batteries (GCC, 2019). With regards to coaches, a study on the future alternative fuel coaches assumes an average annual mileage of 60,000 km (of which only 10% in urban areas) (IRU, 2019). In other words, these vehicles face different operating conditions than urban buses. The market maturity is lower for electric coaches than for electric buses. (IRU, 2019) asserts that the technology maturity of even diesel-electric coaches is currently low.

[54] The range in these models is, however, based on the New European Driving Cycle (NEDC).

**Table 5-5. Selection of electric buses in Europe, by characteristic**
**Source: adapted from (J. Gómez Vilchez, 2019)**

| Type | Length | Manufacturer | Model | Battery | Capacity [kWh] | Charging time | Supplied by | Seats / max. PAX | Year |
|---|---|---|---|---|---|---|---|---|---|
| PHEV | 12m | Businova / SAFRA | Standard | LFP | 132 | 4-6 h | EVE System | N/A 100 | 2017 |
| BEV | 12m | ADL | Enviro200 EV | LFP | 324 | 4 h | BYD | N/A / 90 | 2016 |
| | | ALSTOM / NTL | Aptis | Sodium nickel | *309* | 7-8 h | Fiamm | N/A / 77 | 2017 |
| | | ALSTOM / NTL | Aptis | NMC | N/A | N/A | Foresee Power | N/A / 95 | 2019 |
| | | Bollore | BlueBus | Lithium metal polymer | 240 | 5 h | Blue Solutions | N/A / 97 | 2016 |
| | | Bozankaya | Sileo S12 | LFP | *215* | 2-8 h | Bozankaya | N/A / 79 | 2015 |
| | | BYD | 12m | LFP | 330 | 4-4.5 h | BYD | 31 / 90 | 2013 |
| | | Irizar | ie | Sodium nickel | 376 | 6-7 h | Fiamm | N/A / 82 | 2014 |
| | | Daimler | eCitaro | NMC | 243 | N/A | AKASOL | 29 / 93 | 2019 |
| | | Skoda Electric | Perun HE | LFP | 230 | 4-6 h | various | N/A / 82 | 2013 |
| | | Solaris | Urbino 12 electric | LFP/ Lithium titanate | ≤ 240 | *32 min - 3 h* | Solaris | 38 / ≤ 90 | 2012 |
| | | VDL | Citea SLF-120 | various | *133* | 5 min - 4.5 h | various | N/A / 92 | 2014 |
| | | Volvo | 7900 electric | LFP | 76 | 3-6 min | SAFT | 35 / ≤ 95 | 2016 |
| | | Yutong | E12 | LFP | 324 | 5.5 h | CATL | N/A / 77 | 2017 |
| | 18m | Bozankaya | Sileo S18 | LFP | *215* | 3-8 h | Bozankaya | N/A / 137 | 2016 |
| | | BYD | 18m articulated | LFP | 547 | 2 h | BYD | ≤ 60 / ≤ 180 | 2016 |
| | | Irizar | ie tram | various | *150* | 5-10 min - 2 h | various | N/A / ≤ 150 | 2017 |
| | | Solaris | Urbino 18 electric | LFP/ Lithium titanate | ≤ 240 | *32 min - 3 h* | Solaris | 48 / ≤ 129 | 2013 |

One option to electrify heavy freight transport is hybrid trolley trucks (dena, 2018). Several truck manufacturers claim to be developing hybrid and electric solutions (e.g. (DAF, 2018) (MAN, 2019b) (Volvo, 2018)). Concerning electric HCVs, a three-axle 25t vehicle with a battery capacity of 310 kWh and an e-range of up to 300 km (the maximum speed is 85 km/h) is being tested in Switzerland (ABB, 2019). Furthermore, pre-production tests on a 26t 100% electric refuse collection vehicle with a battery capacity of 200 kWh and an e-range of up to 200 km is being performed in France (Volvo, 2019a).

The technology to power railway vehicles with electricity is mature. In electrified railway lines, this technology is dominant. In non-electrified routes, battery-powered railway vehicles are an option. For instance, the 'TALENT 3' features a LIB that can be charged at stations (Bombardier, 2018) while the 'Desiro ML ÖBB Cityjet eco' has a battery capacity of 528 kWh and allows a maximum speed of 120 km/h (Siemens, 2019a). Advanced batteries such as solid-state and zinc-air emerge as promising technology options (personal communication by ALSTOM).

Electricity use in the water transport system can be considered for stationary and non-stationary operation. The latter is included in (EU, 2014) as shore side electricity supply to vessels at berth.

Battery-powered electric vessels represent an option to achieve zero emissions in inland waterway transport (Moirangthem, 2016) (LR/UMAS, 2017) (EC, 2018c). This propulsion technology is mature for some applications such as small vessels or vessels with short and repetitive sailing patterns (e.g. ferries) (personal communication by CCNR).

In maritime transport, battery-powered electric propulsion was identified as an option by (Moirangthem, 2016) (DNV-GL, 2018b) (T&E, 2018b). (EC, 2018c) indicated that this technology may be feasible for short sea shipping. However, for deep sea vessels it is currently not sufficiently mature because of the limited range delivered by the battery (personal communication by IOGP) (see also (DNV-GL, 2019b)).

Electricity use in the air transport system can be considered for stationary and non-stationary operation. The latter is included in (EU, 2014) as electricity supply to stationary aircraft at airports. (Brelje & Martins, 2019) recently surveyed electric aircraft conceptual studies, prototypes, demonstrators and commercial products, concluding that challenging practical problems remain. Battery energy density has improved in recent years (EVI, 2017) but differences between types of LIBs persist. For aviation, a density of 500 Wh/kg is considered acceptable (RB, 2017). But this is still far from the current density of LIBs. According to (NAP, 2016), major advancements in the state-of-the-art of electrical technologies are required to use turboelectric propulsion for commercial aircraft operations.

Battery-powered electric aircrafts are under development (EC, 2018c). (RB, 2017) surveyed about 70 electrically-propelled aircraft development programmes, of which a few are for large commercial aircraft. Fully electric flights are still regarded as an unrealistic option, with the exception of lightweight applications such as air taxis (personal communication by Lufthansa).

**Infrastructure**: The adoption of EVs is also dependent on the availability of EV charging infrastructure. The development of this infrastructure needs to be carefully considered so that it serves the needs of EV owners but also encourages more consumers to purchase electric vehicles.

Depending of the power level giving the speed of charging, the recharging points are classified according to (Commission, 2014) in normal power recharging points that can assure up to 22kW (AC), and high power recharging points, delivering more than 22 kW (AC or DC). The charging points can be divided into categories based on charging mode and charging type (for an overview see (Spöttle, M. et al., 2018)).

Due to the technological developments and EV range growth, the charging speed / power of the infrastructure is also increasing. Several EU funded projects involving consortiums of partners (automakers, utility companies, etc.) aim to deploy DC ultra-fast recharging points of up to 350 kW, especially on the TEN-T Core Network (see for details **Table 5-6**).

**Table 5-6. Characteristics of ongoing DC ultra-fast recharging infrastructure deployment co-financed by CEF**
**Source: own elaboration based on Innovation and Networks Executive Agency (INEA) (personal communication) and (ICCT, 2018b)**

| Network name | Region | Number of high power recharging stations | Recharging points power | Major partners and funders | Timeline |
|---|---|---|---|---|---|
| ultra-E (ultra-E, 2015) | Germany,<br><br>Netherlands,<br><br>Belgium, Austria | 25 locations,<br><br>50–100<br><br>recharging points | 175–350 kW | Allego, Verbund, Smatrics, Bayern Innovativ, Audi, BMW, Magna, Renault, Hubject, European Union | To be completed by December 2019 |
| MEGA-E (MEGA-E, 2017) | Central Europe,<br><br>Scandinavia (20 countries) | 163 locations<br><br>Up to 652 recharging point<br><br>+ 39 hubs<br><br>+/- 1000 recharging points | Up to 350 kW | Allego, European Union | To be completed by December 2021 |

| | | | | | |
|---|---|---|---|---|---|
| NEXT-E (NEXT-E, 2016) | Croatia, Czechia, Hungary, Romania, Slovakia, Slovenia | 200 (50 kW) & 30 (150-350 kW) locations 222 recharging points (50kW) | 50–350 kW | E.ON Group, MOL Group, PETROL, Nissan, HEP, BMW, European Union | To be completed by December 2020 |
| E-VIA FLEX-E (E-VIA FLEX-E, 2016) | Italy, France, Spain | 14 locations 28-112 recharging points | 150 - 350 kW | Enel (coordinator), EDF, Enedis, Verbund, Nissan, Renault, Ibil, European Union | To be completed by March 2021 |
| CEUC – Central European Ultra Charging (CEUC, 2017) | Austria, Czechia, Bulgaria, Italy, Hungary, Slovakia, Romania | 118 locations Up to +/- 500 recharging points | Up to 350 kW | VERBUND (coordinator), ENEL X, OMV, GreenWay, SMATRICS, European Union | To be completed by May 2021 |
| High speed electric mobility across Europe (E.ON, 2016) | Germany, France, Norway, Sweden, UK, Italy and Denmark | 158 locations 216 recharging points (2 points per station) | 150 - 350 kW | CLEVER, E.ON, European Union | Construction from 2017 - 2020 |
| EUROP-E (EUROP-E, 2019) | Europe (13 countries) | 340 locations At least 680 recharging points | up to 350 kW | Ionity (a joint venture established by BMW, Daimler, Ford, and Volkswagen with its subsidiaries Audi and Porsche), European Union | Construction from 2017 - 2021 |
| AMBRA-E (2018) | Italy, Romania, Spain | 30 locations At least 60 recharging points | Up to 350kW | Enel X s.r.l. | To be completed by December 2022 |
| SYNERGY | Austria, Germany | 10 locations equipped with stationary battery storage system for ultra-fast recharging points | 500kW per location | Verbund AG | To be completed by December 2019 |

Technology is progressing for recharging points also because of increasing interest for electric heavy-duty vehicles (buses and trucks). There is growing interest in mega recharging points that could charge at 1 MW or more (e.g. for use in trucks, shipping and aviation) (IEA, 2019c).

The electric buses are supplied with electricity by recharging points located in depots (depot charging) and/or along or at the end of the bus routes (opportunity charging). According to (ACEA, 2017a), their choice depends on the structure of the bus line (route length, speed, number of stops, topography, passenger capacity and other parameters), energy strategy, battery capacity/functionality, etc. The size of the energy storage system will be dependent on the charging strategy bridging from large storage for only overnight depot charging, up to small storage when charged also at bus stops (opportunity charging) or by dynamic charging (ERTRAC, 2017). A recent real-world example of fast opportunity charging for electric buses by means of 200 kW ground recharging infrastructure in the context of the European project PALOMA can be found in (SustainableBUS, 2019).

For the deployment of publicly accessible charging infrastructure, two main approaches exist (Spöttle, M. et al., 2018). The demand-oriented approach consists in placing the charging infrastructure at those sites where existing and future demand can be determined which would allow an optimal allocation and utilisation of all recharging points and also an avoidance of redundancies. The coverage-oriented approach follows the idea that the charging infrastructure should guarantee a minimum standard of service to the widest possible public by minimising the distance between the charging points, which would diminish the drivers' range anxiety by providing a safety net for emergencies. In its AFI Directive (EC, 2014), the EC followed a hybrid approach by requesting the MSs to have deployment strategies for the more populated urban and suburban areas (demand-oriented approach) and for the main roads included in the TEN-T Core Network (coverage-oriented approach that would allow cross-border continuity throughout the EU).

Alternatives to the current conductive charging technologies – AC or DC recharging points with a cord that connects to the vehicle - have raised interest with the promise of alleviating some of the existent drawbacks (e.g. the length of charge time, the weight of the battery, etc.) but the majority of these are not yet commercially viable on a large scale. We consider here the following alternative charging technologies: battery swapping and electric road systems (ERS).

Battery swapping stations can offer the advantage of reduced recharging time since they allow replacing the entire battery pack in few minutes. This concept attracted the greatest level of interest and investment in the early years of electro-mobility (2008-2014), when countries like China, Denmark and Israel deployed public battery swapping stations (Spöttle, M. et al., 2018). However, this solution required all vehicles to be designed for easy battery access and standardisation across vehicles that constituted a barrier to being adopted widely and caused the concept to be dropped in many countries. One exception is China, where the EV manufacturer Nio built in 2018 a network made of 18 battery swap stations located in 14 service areas near main cities along a major transit route running from Northern to Southern China (Beijing to Shenzhen) and 8 battery swap stations from Beijing to Shanghai (NIO, 2018). In Europe, currently only the concept vehicle SEAT Minimó is featuring a battery swap system (SEAT, 2019), a quadricycle being proposed as a solution for urban micro mobility in the future.

Electric Road Systems (ERS) can be defined as roads supporting dynamic power transfer to the vehicles from the roads on which they are driving (Chen, Taylor, & Kringos, 2015). The two most common ways for this transfer are the conductive and the inductive or wireless solutions.

In a conductive system, energy is transferred by establishing a physical contact between the vehicle and a conductor. These systems can use overhead transmission lines (the vehicle connects to the transmission lines through a type of pantograph) or road-based technologies (the supply of electricity is through a physical pick-up that connects to an electrified rail in the road) (Taljegard, Thorson, Odenberger, & Johnsson, 2019).

The eHighway system (Siemens, 2019b) is providing a continuous energy supply to heavy commercial vehicles by active pantographs that can easily connect to and disconnect from the overhead contact line at speeds ranging from 0 to 90 km/h. The first eHighway system on a public road was inaugurated in June 2016 in Sweden (two-kilometre stretch of the E16 highway north of Stockholm) and was tested for two years with two adapted diesel-hybrid trucks manufactured by Scania. In May 2019, within an eHighway project in the German state of Hessen were inaugurated ten kilometres of the A5 autobahn near Frankfurt Airport while other two projects are under development in the states of Schleswig-Holstein (FESH, 2019) and Baden-Württemberg. From 2019, Scania is to supply 15 trucks for the German eHighways projects (Scania, 2018b).

In April 2018, within the electric road eRoadArlanda project were inaugurated two kilometres of electric rail installed in a public road close to Arlanda Airport outside Stockholm in Sweden (eRoadArlanda, 2018). The electrified road works by transferring energy to the vehicle in motion from a rail in the road through a movable arm and are used by electric trucks developed as part of the project.

With inductive technology, the energy is transferred wireless through a magnetic field and no physical connection between the road and the vehicle is required. The main advantages of this technology are the simplicity, reliability, and user friendliness. On the other hand, compared to current conductive solutions it is more expensive and less efficient due to the transfer of power through the air. Wireless charging is a technology under development for commercial launch, with complex operational and safety issues that must be addressed (Spöttle, M. et al., 2018) (e.g. electromagnetic compatibility issues, limited power transfer). In the last years, several European funded projects studied the technical feasibility, built prototypes and performed tests related to the inductive charging technology ((FASTINCHARGE, 2015), (UNPLUGGED, 2015), (FABRIC, 2017), (MICEV, 2019)).

Two major applications are being developed, static and dynamic wireless charging systems (Panchal, Stegen, & Lu, 2018). The static systems are utilised when the car is parked or in stationary modes, such as in car parks, garages and at traffic signals. In 2018, BMW has introduced a factory-fitted, integrated static inductive charging feature for its 530e iPerformance PHEV (BMW Group, 2018). The system started as a leasing option in Germany, and subsequent rolling out in the UK, the US, Japan and China was announced. It consists of a GroundPad, which can be installed in a garage or outdoors, and a CarPad fixed to the underside of the vehicle. The system has a charging power of 3.2 kW and an efficiency rate of around 85 percent.

For dynamic wireless charging systems, the charging technology is embedded in the roadway and vehicles are charged when they drive over it. This latter is considered to be a solution for future EV automation (Spöttle, M. et al., 2018), a promising technology option according to ALSTOM (personal communication) and is also known as ‟roadway powered”, ‟on-line” or ‟in motion”. Compared to stationary wireless charging, this technology option is farther from commercial viability and more costly because it needs to be built into lengths of roadway. It is being pursued especially for bus or other fleet operations that drive a fixed route, where the cost of roadway upgrades could be limited. A demonstration road system project (Smart Road Gotland, 2019) with dynamic wireless power transfer started in 2019 on the island of Gotland in Sweden. It is expected that in 2022 a 1.6 km long electric road will charge inductively both an electric truck and a bus while in full motion.

Shore-side electricity (SSE) supply / cold ironing / shore connection / shore-to-ship power / alternative maritime power / on-shore power supply (OPS) are names given to the technology that allows the ship at berth to be connected to the land based electricity grid while its main and auxiliary engines are turned off and thus to eliminate emissions, noise and vibration to the local surroundings. The implementation of SSE has been rather challenging since significant investment is required for the shore-side installations and for the connecting technology on board of the vessels (Sciberras, Zahawi, & Atkinson, 2015).

SSE infrastructure is financed through CEF in several EU ports and the list of these project is presented in **Table 5-7**.

**Table 5-7. Projects on SSE infrastructure co-funded by CEF**
**Source: INEA (personal communication)**

| | | |
|---|---|---|
| 2014-EU-TM-0066-M | The Northern ScanMed Ports - Sustainable Maritime Links | Ports of Stockholm (VArtahamnen and Kappelskär): OPS installations<br><br>Port of Naantali: studies on LNG bunkering and OPS<br><br>Port of Turku: OPS (preliminary installations) |
| 2014-EU-TM-0489-S | Zero Emission Ferries - a green link across the Öresund | High Voltage (10 400 V) Battery Charging - Ports of Helsingor and Helsingborg |
| 2014-EU-TM-0640-M | Sweden-Poland Sustainable Sea-Hinterland Services "Sustainable Swinoujscie-Trelleborg MoS based on upgrading port infrastructure, developing intermodal transport and integrating hinterland corridors." | Port of Swinoujscie |
| 2015-EU-TM-0178-M | Bothnia Bulk - Environmental upgrade of year-round supply in the northern Baltic Sea | Luleå |
| 2015-EU-TM-0417-S | Masterplan for OPS in Spanish ports | Santa Cruz, Palma de Mallorca – in preparation phase, Las Palmas (not yet decided) |
| 2015-EU-TM-0235-S | ELEMED – ELectrification of the Eastern MEDiterranean area (use of Cold Ironing and electricity as a propulsion alternative) | Kyllini |
| 2016-EU-TM-0277-S | BENEFIC | Antwerp, Wijnegem (INLAND) |
| 2017-SE-TM-0061-W | Long-term achievements - ready for a sustainable core port in Trelleborg (LARS) | Trelleborg |
| 2017-EU-TM-0135-W | TWIN-PORT 3 | Helsinki, Tallinn |

Aircraft emissions and noise can be reduced if airports provide Fixed Electrical Ground Power (FEGP) and Pre-Conditioned Air (PCA) to aircrafts at the airport gate. This would allow aircrafts to switch off their auxiliary power units (APU) at terminal gates and to obtain electricity direct from the local grid, reducing fuel consumption and pollutants. The provision of Pre-Conditioned Air (PCA) would allow aircrafts to use the airport's air conditioning system to control the temperature on board (EC, 2017b).

### 5.1.2 DATA ON VEHICLES AND INFRASTRUCTURE

By far, the largest EV market is China, with stocks by the end of 2018 of over 300 million electric two- and three-wheelers, 2.3 million electric cars, 138,000 electric LCVs, 460,000 electric buses and around 5,000 electric HCVs (IEA, 2019b). For comparison, the stocks of electric road vehicles in the EU in 2018 were: ca. 75,000 light electric vehicles (L category), 1.1 million electric cars (M1 category), over 74,000 LCVs (N1 category), 2,000 buses (M2-3 category) and 172 electric trucks (N2-3 category) (EAFO, 2019).

**Figure 5-11**Figure 5-11 shows the best-selling EV models worldwide in 2017 and 2018. Global electric car sales and stocks over the period 2013-2018 are respectively shown in **Figure 5-12** and **Figure 5-13**.

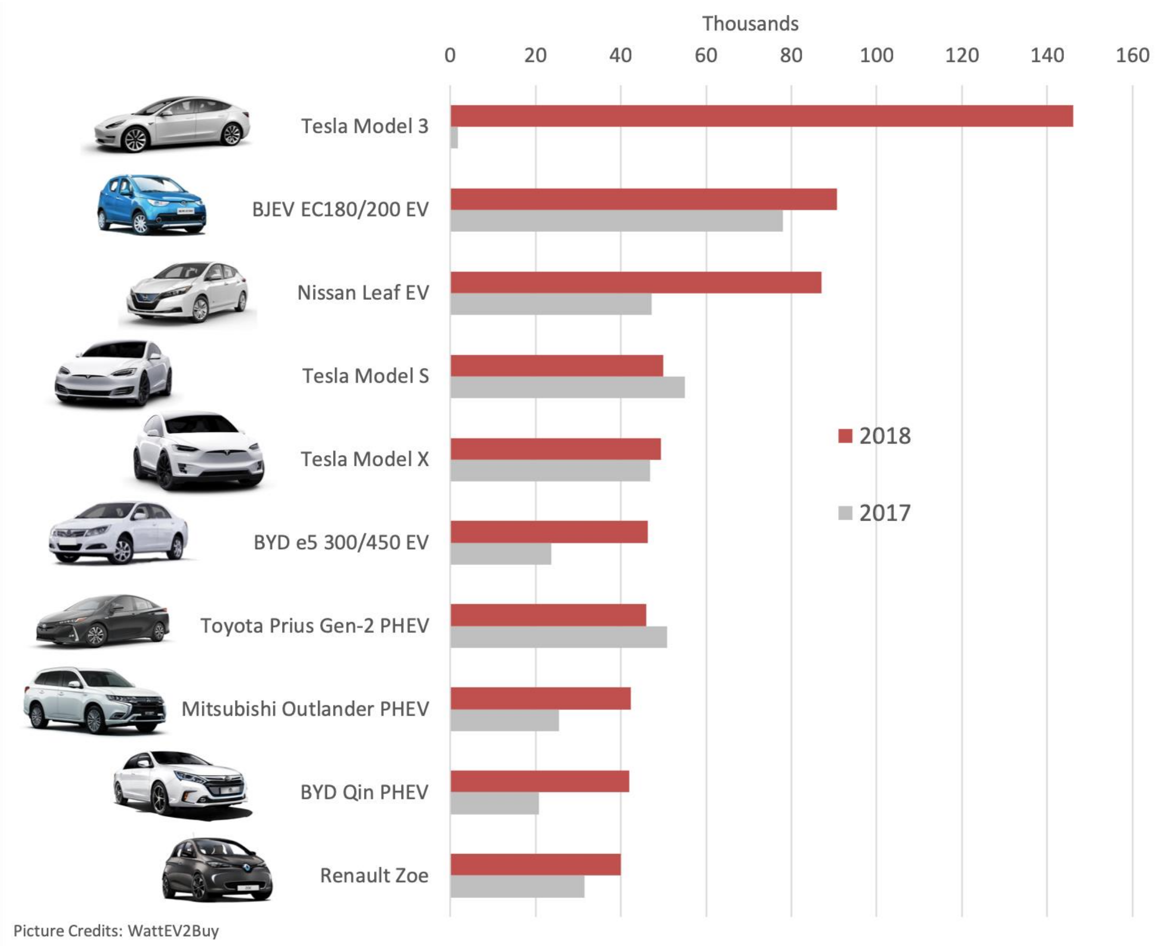
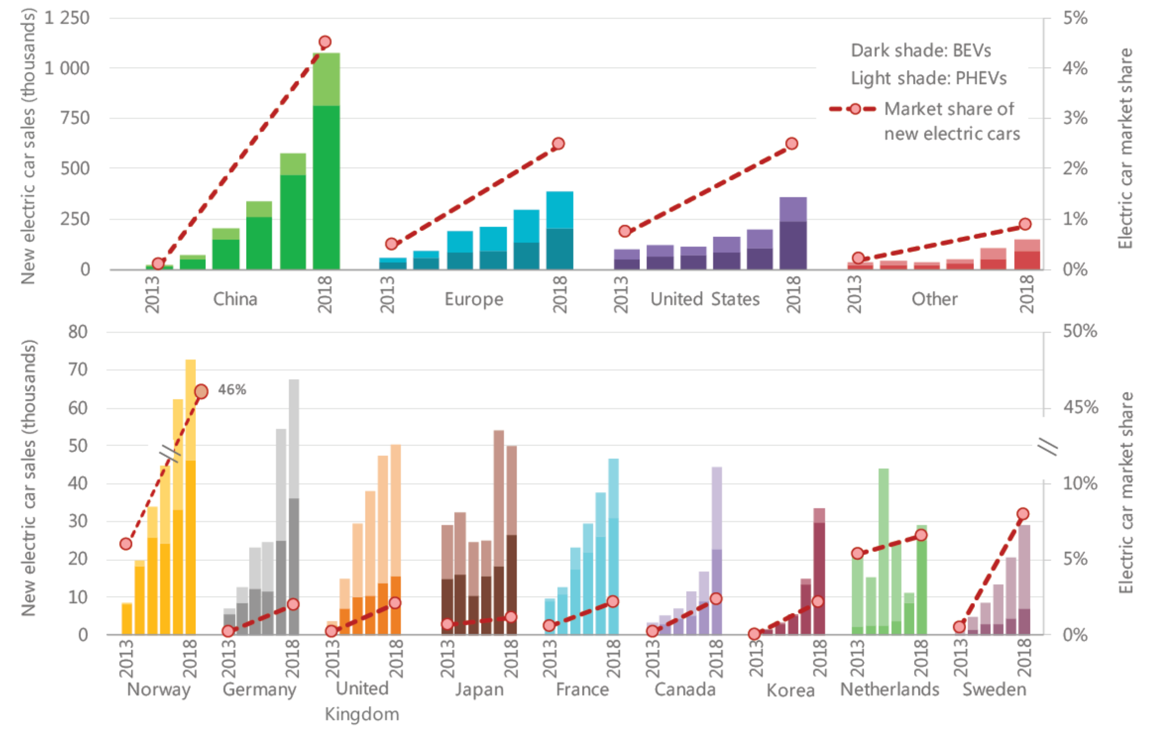



**Figure 5-11. World best-selling EV models in 2017 and 2018**
**Source: EVvolumes, 2019**

**Figure 5-14** shows the evolution of EV model availability between 2010 and 2017. This upward trend of EV model availability is expected to continue in the next years as OEMs are still announcing or updating their plans. For instance, Daimler plans to offer electric vans, buses and trucks as well as 130 electrified car variants, of which at least ten will be BEVs or FCEVs (Daimler, 2019a). Groupe PSA communicated that a hybrid or electric version of every new model as of 2019 will be available and the line-up will be fully electrified by 2025 (PSA, 2019). Volkswagen recently corrected its electro-mobility plans upwards and announced the launching of ca. 70 new electric models in the next ten years, that is twenty more than initially planned (VW, 2019f). BMW is bringing its 25 planned EV to 2023 instead of 2025 (FAZ, 2019). (BNEF, 2018b) expects 289 EV models to become available by 2022.

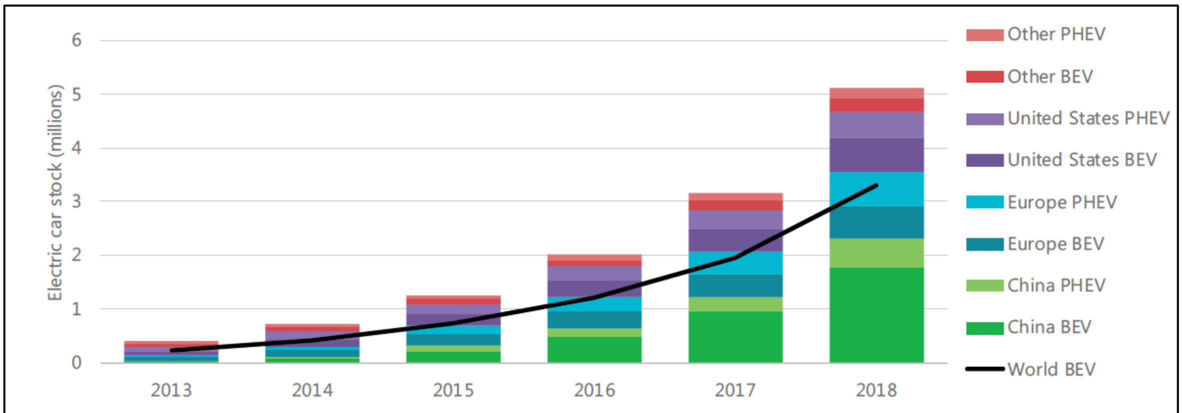
In part thanks to increased EV model availability, 2018 marked the year in which EVs accounted for 2% of the new car sales registrations in the EU. In Europe, Norway is the leading EV market, measured both in terms of market shares and stock, with almost half of the new car sales being EVs in that year (EAFO, 2019).




Notes: BEVs = battery electric vehicles; PHEVs = plug-in hybrid electric vehicles. Europe includes Austria, Belgium, Bulgaria, Croatia, Cyprus,[2] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom. Other includes Australia, Brazil, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand.

Sources: IEA analysis based on country submissions, complemented by ACEA (2019); EAFO (2019); EV Volumes (2019); Marklines (2019); OICA (2019).

**Figure 5-12. World electric car sales, by type of EV and region**
**Source: IEA, 2019b**




Notes: BEV = battery electric vehicle; PHEV = plug-in electric vehicle. Other includes Australia, Brazil, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand.

**Figure 5-13. World electric car stock, by type of EV and region**
**Source: IEA, 2019b**

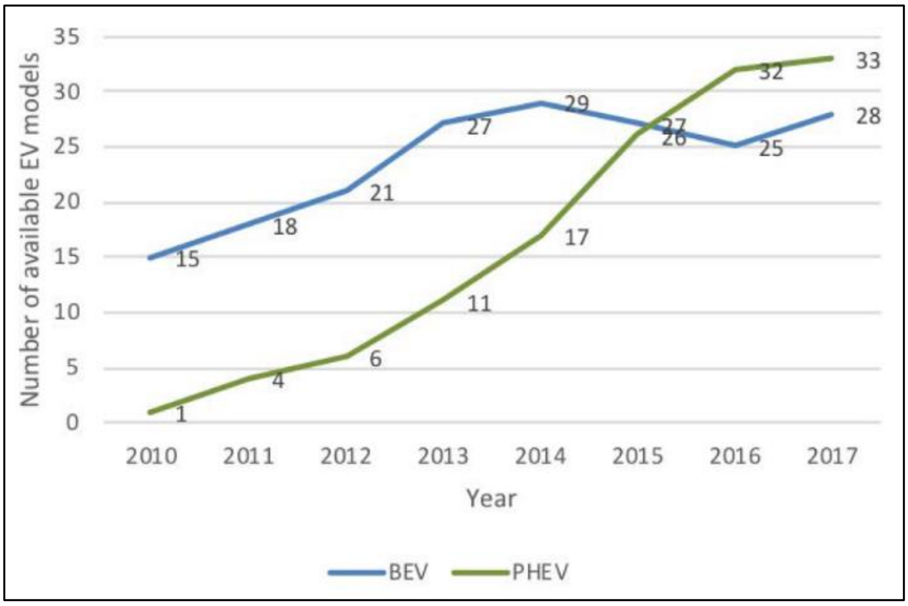



**Figure 5-14. M1 EV models in Europe**
**Source: Tsakalidis & Thiel, 2018**

Since 2016, electric cars are the most successful alternative powertrain technology sold in the EU, after overtaking LPG cars. In 2017, PHEVs were slightly more attractive to EU new car purchasers than BEVs (see **Figure 5-15**). In 2018, BEVs was the best-selling alternative powertrain in the EU, with almost 200,000 units, closely followed by PHEVs (EAFO, 2019).

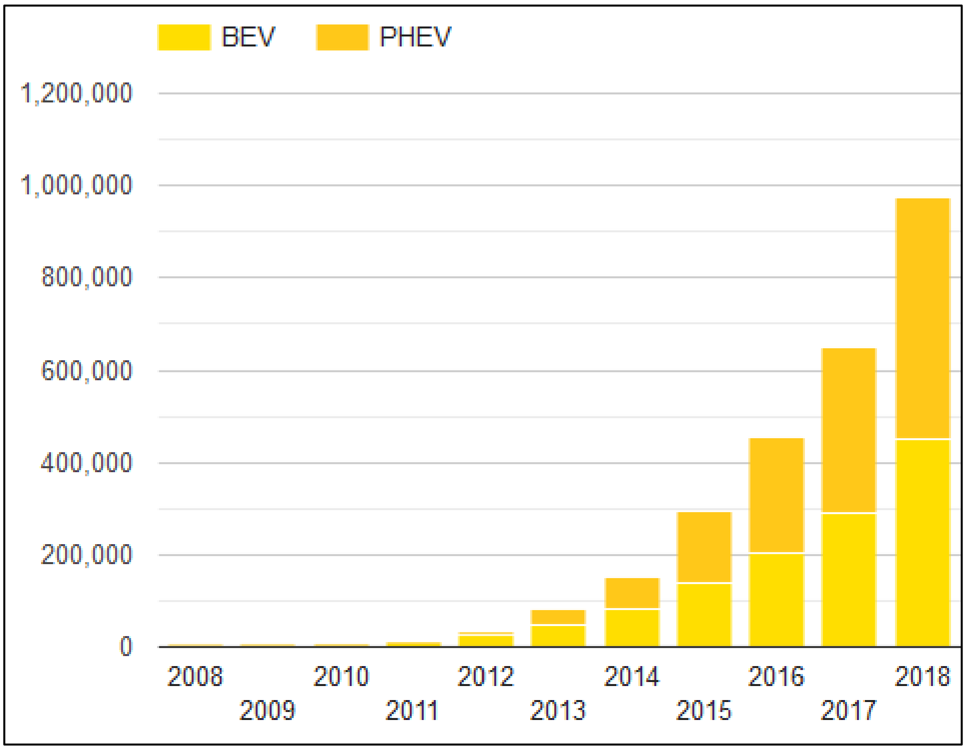



**Figure 5-15. Passenger car stock in the EU28, by type of EV**
**Source: EAFO, 2019**

Electric LCVs are an option for short-haul and urban services (Leopoldina, 2017). As can be seen in **Figure 5-16**, electric LCVs are solely BEVs in this market, at least until the end of 2018.

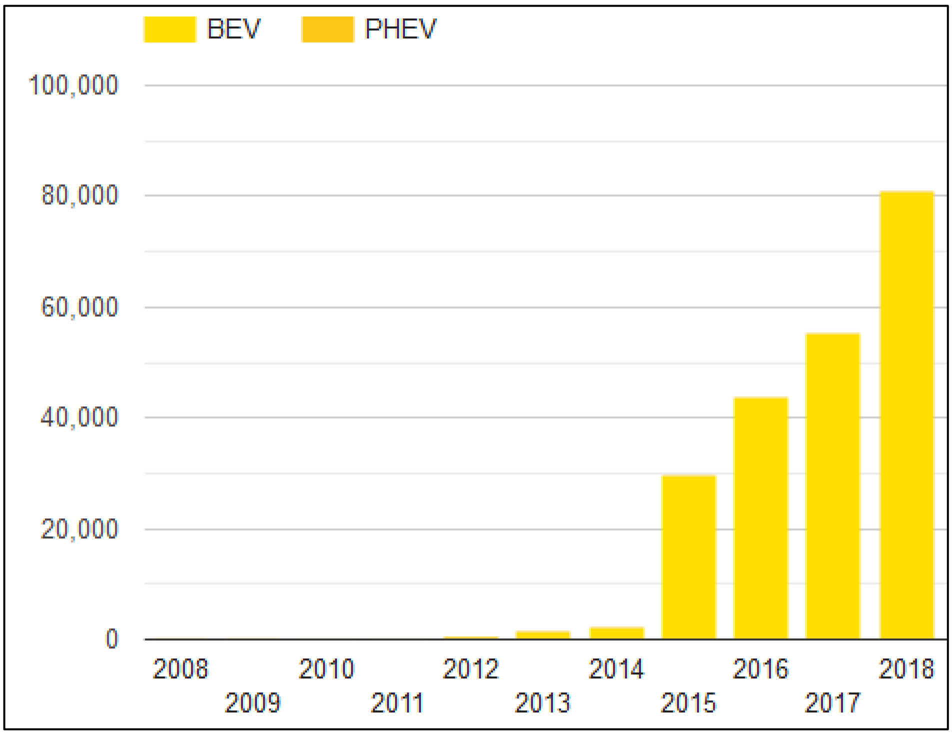



**Figure 5-16. LCV stock in the EU28, by type of EV**
**Source: EAFO, 2019**

**Box 2. FREVUE project (2013-2017)**

The objective of the FReight Electric Vehicles in Urban Europe (FREVUE) project was to validate the use of electric vehicles to operate 'last mile' freight movements.

Key information:

80 electric LCVs and trucks subjected to the daily rigours of the urban logistics environment;

Demonstrators deployed in Amsterdam, Lisbon, London, Madrid, Milan, Oslo, Rotterdam and Stockholm.

Funding / coordination: €14.2 million (€8 million EU funding) / coordinated by Westminster City Council

Source: (FREVUE, 2019)

The disaggregation of bus orders in Europe in 2017 by type of electric bus and charging method can be seen in **Figure 5-17**. **Figure 5-18** shows the evolution of electric bus stock in the EU. For a recent overview of electric bus market development in the EU, see (J. Gómez Vilchez, 2019). For the differences in total cost of ownership (TCO) arising from opportunity charging versus overnight charging under several assumptions and sensitivity analysis, see (T&E, 2018a). For a landmark EU project, see **Box 3**.

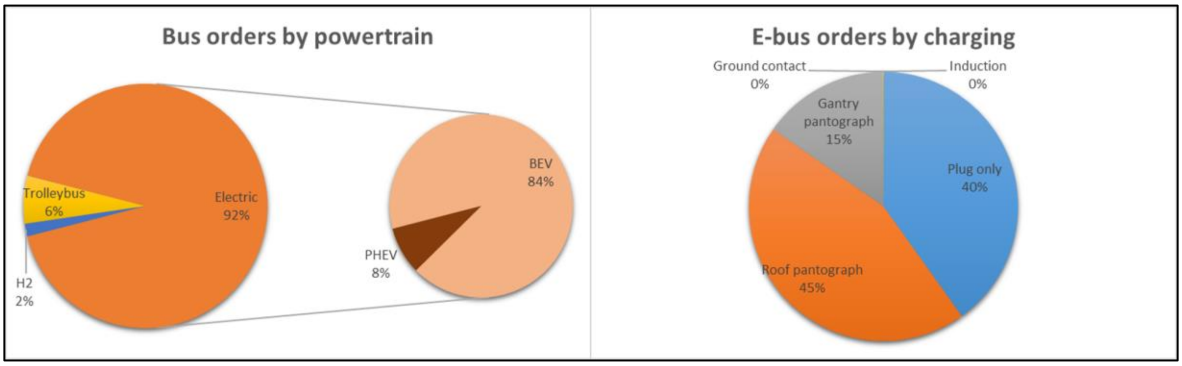



**Figure 5-17. Electric bus orders in Europe in 2017**
**Source: own work based on (ADL, 2018b)**

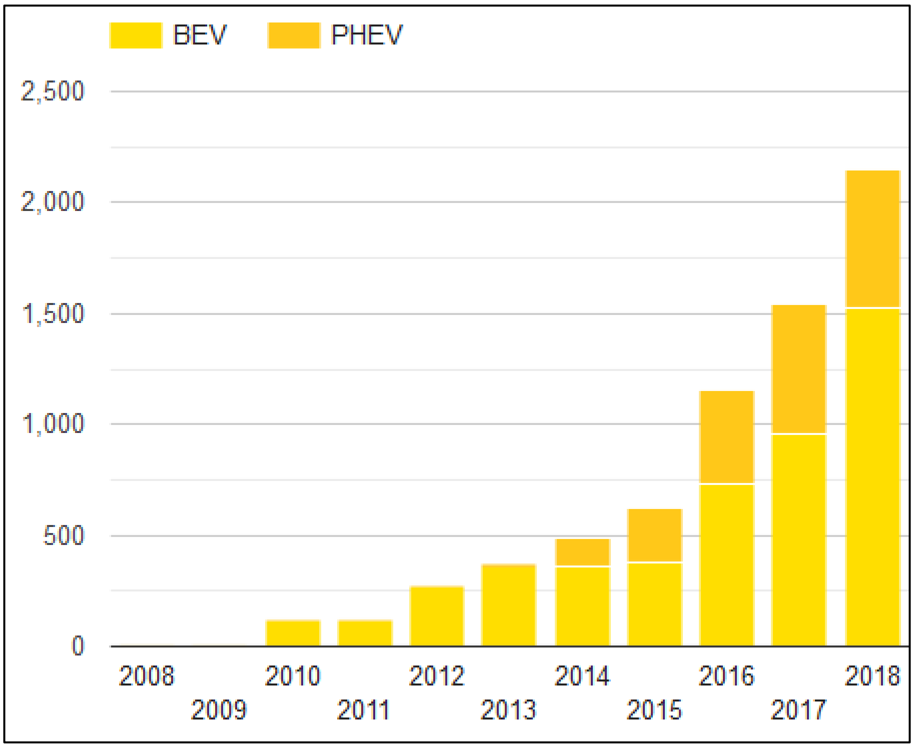



**Figure 5-18. Bus/coach stock in the EU28, by type of EV**
**Source: EAFO, 2019**

**Box 3. ZeEUS bus project (2013-2017)**

The objective of the project was to pave the way for electric urban bus uptake in Europe via testing and demonstrations.

Key figures from seven cities:

1,458,161 km travelled on electric mode by ZeEUS buses;

523,998 litres of diesel fuel saved [assuming 38l/100km];

751.6 tonnes of $CO_2$ avoided.

Funding / coordination: €22.5 million (€13.5 million euro EU funding) / coordinated by UITP

Source: (ZeEUS, 2016) (ZeEUS, 2017)

Already in 2010, 7.5t HCVs were being retrofitted with a 62 kWh lithium iron phosphate (LIFEPO) battery capacity in Germany, with an electric range of 80-100 km (up to 130 km without the 3.5t payload) (EFA-S, 2010). In 2016, Daimler presented the eActros, with a battery capacity of 240 kWh and an e-range of up to 200km. Two variants (18t and 25t) are being tested under real-world operation by customers (Daimler, 2018). DAF is experimenting with customers a full size articulated model. **Figure 5-19** shows the evolution of HCV stock in the EU, with modest but increasing numbers.

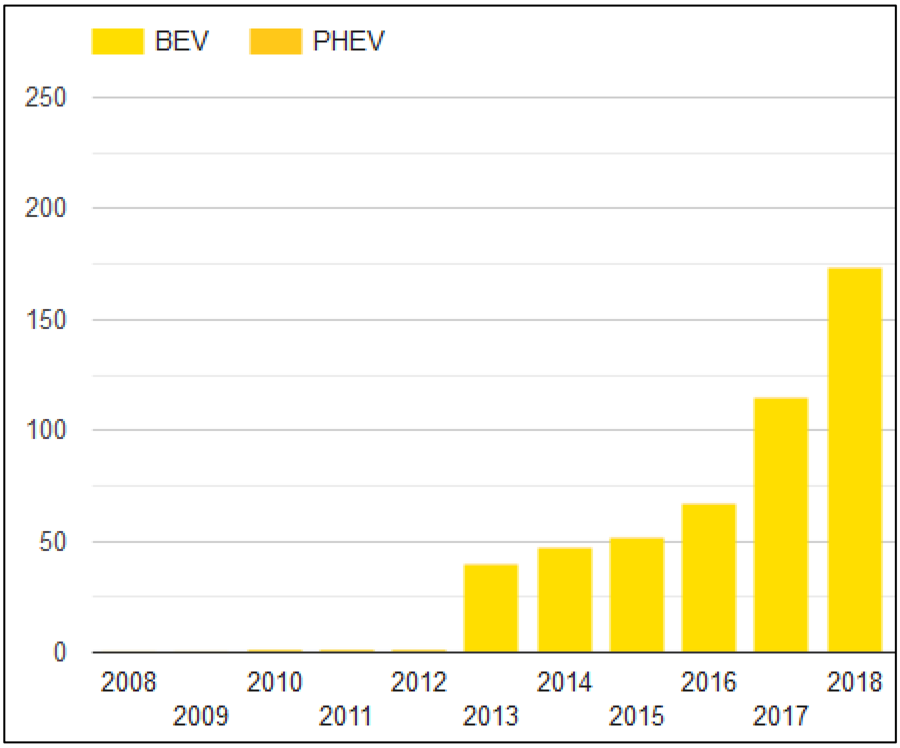



**Figure 5-19. HCV stock in the EU28, by type of EV**
**Source: EAFO, 2019**

Germany and the United Kingdom have the largest stocks of railway vehicles in the EU. In 2015, there were 5,743 railcars (VIZ, 2018) and almost 4,200 locomotives in use in Germany, of which ca. 57% were electric and the rest diesel (DB, 2015). In the United Kingdom, there were 14,025 railway vehicles in 2018, of which 10,154 were electric (Angel, 2018). The whole stock of electric trains is powered by renewables in the Netherlands (100% wind energy) and Sweden (100% hydropower) (CER, 2019).

European transport electrification is clearly led by the railways, with 80% of the traffic operating in electrified lines (EC, 2017b). In non-electrified routes, battery-powered railway vehicles are being reintroduced for passenger services in Europe (Bombardier, 2018). Such trains will be deployed in Austria in late 2019 (RailTech, 2017).

Battery-powered local ferries and vessels for day trips were mainly introduced in Amsterdam in 2016 (CCNR, 2018). A fully electric inland vessel for multimodal urban logistics in the Paris area is the 'FLUDIS', a warehouse vessel supported by 30 electric cargo (250 kg) bikes for last-mile delivery (EIBIP, 2019). According to EFIP, less than 0.5% of inland waterway vessels are hybrid/electric (personal communication). For large freight vessels, hybrid systems are being deployed (personal communication by CCNR). The first commercial freight vessel powered by electricity on the European IWWs is the 'Sendoliner', which features diesel-electric propulsion and a 500 kWh battery that allows 3 hours of zero emission operation. This dry cargo vessel has a loading capacity equal to 164 TEU (EIBIP, 2019) (8% more than its conventional counterpart (DAMEN, 2019)). (CCNR, 2019) recently received replies from 55 day-trip navigation companies to a questionnaire that covered 'greening' activities. The two most frequent alternative fuel technologies indicated by the respondents were diesel-electric vessels and pure electric vessels (44% and 34%, respectively).

Electricity use in the maritime transport system can be considered for stationary and non-stationary operation. The former is referred to as 'shore-side electricity supply' and defined in (EU, 2014) as: "*the provision of shore-side electrical power through a standardised interface to seagoing ships or inland waterway vessels at berth*" (p. 10). The number of battery-powered vessels in use is on an upwards trend. In 2019, there are 166 battery-powered vessels in operation (of which 56% are passenger ferries) (DNV-GL, 2019a). When battery-powered vessels under construction are added, the 300 milestone is exceeded, with 42% of the vessels being registered in Norway and 16% of them being fully electric (DNV-GL, 2019a).

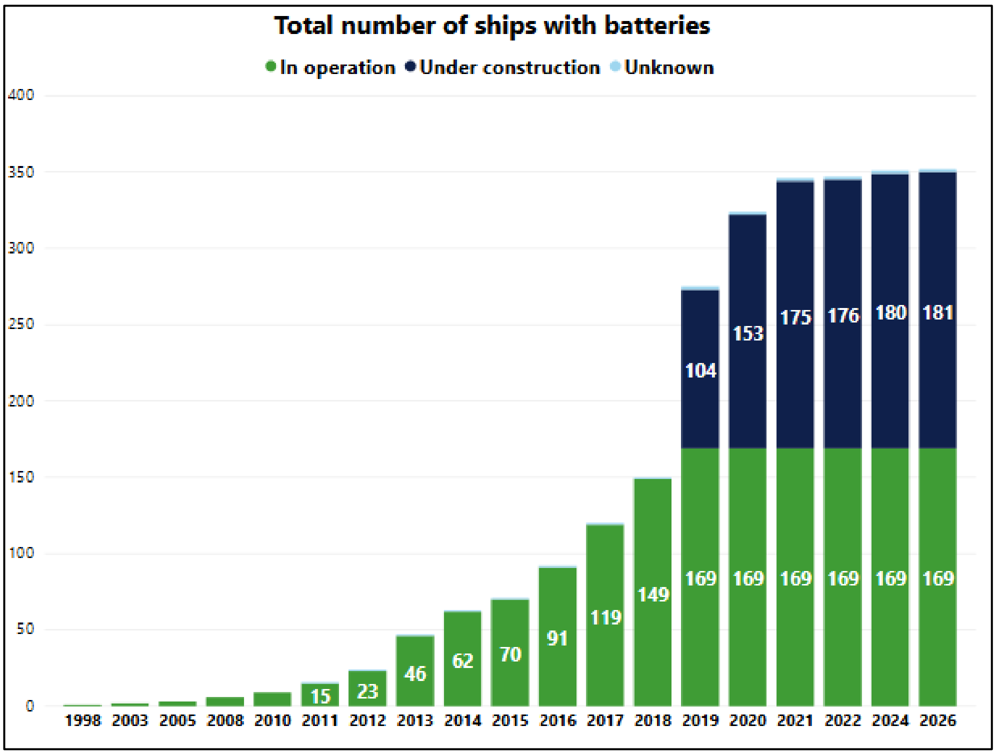



**Figure 5-20. Global stock of battery-powered vessels, by status**
**Source: DNV-GL, 2019a (reproduced with permission from DNV GL)**

Small non-commercial electric aircrafts are already under operation (EC, 2018c). Hybrid electric aircrafts have been ordered. For instance, (XTI, 2019) reports that 80 orders have been placed for their TriFan 600 vertical take-off airplane. A retrofitted hybrid electric aircraft will be trialled on commercial routes in Hawaii in late 2019, with certification by the US Federal Aviation Administration expected for 2021 (Ampaire, 2019). To our knowledge, no commercial fully electric aircraft has been deployed for regular operation.

**Infrastructure**: The Commission has funded 34 recharging infrastructure projects through the CEF funding instrument, which have delivered 11,974 recharging points. In addition, 700 recharging points were deployed as part of road actions focusing on hydrogen, 892 recharging points as part of road actions focusing on CNG/LNG infrastructure and 1,061 recharging points as part of road actions focusing on CNG-only infrastructure (see **section 5.2.2, p. 161 and section 5.4.2, p. 185**).

The evolution of the public charging infrastructure in the period 2010-2018 is presented in **Figure 5-21** at global level and at EU level for the five MSs with the highest number of publicly accessible recharging points.

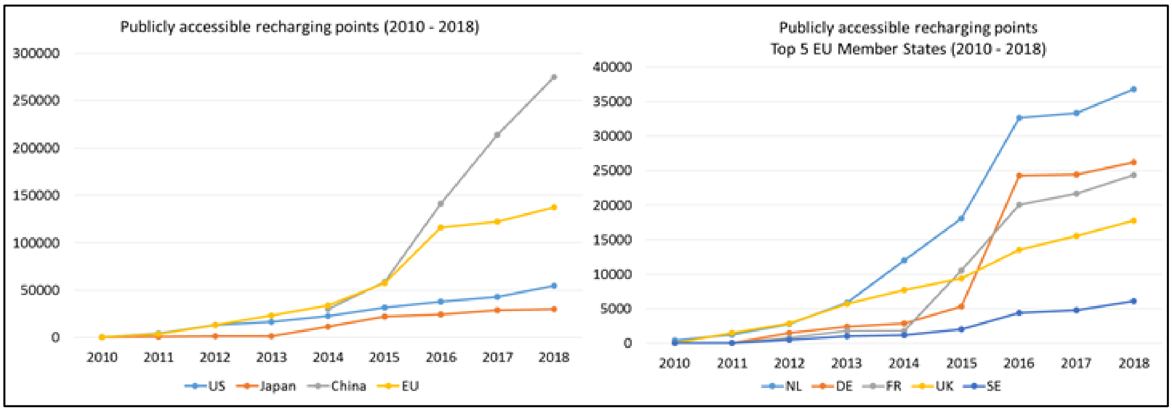



**Figure 5-21. Evolution of publicly accessible recharging points at global and EU level Source: own elaboration based on data from (IEA, 2019c) and (EAFO, 2019)**

Data from (EAFO, 2019) suggests that public recharging infrastructure has grown rapidly in recent years, becoming the most widely available alternative fuels infrastructure in the EU. **Figure 5-22** presents the evolution of the number of recharging points disaggregated by charging power types in the period 2010 - 2018. It also shows the increasing share of high power recharging points.

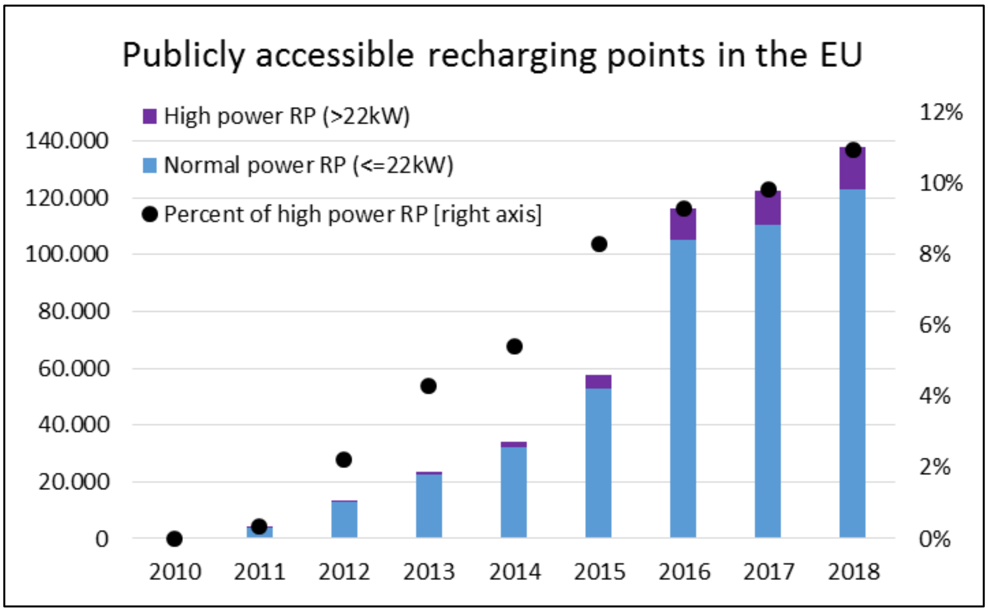



**Figure 5-22. Situation of the publicly accessible recharging points in EU (2010–2018) Source: own elaboration based on data from (EAFO, 2019)**

The situation at the end of 2018 of the number of publicly accessible recharging points for all EU MS is presented in **Figure 5-23**. The proportion of high power charging infrastructure is also displayed for each MS. At EU level, the average percentage of high power recharging points is 10.96%.

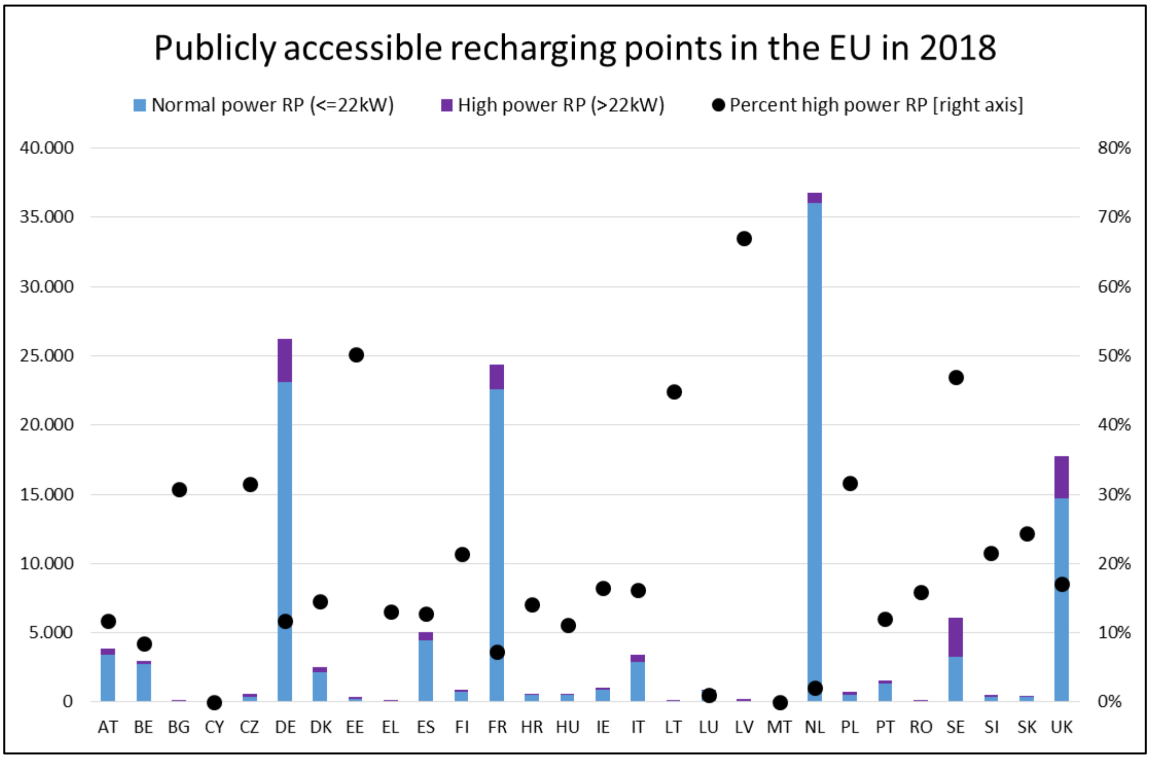



**Figure 5-23. Situation of the publicly accessible recharging points in 2018 across EU**
**Source: own elaboration based on data from (EAFO, 2019)**

According to (IEA, 2019c), there were 3,000 bus recharging points in Europe in 2018. They are typically rated up to 300kW (Spöttle, M. et al., 2018). In 2016, ABB introduced a 600 kW flash charger that is designed to top up bus batteries in about 15 seconds at bus stops (Green Car Congress, 2016). OppCharge offers Opportunity Charging solutions with power ratings of 150, 300 and 450 kW (OppCharge, 2019) using a mast pantograph (in May 2019, 763 vehicles can charge at 164 OppCharge stations in 13 countries).

A review in more than 90 European cities with almost 750 electric buses shows that around 90% of electric buses uses overnight depot charging but almost all also use fast charging during operating hours, mostly pantograph charging ((IEA, 2019c) and (ZeEUS, 2017)).

**Box 4. REMETBUS2 Rotterdam (2013-2021)**

The Action is implementing a zero emission service network for public transport in the Urban Node of Rotterdam by deploying a full battery electric bus (ZEB) fleet and the charging infrastructure in the city.

The deployment of 24 opportunity and 50 overnight recharging stations, as well as the introduction of 105 ZEBs will occur in two steps.

The Action covers about 40% of the Global Project, which aims to equip the urban region of Randstad with full zero emission public bus transport service as of 2025.

Total eligible costs: €41,825,600

Maximum EU contribution: €3,266,579

Coordinator: ROTTERDAMSE ELEKTRISCHE TRAM N.V. (Netherlands)

Source: INEA

In 2016, 53.7% of the railway lines in use in the EU were electrified (EC, 2018e) and the situation at the MS level is displayed in **Figure 5-24**. According to (EC, 2017b), 80% of the total traffic is running on electrified lines.

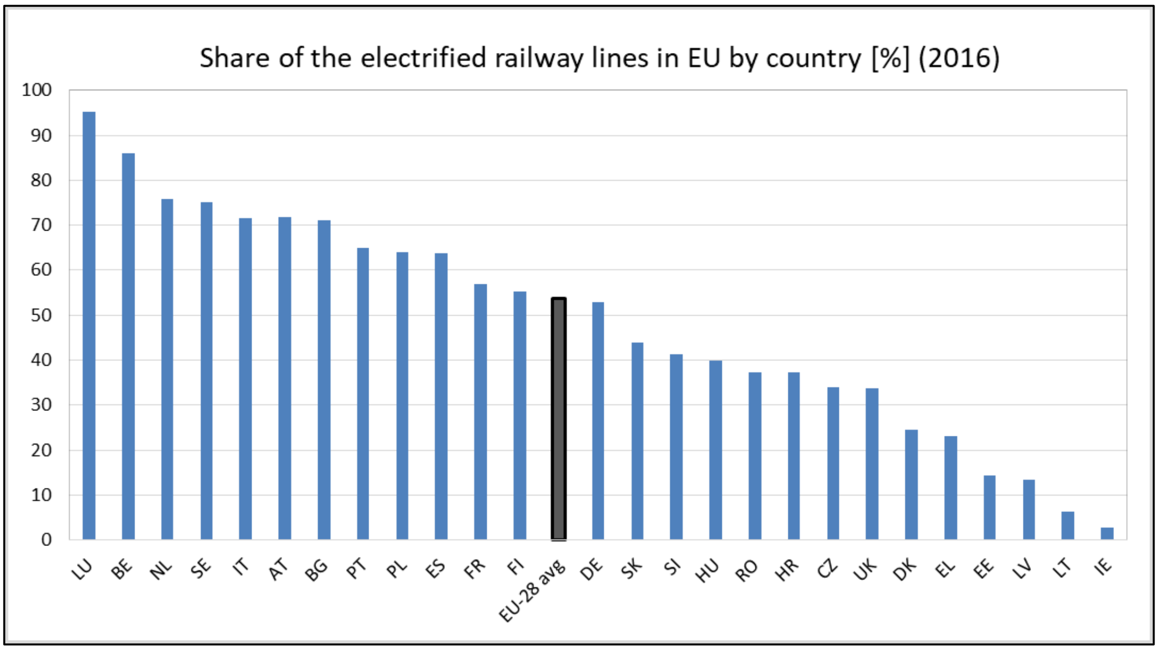



**Figure 5-24. Situation of electrified railway lines in 2016 across EU**
**Source: own elaboration based on data from (EC, 2018e)**

In 2015, there were only 20 maritime ports in Europe providing SSE supply (high or low voltage). The **Table 5-8** lists the European maritime ports with SSE supply mentioning also the year since it is available.

**Table 5-8. European ports providing SSE in 2015**
**Source: own analysis based on (Innes & Monios, 2018), (WPCI, 2015) and (TrainMoS II, 2015).**

| Port name | Country | Year of introduction | | Port name | Country | Year of introduction |
|---|---|---|---|---|---|---|
| Göteborg | Sweden | 2000 | | Karlskrona | Sweden | 2010 |
| Zeebrugge | Belgium | 2000 | | Amsterdam | Netherland | 2010 |
| Piteå | Sweden | 2004 | | Oslo | Norway | 2011 |
| Kemi | Finland | 2006 | | Rotterdam | Netherland | 2012 |
| Kotka | Finland | 2006 | | Helsinki | Finland | 2012 |
| Oulu | Finland | 2006 | | Ystad | Sweden | 2012 |
| Helsingborg | Sweden | 2006 | | Trelleborg | Sweden | 2013 |
| Stockholm | Sweden | 2006 | | Riga | Latvia | 2014 |
| Antwerp | Belgium | 2008 | | Hamburg | Germany | 2015 |
| Lübeck | Germany | 2008 | | Civitavecchia | Italy | 2015 |

In 2019, there are 55 ports in Europe and 44 ports in EU that provide SSE supply according to EAFO that gathered information from several sources (EAFO, 2019). Out of the 44 EU ports, 22 are ports on TEN-T Core Network and 11 are ports on the TEN-T Comprehensive Network. More than 189 berths with SSE exist in these EU ports with voltage ranging from 0.4 to 11 kV and power ranging from 0.015 to 10 MW.

A cooperation agreement was signed in 2016 between Finland, Sweden and Estonia (Ports of Helsinki, Turku, Stockholm and Tallinn) on a common approach to promote the usage of SSE on the Baltic Sea (Port of Tallinn, 2016).

In December 2018, the first SSE facility in the Eastern Mediterranean at the Greek port of Killini was inaugurated, developed within the EU co-funded programme „ELEMED – ELectrification of the Eastern MEDiterranean area" (elemed, 2018) (see also **Table 5-7**).

In 2016, there were 329 airports in use in the EU, excluding those with a carrying capacity of less than 15,000 passengers per year (EC, 2018e).

According to an ACI EUROPE survey from 2018 based on the replies of 51 airport responses representing 60% of the total EU28+EFTA passenger numbers, 82% of respondents declared to provide FEGP to aircraft on-stand and 58% of respondents mentioned to provide PCA (EASA, 2019b). For example, Munich Airport has installed 64 PCA systems at all pier side aircraft positions of both terminals and the satellite facility considering that they represent the biggest contributing factor towards achieving the target of $CO_2$ neutral operations by 2030 by saving 23,500 tonnes of $CO_2$ in one year (Munich Airport, 2019). Zurich Airport provides both FEGP and PCA at all hard stands and FEGP at most recent open stands (Zurich Airport, 2018).

<u>Standards for electric recharging points</u>

Following the mandate M/533 given by the Commission to the European Standardisation Organizations (ESOs) CEN-Cenelec, the ESOs recommended to the Commission the standards to be applied to supplement or to amend the technical specifications established in Annex II of Directive 2014/94/EU for recharging points for L–category and shore-side electricity supply for inland waterway vessels:

- The standards EN 62196-2 'Plugs, socket-outlets, vehicle connectors and vehicle inlets. Conductive charging of electric vehicles. Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories' and IEC 60884-1 'Plugs and socket-outlets for household and similar purposes – Part 1: General requirements' should apply to those recharging points. These standards should apply for recharging points for L-category vehicles

- The standards EN 15869-2 'Inland navigation vessels - Electrical shore connection, three phase current 400 V, up to 63 A, 50 Hz - Part 2: Onshore unit, safety requirements (in process of being amended to increase amperage from 63 to 125)' and EN 16840 'Inland navigation vessels – Electrical shore connection, three phase current 400 V, at least 250 A, 50 Hz' should apply to that electricity supply.

These two standards have been included in Directive 2014/94/EU through the Commission Delegated Regulation (EU) 2019/1745.

CEN-Cenelec are working to develop the standards for "recharging points for electric buses" and "wireless recharging points for motor vehicles" whose adoption by the ESOs is expected by the end of 2020.

### 5.1.3 COST OF VEHICLES AND INFRASTRUCTURE

The cost[55] of EVs is mainly affected by the battery system cost. EV battery prices have declined faster than anticipated in the 2015 report. In 2018, the average LIB pack price stood at 153 €/kWh (BNEF, 2019a), though differences in cost and prices among types of LIBs and suppliers persist (see e.g. (FT, 2018)). The historical and expected evolution of the battery price is shown in **Figure 5-25** (see (Blanco, Gómez Vilchez, Nijs, Thiel, & Faaij, 2019) for the assumptions underlying this chart and for the original sources of information). The uncertainty of the future evolution of the LIB pack cost under a low, medium and high deployment scenario is reflected in **Figure 5-26**.

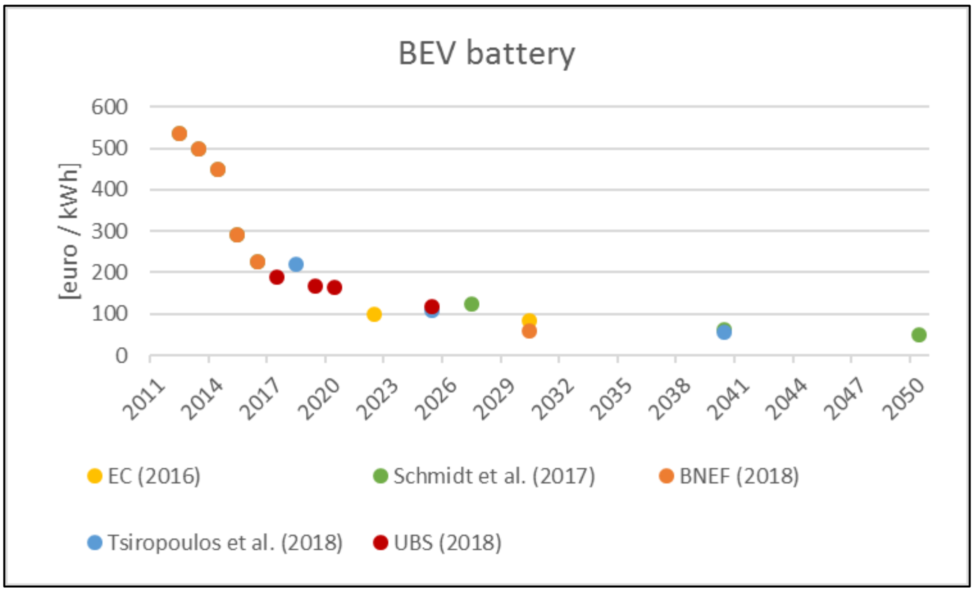



**Figure 5-25. Battery price evolution**
**Source: adapted from (Blanco et al., 2019)**

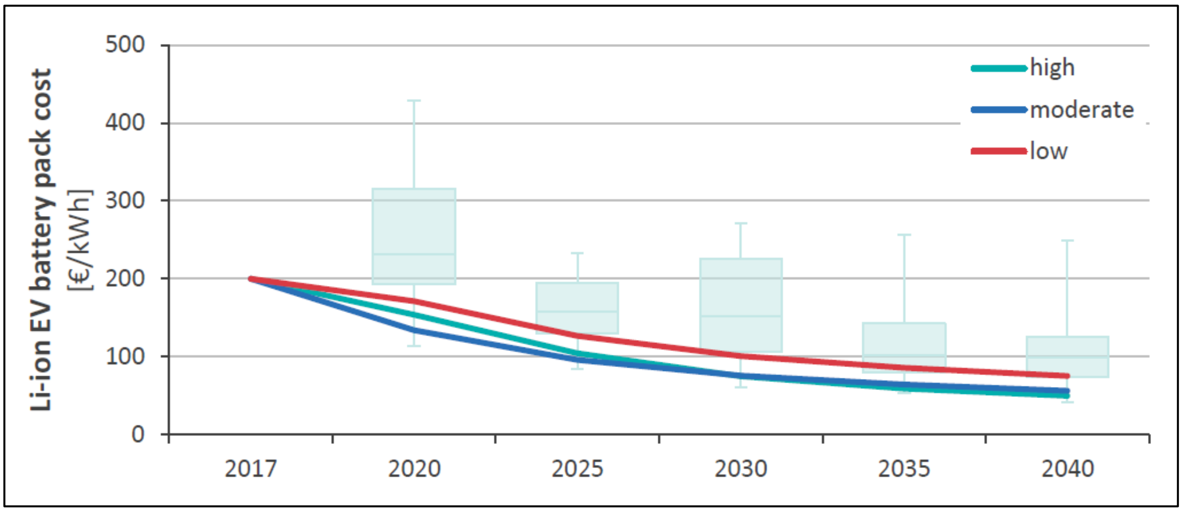



**Figure 5-26. LIB battery cost, by scenario**
**Source: I. Tsiropoulos, D. Tarvydas, 2018**

[55] For costs and prices, the exchange rate assumed in this report is 1.15 dollar/euro. Energy prices are considered as part of the vehicle operating cost.

Material costs represent 66% of the battery pack costs, but can be reduced if silicon-based LIBs are used. In 2020-2025, silicon-based batteries could cost 87 €/kWh (this could also be the case for NMC batteries, though in 2025-2030) (personal communication by AVERE, which seems to be fully in line with the analysis found in (Berckmans et al., 2017)). **Figure 5-27** shows the battery cost components of various cathode chemistries.

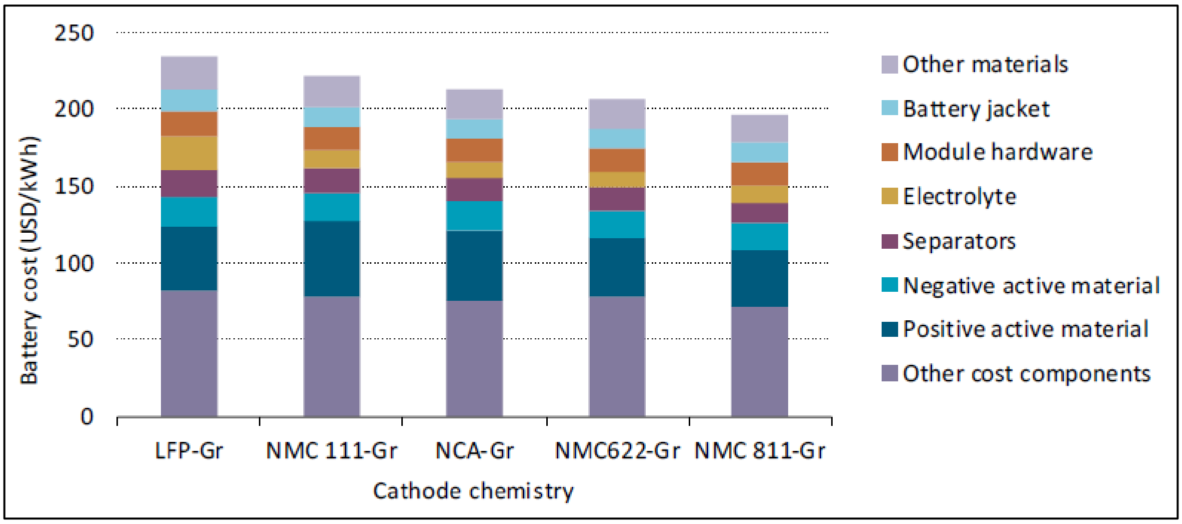



**Figure 5-27. Battery cost, by type**
**Source: EA, 2018a**

**Figure 5-29** shows the average price of selected electric cars and comparable conventional cars in eight European countries in 2014. As can be seen, there was a systematic price differential.

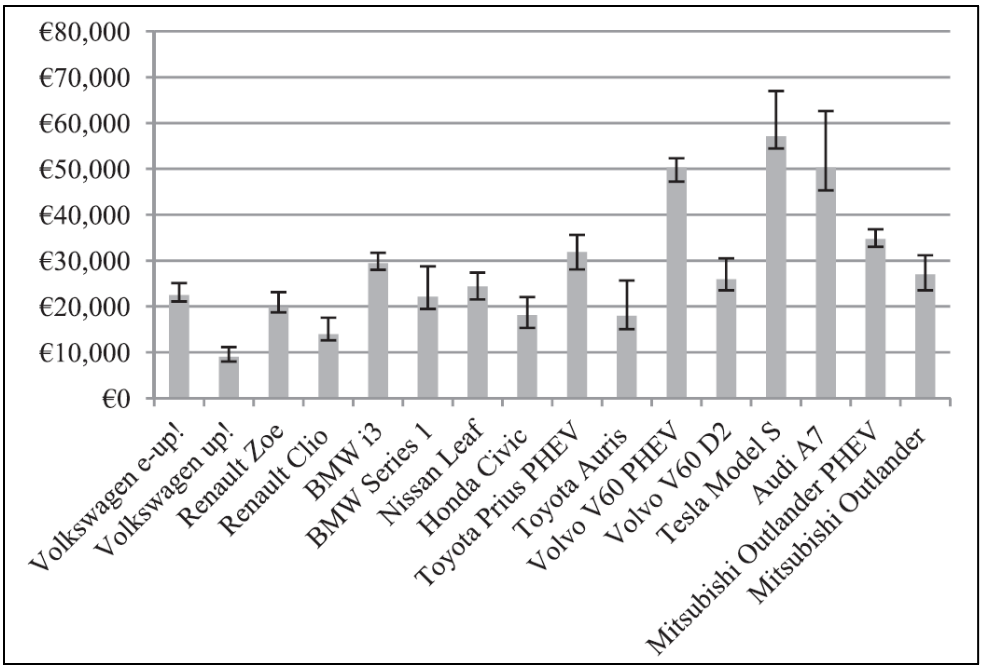



**Figure 5-28. Car prices in the EU, conventional versus electric in 2014**
**Source: Lévay, Drossinos, & Thiel, 2017**

**Figure 5-29** shows the situation for selected electric cars in the German market[56] as of mid-2019. As can be seen, four of those models correspond to the best-selling ones in 2017 and 2018 (recall **Figure 5-11**).

In the last years the situation has changed, but it is difficult to draw any conclusion at the present moment, as the study by (Lévay et al., 2017) has not been updated yet. As an example, a price differential between the e-Golf (e-range equal to 233 km under WLTP) and the Golf was still found in mid-2019 for the German market based on (VW, 2019b): €4,000 to €10,500 depending on the ICE variant. The future evolution of electric car prices in the EU is uncertain and battery cost reductions (see **Figure 5-26**) may not necessarily translate into lower purchase prices, as the Model S seem to indicate despite the fact that the reported values are in nominal terms, particularly if energy density remains unaltered and batteries with greater capacity are deployed. FIAT introduced the 120 concept car with a modular battery approach, and it is likely that, as the market matures, and customers become more aware of the real use of electric vehicles an optimal compromise between battery size and fast charging capabilities is reached and the race to bigger and bigger batteries is stopped with modular or multiple battery sizes for each model becoming the norm. Furthermore, it can be reasoned that greater EV model availability might lead in the future to increased OEM competition and lower purchase prices. Though their study focused on the US market, (ICCT, 2019c) recently concluded that cost parity between conventional and electric vehicles is likely to occur in 2024-2025 (short-range EVs) and 2026-2028 (long-range).

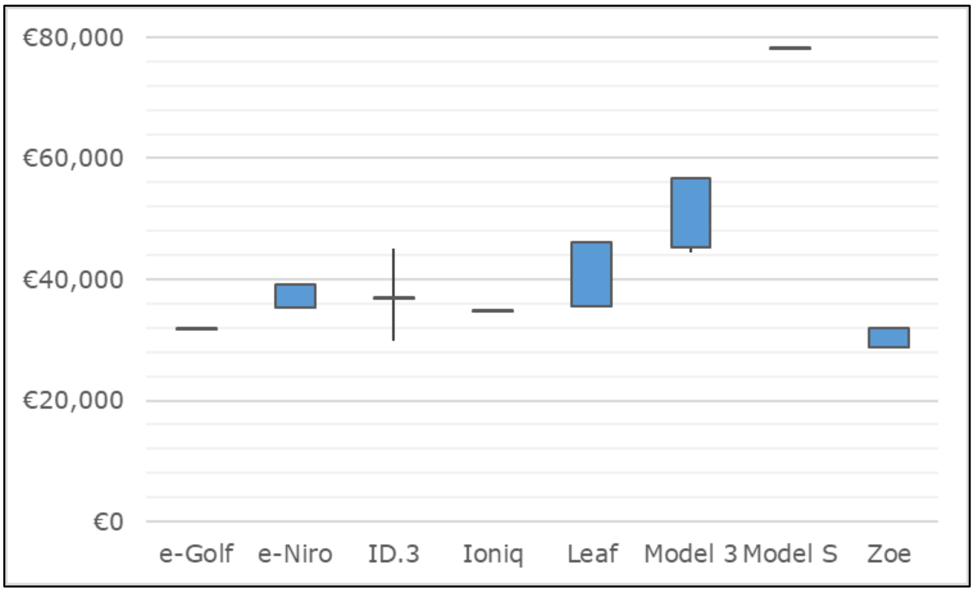



**Figure 5-29. Selected battery electric car prices**
**Note: the range in values reflects alternative battery capacities**
**Source: own work based on (Hyundai, 2018b) (Kia, 2019) (Nissan, 2019a) (Renault, 2019a) (Tesla, 2019a) (Tesla, 2019b) (VW, 2019b)**

Vehicle efficiency has implications for operating costs. The conversion efficiency of BEVs is 69% (Leopoldina, 2017). Compared to petrol and diesel cars, the energy cost to power BEVs is lower, leading to a reduction in operating cost.

The FREVUE project (see **Box 2**) concluded that the TCO may be favourable for a <3.5t electric LCV within five years if the daily driving distance is 60 km (FREVUE,

[56] As this is Europe's largest car market. Note, however, that the Leaf and Zoe prices are from another major market (Spain) as figures for the 62 kWh version of the Leaf and Zoe (non-leasing options) were not found for Germany.

2017c). For a medium-sized electric freight vehicle, the TCO may be favourable under specific circumstances (see (FREVUE, 2017a)).

A scenario of plausible future cost evolutions of the batteries for electric cars and buses is shown in **Figure 5-30**. **Figure 5-31** shows estimated CAPEX values for three bus options. (E-trofit, 2019) claims that the cost of retrofitting an electric bus is on average 50% lower than the cost of purchasing a new electric vehicle.

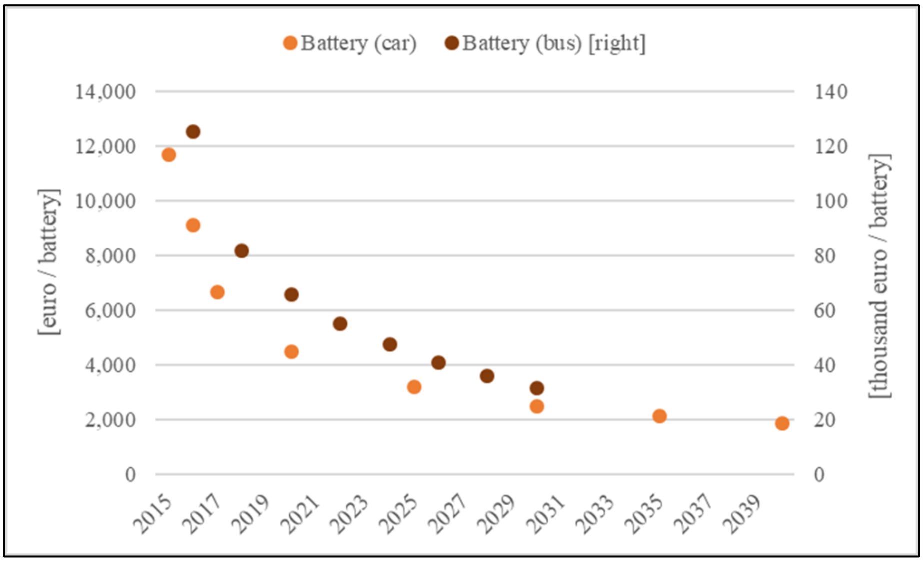



**Figure 5-30. Electric car and bus battery costs**
**Source: own work based on (I. Tsiropoulos, D. Tarvydas, 2018) (BNEF, 2018b) (BNEF, 2017)**

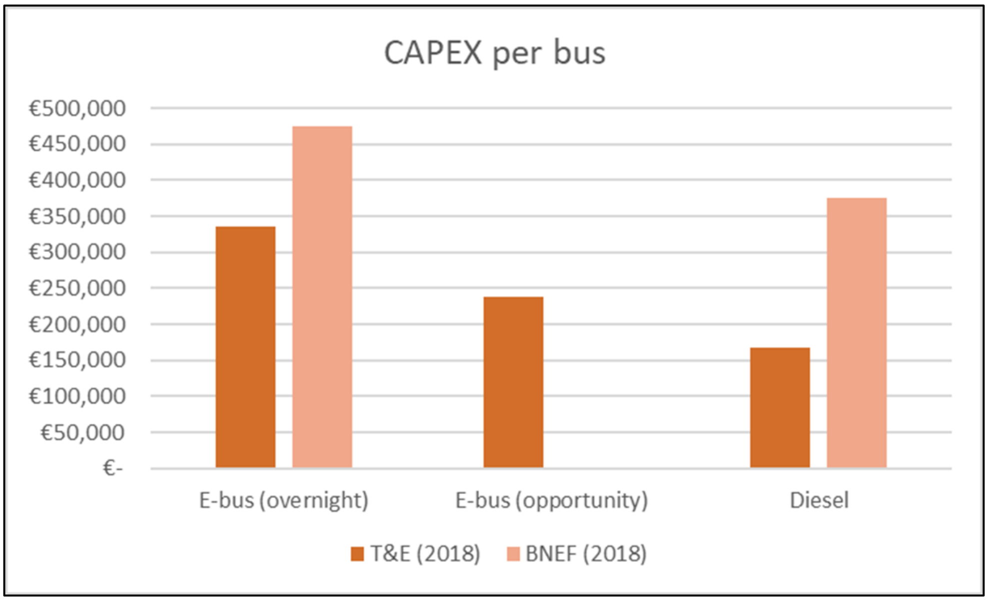



**Figure 5-31. Bus CAPEX (excl. infrastructure), by powertrain**
**Source: own work based on (BNEF, 2018a) and (T&E, 2018a)**

In 2017, (FREVUE, 2017b) concluded that the lower operating costs associated with the use of rigid (small rigid being 12-13t and medium-sized rigid being 18-19t) electric freight HCVs were not sufficient to offset the higher purchase price, when compared with diesel trucks. More recently, (Daimler, 2019h) claims that their 7.49t eCanter, with a payload of 3.5t and a battery capacity of 83 kWh achieving an e-range of over 100km, can lower operating costs by €1,000 per 10,000km in comparison with a diesel counterpart.

The aforementioned battery-powered trains to be deployed in Austria are estimated to cost 6 million euro per unit (RailTech, 2017). ALSTOM provided the following information (personal communication): For the rail transport system, a 40% fall in the cost of the NMC battery (at cell level) was achieved between 2015 and 2019. Currently, this cost is around 600 €/kWh. By 2030, the cost might be lowered to 350-400 €/kWh. At system level, the cost evolution might be 1,200-1,500 €/kWh by 2030, down from 1,500-1,800 €/kWh today. In the future, advanced batteries might reach costs of less than 100 €/kWh at cell level and less than 1,000 €/kWh at system level.

Compared to road vehicles, vessels have a longer average lifetime (Levinson, 2016) and, depending on the order book, may take two to three years to build (Stopford, 2008). Retrofitting is thus an option for vessel owners.

The price differential between HFO and MGO is considered to play a role in owners' decision to retrofit their vessels with a scrubber. Scrubber equipment cost ranges from one to five million euro (Reuters, 2018a). For vessel owners not attracted by the scrubber option, vessels powered by alternative energy sources are available. One of these options is electricity, as highlighted by (Moirangthem, 2016).

Hybrid electric and fully electric vessels turned out to be the least competitive options for low or zero emission maritime vessels, according to an economic assessment made by (LR/UMAS, 2017). According to a shipper stakeholder survey reported by the same authors, the incremental cost of zero emission vessels should not exceed 10%.

(Port-Liner, 2019) claims that a break-even TCO for fully electric and conventional diesel inland waterway vessels is possible. This was supposed to be investigated in a project that has been pre-terminated (CEF, 2019). As an example, the battery-powered vessel 'Yara Birkeland' is estimated to cost almost 22 million euro (personal communication by EFIP). But it has to be borne in mind that the cargo capacity of this vessel is 120 TEU (i.e. much lower than the representative value mentioned at the beginning of the chapter).

Aircraft electric propulsion is expected to lower operating costs, thanks to reduced maintenance costs and energy consumption (Brelje & Martins, 2019). Aircraft cost data was not available at the time of writing. Lufthansa considers that electric air taxis might become cheaper than helicopters (personal communication). However, differences in travel patterns (e.g. intra- versus inter-urban) and thus flying ranges need to be taken into account.

**Infrastructure**: The hardware part of the charging infrastructure has seen substantial cost declines over the last years due to new technological innovation and larger production scale. However, the costs related to installation, land procurement, administration, and maintenance tend to remain constant or have only a minor decrease.

Total costs (including administrative, installation, and siting costs) per normal power (Level 2) recharging point can range from €4,400 to €13,300 according to (ICCT, 2017b). These costs are situated from €10,500 to €14,000 (hardware part €3,000 – €7,000, installation and siting costs around €7,000) according to (DGE, 2019), around €12,000 (hardware part €5,000 and installation €7,000) according to IONITY (personal communication), around €10,000 (hardware part €5,000 and installation €5,000) according to (NPE, 2015) and around €5,000 according to UPEI (personal communication). (NKL, 2018) reported that in the Netherlands the total costs decreased by about 30%, from €4,665 (in 2013) to €3,270 (in 2018) while the use rose steadily with an increase of around 100%, from 5kWh/day in 2013 to 9.9kWh/day in 2018.

Total costs per 50 kW DC high power recharging station can range from €20,000 to €40,000 according to UPEI (personal communication),from €20,000 to €40,000 according to (NPE, 2015) and from €26,500 to €51,500 (hardware part €15,000 – €40,000, installation and siting costs around €11,500) according to (DGE, 2019), depending on the type of charging station (including its networking capabilities) and the setting (urban versus rural, mounted on walls or on posts). Not considering costs for supplying high electric power to the station, civil costs or costs for connection to grid, a 50 kW DC high power recharging point is estimated to cost around €35,000 (hardware part €30,000 and installation €5,000) by (SDG, 2017) and around €45,000 (hardware part €25,000 and installation €20,000) by IONITY (personal communication).

Costs for high power recharging points corresponding to the CEF funded Actions and provided by INEA (personal communication) are presented in **Table 5-9**.

**Table 5-9. Costs of high power recharging points**
**Source: INEA (information collected from CEF funded Actions)**

| | Charger | Grid connexion | Site adaptation | Installation | Total |
|---|---|---|---|---|---|
| **High power recharging point 22-50kW** | €25,000 (a) | €7,000 | €6,000 | €2,000 | €40,000 |
| **High power recharging point 50-350kW** | €120,000 (b) | €50,000 | €25,000 | €5,000 | €200,000 |

(a) This average amount derives from previous Action's implementation and various studies. Actual cost tends to decrease around €18,000. However grid connection may be expensive in remote areas so this calculation is rather comfortable.
(b) This average price is below the costs noted on on-going Actions. However, charger's price is decreasing rather swiftly. Moreover by putting a lower limitation to the cost, we limit public support to the part serving mass market (vehicle able to charge at a lower voltage than 400 volts) and the beneficiary supports the extra CAPEX for niche market (vehicles charging at a voltage 400-800 volts) which is not linked to mass market adoption

A 100 kW DC high power recharging point was estimated to cost around €60,000 by (EY-COWI, 2019) and (SDG, 2017). A 150 kW DC high power recharging point costs around €150,000 according to (EY-COWI, 2019) and around €75,000 (hardware part €45,000 and installation €30,000) according to IONITY (personal communication). The average cost of a 350 kW recharging point was estimated at €575,000 (insideevs, 2019).

The costs for some cases of electric bus recharging infrastructure, in an increasing complexity order, are presented in **Figure 5-32**.

| DC 80kW | Gantry | Pantograph | Catenary |
|---|---|---|---|
| € 13,000 | € 50,000 | € 450,000 | € 1,700,000 |
| per plug charger | per mast | per mast | per km |

**Figure 5-32. Electric bus infrastructure cost**
**Source: own work based on (ADL, 2018b) and (Elin, 2016)**

The examples are those from an overnight charging with an 80kW DC plug charger in Kraków (Poland), a gantry mast from Hannover (Germany), a pantograph mast, including charger, grid connection and installation, from Ostrava (Czechia) and finally the cost per kilometre of a more complex installation, an in-motion charging system for trolleybus catenary from Osnabrück, Germany).

For railway infrastructure, the EU has invested €23.7 billion of co-funding to extend the high-speed rail infrastructure since 2000 (ECA, 2018). Such infrastructure is electrified.

The cost for electrified railway depends of various factors but the main is ground configuration. In 2006, the cost of electrification in France was around €1.5 million (adjusted for 2018) per double-track kilometre (Pedestrian Observations, 2018). In 2011, at EU level, (ETSAP, 2011) mentions that the cost for 1 km single track was varying between €56,800 and €472,700. According to HYDROGEN EUROPE (personal communication), a cost estimate of electrification of rail infrastructure is around €1.5 million per km.

The cost of a SSE supply can vary a lot depending on port location, power demand, voltage and frequency and vessel type.

A report of the Interreg project „Green Cruise Port" (GCP, 2018) provides estimates for the costs of installing SSE high-voltage supply adapted for cruise ships with an average expected capacity demand of 5.5 MW in five European maritime ports (Bergen, Hamburg, Rostock, Tallinn and Helsinki). The SSE construction costs are provided for the two main elements: the grid connection and the shore-side installation. The cost for one connection point varies in between €0.25 million (Hamburg) and €2 million (Tallinn) for the grid connection part, in between €3.4 million (Bergen) and €6.67 million (Rostock) for the shore-side installation and in between €3.77 million (Bergen) and €8.53 million (Rostock) for the overall construction.

According to EFIP (personal communication), a new power supply terminal (4 x Powerlock at 400 A, 12 x CCE 125 A) was built in 2012 at the inland port of Basel for €2.5 million.

According to (Guinault, 2019), the use of ground equipment to replace the APU could generate fuel savings of €150,000 to €600,000 per year, per aircraft, depending on the type of aircraft. The required investments for the 400Hz FEGP/PCA systems designed and implemented for Zurich Airport vary between €340,000 and €1 million (about 30% for the 400 Hz systems and 70% for the PCA system) depending on the required service level and the possibility to plan one comprehensive system rather than upgrading an existing 400 Hz FEGP system with PCA (Zurich Airport, 2018).

### 5.1.4 PERSPECTIVES FOR MARKET DEVELOPMENT

In terms of stock, the market perspectives for electric cars in the EU based on (EC, 2018c) under two scenarios[57] are shown in **Figure 5-33**. By 2030, electric cars are projected to account for slightly less than 15% of the EU car stock under current trends and policies (i.e. Baseline scenario). As can be seen, BEVs dominate over PHEVs in all of the scenarios considered. Under the most ambitious 1.5TECH climate-neutral scenario, PHEV are expected to play a marginal role in 2050.

[57] The scenarios included in this report are the Baseline and 1.5TECH. See (EC, 2018c) for the definition of each of them as well as for information on additional scenarios.

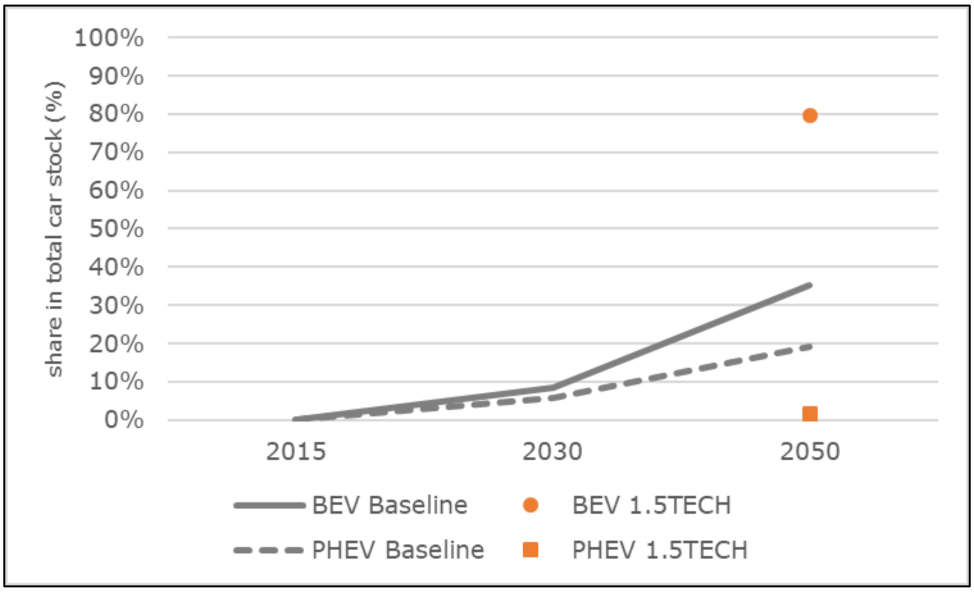



**Figure 5-33. Shares in total EU car stock by drivetrain technology in the Baseline and 1.5TECH scenarios**
**Source: own work based on (EC, 2018c)**

A 2018 survey asked 26,500 Europeans about their propensity to purchase a hybrid or electric vehicle[58]. The results by urbanisation level of area of residence are shown in **Figure 5-34**. The figure also compares the results of the survey with those of a similar survey carried out in 2014. (Christidis & Focas, 2019) concluded that the declared propensity to purchase a hybrid or electric vehicle rose between 2014 and 2018 across all socio-economic groups. As can be seen, that propensity increased with the level of urbanisation in 2018, in line with the results of the 2014 survey.

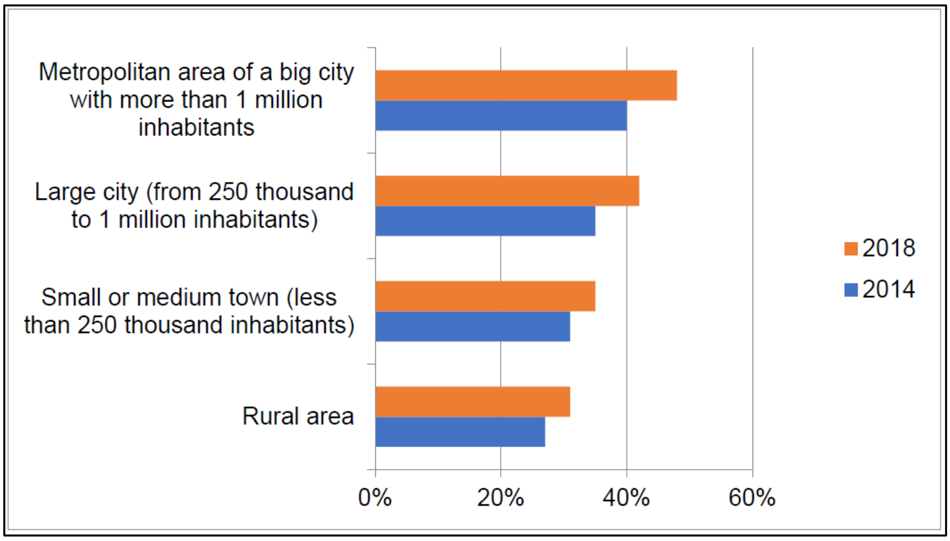



**Figure 5-34. Propensity to purchase a hybrid or electric vehicle, by area**
**Source: Christidis & Focas, 2019**

[58] These comprise HEV, PHEV, REEV, BEV and FCEV.

The low availability of models and sizes can limit the uptake in the LCV market. The market perspectives for electric road freight vehicles in the EU based on (EC, 2018c) under two scenarios are shown in **Figure 5-35**. As can be seen, market penetration of electric trucks[59] is expected to be low in these scenarios.

Due to the weight of the large battery required for long e-range and its associated cost, the deployment of fully electric trucks for long-haul freight applications was not expected by (UBA, 2016) (Öko-Institut, 2016). For these authors, overhead wires supplying trucks with electricity are an option worth considering instead. Intelligent pantographs are being used in the context of the eHighways projects, where two adapted diesel hybrid trucks are being tested in Sweden while 15 trucks are expected to be supplied from 2019 in Germany where tests recently started and are expected to continue until the end of 2022 (Scania, 2018b). It is estimated that the cost of such a system is about one million euro per km (Heise, 2019) (see also (IEA, 2017)). (Sripad & Viswanathan, 2017) identified the key specifications required for making electric trucks a real option in practice. Notwithstanding this, Tesla is advertising an electric truck (Class 8; see (FHWA, 2014)) with 800 km of e-range at a base price of €157,000 for the US market (Tesla, 2019c). However, its production has recently been postponed to 2020 (Electrive, 2019b). Customer trials of the aforementioned eActros are taking place until mid-2020, with series production scheduled from 2021 (Daimler, 2019d). Furthermore, Daimler has unveiled a fully electric 23t truck with a payload of 11t. The truck, with a battery capacity of 300 kWh providing 350 km of e-range, might be commercialised within 2023 (Daimler, 2019e).

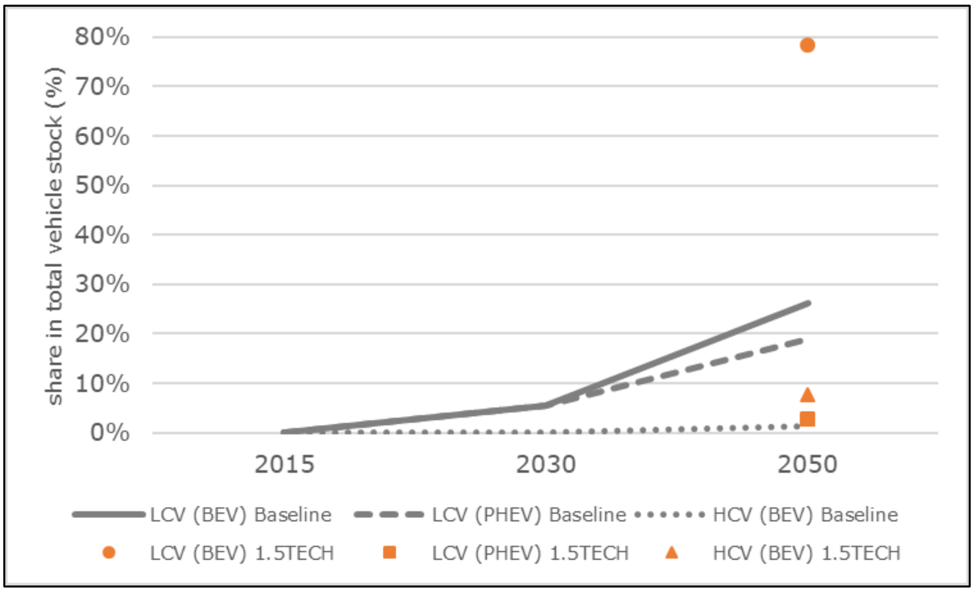



**Figure 5-35. Shares in total EU LCV and HCV stocks by drivetrain technology in the Baseline and 1.5TECH scenarios**
**Source: own work based on (EC, 2018c)**

With regards to buses, the revised 'Clean Vehicles' Directive (2019/1161) sets minimum procurement targets over 2021-2030 for zero and low emission technologies not only for trucks ($N_2$ and $N_3$ vehicle categories) but also for buses ($M_3$) (EU, 2019).

The analysis so far has focused on road vehicles at the EU level. Besides the $CO_2$ emission standards for the average new LDV and HDV sold in Europe, the speed of transport electrification will likely depend on a series of reinforcing developments.

[59] (EC, 2018c) reports electric (reported here as BEV) and hybrid HCVs, but not PHEVs. Hybrid HCVs account for 29% and 20% of the 2050 stock under respectively the Baseline and 1.5TECH scenarios.

Given the fact that manufacturing of vehicle technology has a global nature and the potential for spill over into other sub-systems, the analysis should be expanded by considering developments by OEMs and in: (i) key non-EU markets; (ii) railway vehicles, vessels and aircraft; and (iii) non-transport systems.

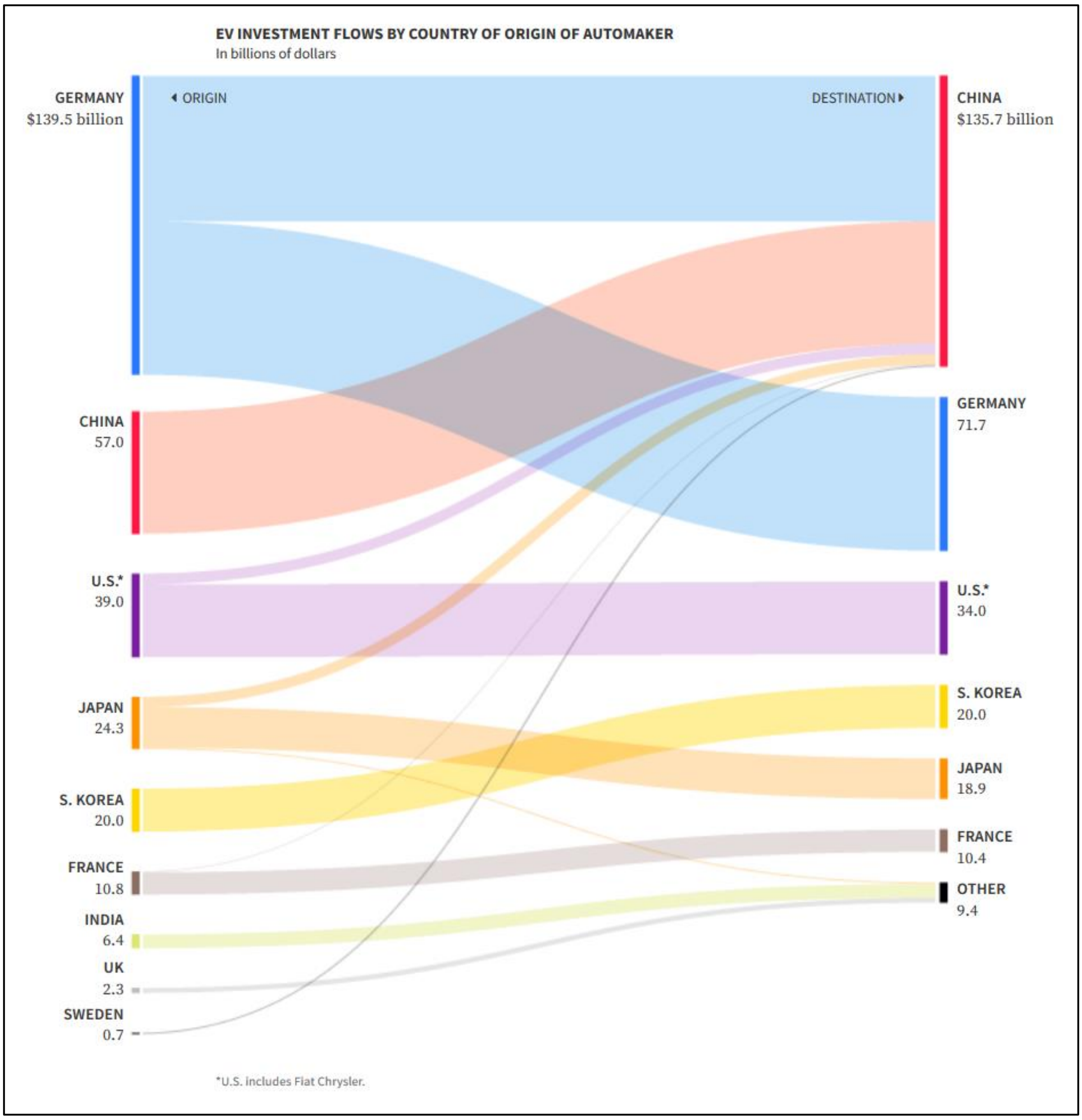



**Figure 5-36. Origin and destination of OEM investment in EVs in the next 5-10 years**
**Source: Reuters, 2019a**

Two supply-side leading indicators may provide insights into market development: R&D investment and model availability. Another indicator that is linked to model offering is the degree of vehicle platform sharing. For instance, Groupe PSA and Volkswagen have respectively developed the electric Common Modular Platform (e-CMP) and Modularer E-Antriebs-Baukasten (MEB) platforms (PSA, 2018) (VW, 2018a). It remains to be seen how OEM interaction leads to a high degree of platform sharing, at least for EVs, and thus cost reduction and increased model offerings. For instance, Ford has recently committed to using Volkswagen's MEB in Europe in 2023 ((VW, 2019c); see also (Toyota, 2018)). Developments in major non-EU markets can influence alternative fuels in EU transport systems. For instance, the policies of the Chinese government targeting the car market (CN, 2017a) (CN, 2017b) are expected to have an impact on OEMs and in turn on future EV model availability in the EU car market. For OEM investment plans, see **Figure 5-36**.

The uncertainty of worldwide EV uptake in road transport is captured by the following two figures. In **Figure 5-37**, projections of global electric car stocks until 2040 by the Organization of the Petroleum Exporting Countries (OPEC) and by Bloomberg are shown. As can also be seen, there has been a general tendency to correct the projections upwards over the past years.

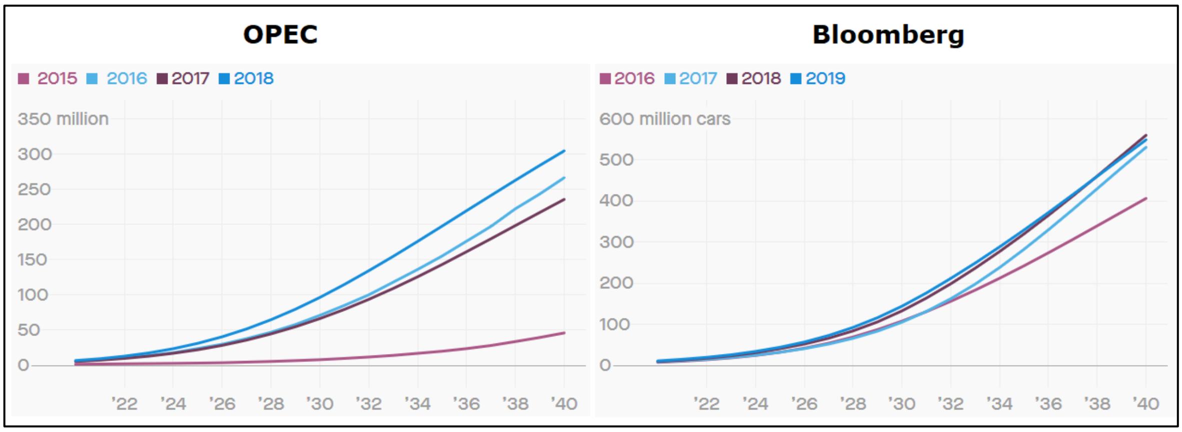



**Figure 5-37. Future global EV stock, by source and year of projection**
**Source: own adaptation of (Quartz, 2019)**

**Figure 5-38** shows the two scenarios reported by (IEA, 2018a), which also includes LCVs and HDVs (i.e. buses and trucks) in addition to passenger LDVs (PLDVs).

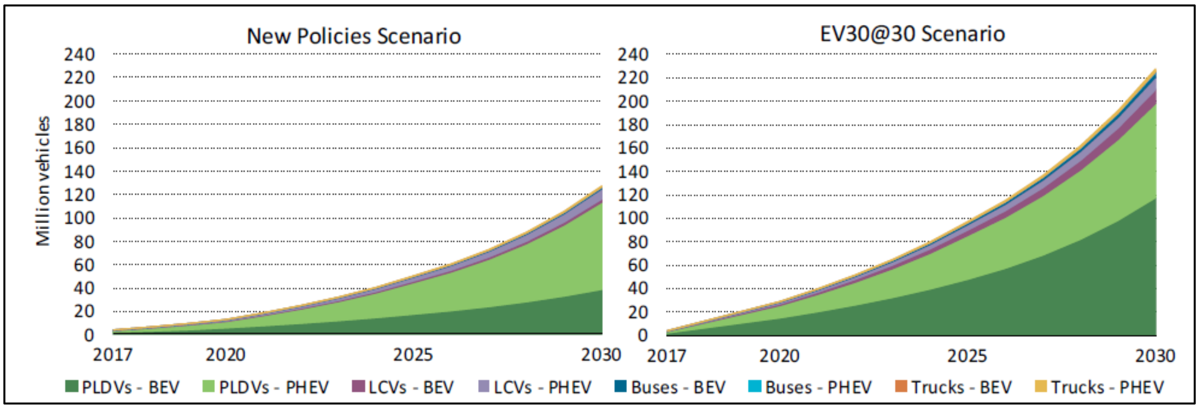



**Figure 5-38. Global EV stock, by scenario**
**Source: IEA, 2018a**

In addition to road vehicles, electrification of the types of vehicles used in other transport modes needs to be considered. There are *intra*-sectoral effects, which can be potentially beneficial (e.g. synergetic effects when stronger demand for batteries from different modes leads to greater investment in manufacturing capacity) or have an adverse impact on the transport market (e.g. when supply side bottlenecks lead to a situation where different transport modes compete for the limited amount of batteries available in the market). Besides *intra*-sectoral effects, *inter*-sectoral effects are also present, with alternative fuels being also in demand by energy-intensive industries such as chemical and steel manufacturing.

It is expected that rail transport will continue to rely mainly on electricity, with an increase in the share of renewable electricity used. A possibility that should not be disregarded is the potential shift of transported goods from road to rail, particularly for goods with high affinity to rail (see e.g. (RFF, n.d.)). This would likely lead to greater electrification of freight transport. Furthermore, there are plans to increase the range of battery-powered railway vehicles operating in non-electrified routes from 40 km to 100 km (BombardierRail, 2018).

The prospects of inland waterway transport electrification remain overall positive (see **Box 4**), but challenges remain. For instance, EFIP expects that battery-powered vessels might account for about 10% of inland waterway vessels by 2030, or more if retrofitting opportunities arise (personal communication). In the aforementioned survey by (CCNR, 2019), German day-trip companies exhibited a greater inclination towards alternative fuel vessels than Dutch, Belgian, Swiss and French companies. Among the main barriers, the surveyed companies indicated insufficient profitability (30% of the answers), uncertain regulatory environment (26%) and start-up finance too expensive / shortage of debt capital (25%).

The electrification of the water transport system seems more promising for inland waterways and short-sea shipping rather than deep-sea shipping (EC, 2018c). The number of battery-powered vessels in operation or on order is expected to continue to grow, as indicated in **Figure 5-20**. For instance, in Norway Hurtigruten is investing €740 million in three hybrid-electric cruise ships, powered by large battery packs, with a capacity of at least 500 passengers (Hurtigruten, 2019). Nuclear propulsion was regarded by (RAEng, 2013) as a medium- to long-term powertrain option.

The aforementioned battery-powered vessel ‘Yara Birkeland’, fitted with a 7 MWh battery, will enter service in 2020, becoming the world’s first autonomous vessel (Yara, 2019) (see also **Box 5**). EVs are expected to co-evolve not only with recharging infrastructure but also with connected and autonomous vehicle technologies (see e.g. (Sperling, 2018)). BMW and Daimler aim at mass deploying Level 4 vehicles by 2024 (AutomotiveNews, 2019).

**Box 5. E-ferry (2015-2020)**

The E-ferry – prototype and full-scale demonstration of next generation 100% electrically powered ferry for passengers and vehicles – project has delivered the *Ellen* electric ferry:

- Medium-sized ferry for up to 198 passengers, cargo and 31 cars or 5 trucks;

- Ferry with a 4.3 MWh of energy storage capacity;

- Travel distance of 22 nautical miles between Ærø and Fynshav (Denmark).

The electric ferry was baptised on 1 June 2019 and is entering operation in July 2019.

Funding / coordination: €21.3 million (€15.1 million EU funding) / coordinated by Ærø Kommune.

Sources: (E-ferry, 2019) (ME, 2019)

**Box 6. Zero Emission Ferries - a green link across the Øresund (2014-2017)**

Introduction of new and innovative concepts and technology by converting two existing complex RoPax ships - originally fuelled by heavy oil - to plug-in all electric powered operation using exclusively batteries. Operation of the vessel in maritime link, connecting the comprehensive TEN-T network ports of Helsingör (Denmark) and Helsingborg (Sweden).

In conjunction with the ships conversion, the required power provision and charging installations in the ports/ferry terminals were realised.

Total eligible costs: €26,300,000

EU funding: €13,150,000

Coordinator: Forsea Helsingør ApS (Denmark)

Sources: INEA

The EU Long-Term Strategy for GHG emissions reduction indicated that the electrification of air transport remains at an exploratory stage (EC, 2018c). According to different sources, aircrafts powered by electricity are under development and are unlikely to be commercially deployed or impact demand before 2030 (EASA, 2019a), 2040 (IHS, 2018) or 2050 (IRENA, 2017a). This view is also shared by Lufthansa, who sees a possible role for hybrid propulsion for short haul passenger flights in 2050. Extra demand can be expected from electric drones and air taxis (personal communication by Lufthansa). In his analysis of realistic alternative fuels for aviation, (Zschocke, 2019) concludes that no viable option to kerosene exists before 2050. The same author considers that a realistic option using kerosene is hybrid technology. The first flight of the E-Fan X hybrid-electric aircraft demonstrator is expected to take place in 2021 (Airbus, 2019).

Technology and policy aspects are shaping EV market development. The former relate to declining battery costs and increasing energy density and e-range. The latter concern, in the EU alone, stricter $CO_2$ emission targets, deployment of recharging infrastructure and purchase subsidies. Taking these developments together, the perspectives for EV market evolution are relatively positive.

In addition to the aforementioned purchase price, two aspects to be improved for the rapid uptake of EVs are the number of model offerings, which is still limited relative to gasoline and diesel makes, and the need to increase the battery energy content to ensure a higher e-range at relatively high average speed (e.g. on the motorway). Worldwide electrification of the transport sector will require adequate investment in battery manufacturing capacity; furthermore, adequate investment in battery manufacturing capacity in Europe will be needed (recall **section 5.1.1, p. 119**), to avoid that electrification of the European vehicle market occur by increasing battery imports, especially from Asia.

The need to ensure the recyclability of batteries was mentioned by at least one stakeholder (personal communication by ALSTOM), echoing the recommendations of European battery recycling companies such as Umicore. VW will operate a pilot line for battery recycling in 2020 (VW, 2019e). (Miller, Gaines, & Spangenberg, 2019) considered that the development of a LIB recycling process that is not only environmentally-friendly but also cost effective is currently a challenge. (Harper et al., 2019) mentioned R&D as a pre-requisite for establishing profitable LIB recycling processes. The pace of market electrification in the EU will also depend on infrastructure developments, considered next.

**Infrastructure:** The analysis of the NPFs required by the AFI Directive shows that 26 MSs provided targets for publicly accessible road recharging points for 2020 and that electricity is the preferred alternative fuel for passenger cars in most Member States (EC, 2019d). By planning around 170,000 publicly accessible recharging points by 2020 (Thiel et al., 2019), the national plans are less ambitious than the European Commission's estimates from the impact assessment of the AFI Directive (EC, 2013) (i.e. around 400,000 publicly accessible recharging points corresponding to 4 million EVs on the road).

The EU aims at fostering a synchronised deployment of EVs and necessary publicly accessible charging infrastructure, a value of 10 for the ratio representing number of EVs over the number of recharging points (sufficiency index) is mentioned in the AFI Directive (EC, 2014) as an indicative appropriate level of charging infrastructure. The 2017 and foreseen 2020 ratios obtained from NPFs are presented in **Figure 5-39**. It can be observed that in many MSs the situation deteriorates and in some MSs the targeted publicly accessible charging infrastructure could become insufficient for the needs of the estimated EV fleet.

The optimal number of publicly accessible recharging points depends on several factors that are country/region dependent like the travel patterns, number of EVs (number of BEVs and PHEVs), number of EV owners with a dedicated private recharging point (dictated by housing type) and with workplace recharging points access (Hardman et al., 2018).

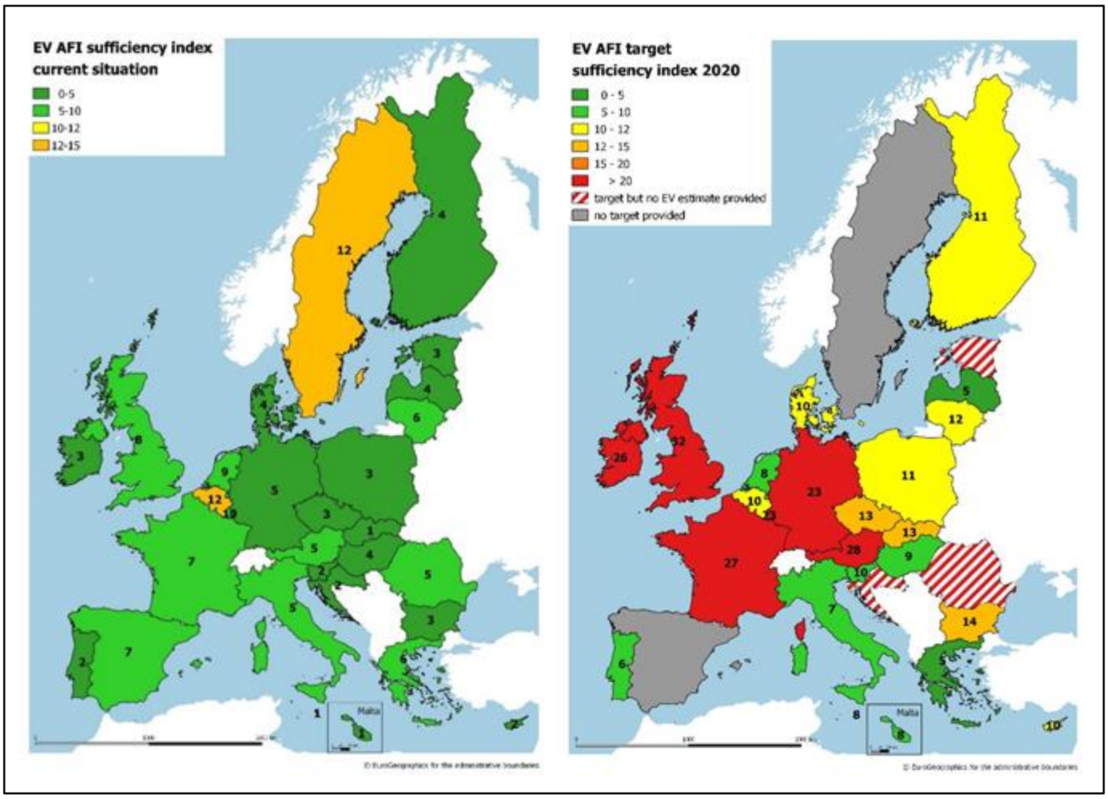



**Figure 5-39. Overview of recharging point sufficiency index across EU, for 2017 (left) and 2020 (right)**
**Source: EC, 2019d**

According to VDA (personal communication), a normal power AC recharging point is estimated to cost €3,175 in 2020 and €3,125 in 2025, a high power 50kW DC recharging point is estimated to cost €25,000 in 2020 and 2025 while a high power 150kW/350kW DC recharging point is estimated to cost €115,000 in 2020 and €100,000 in 2025. According to (NKL, 2018) in the Netherlands, the total cost for a normal power AC recharging point in 2025 – 2030 is forecasted to be around €2,780 (a 15% decrease from the price in 2018) while its use is forecasted to be around 15kWh/day in the period 2025 – 2030 (an increase by 50% from the value in 2018).

Battery swapping could become a viable solution in fleet applications that use only vehicles of one manufacturer especially in view of the development of automated and shared mobility services (Spöttle, M. et al., 2018).

Oslo plans to become the first city in the world to install induction-based wireless charging stations for electric taxis (the Norwegian taxi fleet needing to be zero emission by 2023) (Reuters, 2019b).

A new concept of mobile recharging points emerged recently providing on demand portable recharging services (proposed by E-GAP in Italy (E-GAP, 2019), RAC in United Kingdom (RAC, 2019) and Volkswagen (Volkswagen, 2018)). It is supposed to alleviate user's range anxiety by delivering a solution for emergency situations.

Smart grids could enable EVs to act as flexible loads and decentralised storage resource that could minimise or avoid grid reinforcement (Eurelectric, 2015). With Demand Side Management, the EV charging process could be controlled by shifting the charging period to times of lower demand, reducing or increasing the charging power, or even interrupting the recharge of the vehicle's battery in case of emergency situations. Smart charging can also be the optimisation of charging power profile of an EV with the goal to maximise local energy production from renewable sources (e.g. Solar Smart Charging project ("Smart solar charging", 2018)). From the supporting infrastructure point of view, smart charging in a wide scale should take into consideration the constraints of the power system, the potential for variable energy pricing offered by the energy market and the information about the energy mix.

EVs could bring even greater flexibility to the system by supplying power back to the grid or home in a Vehicle-to-Grid (V2G) or Vehicle-to-Building (V2B) scenario. According to ((Everoze, 2018)), there are 50 V2G projects globally, of which 25 are in Europe (e.g. SEEV4-City project dealing with operational, long term pilots in 5 cities in 5 European countries (SEEV4-City, 2019)). An obvious advantage of a V2X operation is that the vehicle's battery can be used to store energy during times of excess power generation from renewable energy sources and discharge it at times of high demand (Alonso Raposo et al., 2019).

In order for consumers to experience mobility seamlessly, the infrastructure needs to be digitally connected, and the consumers should have real-time access to reliable information about the location and availability of recharging points. Interoperable EU-wide electro-mobility payment systems are also needed (and in development), that are based on open standards and that have transparent, easily understandable and timely price information (Alonso Raposo et al., 2019).

The Implementation Plan for Electrification in rail transport aims to reduce specific average $CO_2$ emissions from train operation by 30%, until 2025 (EC, 2017b). There are no technical obstacles to further electrification, but the cost for upgrading and electrifying the existing rail infrastructure and the expected carbon reduction need to be considered on a case-by-case basis, with EU funding support where necessary.

Within the NPFs required by the AFI Directive, several MSs mentioned plans of increasing the proportion of their electrified railway lines (e.g. Austria, Denmark, Greece, Ireland, Lithuania, Latvia, and Portugal) (EC, 2019d). Denmark foresees that electricity will deliver 85% of train services in 2030, while Finland targets that rail transport would almost fully rely on electricity in 2050 (NPF Finland, 2017).

The AFI Directive states in its article 4 that each Member State shall assess in their NPF the need for SSE supply in maritime and inland ports. In their NPFs, nine MSs provide SSE targets for the future (Estonia and Spain for maritime ports; Hungary for inland waterways ports; Belgium, Croatia, France, Greece, Netherlands, Romania for both types of ports).

Increasing shore based grid connection facilities will allow all ships to connect to an electrical supply whilst in port, thereby reducing ship emissions and offering other benefits such as reduced noise, primarily improving passenger comfort (EC, 2017b). (EC, 2017b). (Winkel, Weddige, Johnsen, Hoen, & Papaefthimiou, 2016) estimated that, if all ports in Europe were to use SSE in 2020, 2.94 billion euro of health costs could be saved as well as 800,000 tonnes of carbon emissions could be reduced.

According to EFIP (personal communication), the average capacity utilisation of SSE supply infrastructure is expected to increase but an accurate estimation for 2030 is difficult due to the high cost of installation and the possible underutilisation by the inland waterway users

With regards to infrastructure in the European inland waterways, it is useful to know that vessels up to 11.45 metres wide and 190 metres long may use the Main-Danube Canal (CCNR, 2018).

According to (EC, 2017b), there is the provision for electrification of APUs and of all non-propulsive systems until 2025. For the airports, the aim is the electrification of services, the targets being that all support vehicles are electrified and airports are equipped for charging auxiliaries.

The AFI Directive states in its article 3 that each Member State shall consider the need to install electricity supply at airports for use by stationary airplanes. This topic is scarcely covered in the various NPFs, with MSs presenting generally only current situation and only three MSs providing clear increasing targets (Luxembourg, Netherlands, Slovenia) for the future (EC, 2019d).

## 5.2 FUEL CELL ELECTRIC VEHICLES AND HYDROGEN VEHICLES

### 5.2.1 MATURITY OF TECHNOLOGY

The key technology in this section is the fuel cell system. The hydrogen storage tank is, for energy supply, cost and safety reasons, another important component in FCEVs. **Box 7** provides information of major European initiatives on hydrogen and fuel cell technologies.

In terms of fuel cell durability, the U.S. Department of Energy set a 2020 target of 5,000 hours (equivalent to a vehicle service life of ca. 240,000 km) of operation time with less than 10% of performance loss (DOE, 2013). A recent report by (NREL, 2019) found that the performance of fuel cell stacks has substantially improved in recent years, with some units already exceeding the 5,000-hour target, "but degradation remains an issue" (p. 11). The authors suggest that the target could be met by the FCEV fleet within four years.

**Box 7. HYCELL-TPS (2004-2007) and FCH JU (2008-2024)**

Two major European initiatives to support research, technological development and demonstration (RTD) related to hydrogen and fuel cell technologies are:

- The Hydrogen and Fuel Cells Technology Platform (HYCELL-TPS), for which the EU contributed with almost 2.4 million euros.

- For the 2014-2020 phase, a budget of 1.33 billion euro was provided to the FCH JU on a matched basis between the European Commission, industry and research.

Sources: (HYCELL-TPS, 2019) (FCH-JU, 2019)

The supply chain for fuel cell stacks is less mature in Europe than in Japan and the US (HE, 2018). Fuel cell car technology is mature but not widely commercialised yet (for instance, it is not available in many car markets), also due to a reduced interest by EU manufacturers over the last few years. The $H_2$ Panel Van, a 4.25t vehicle[60] with over 800 kg of load capacity and up to 500 km of range, is being developed by Streetscooter in cooperation with Ford, with funding from the German government (NOW, 2019). Fuel cell buses have become a mature technology (personal communication by HYDROGEN EUROPE) and are ranked by FCH JU as a TRL9 (personal communication). The same authors credit hydrogen-powered HCVs with a TRL6. FlixBus will soon test fuel cell coaches for long-distance travel, requiring a range of no less than 500 km and a refuelling time of up to 20 minutes (FST, 2019).

**Box 8. H2Bus Europe (2018-2023)**

Innovative large-scale hydrogen refuelling networks with an associated captive fleet of 605 fuel cell buses in daily services of varying type, grouped in three regional clusters to create sufficient demand.

Deployment of three hydrogen logistic centres one in Denmark, United Kingdom and Latvia. Each hydrogen logistic centre will serve a number of hydrogen refuelling stations (HRS) through tube trailers. The hydrogen refuelling stations will be deployed on core urban nodes along the Scandinavian-Mediterranean (2 Copenhagen, Denmark), North-Sea Baltic (3 in Riga, Latvia), and North-Sea Mediterranean (4 in the UK in London and Oxford) corridors.

Total eligible costs: €198,153,000

Maximum EU contribution: €39,630,600

Source: (FLHYSAFE, 2019)

For the rail transport system, fuel cells are a mature technology, and a system of 400 kW of capacity has been deployed in a passenger train (personal communication by HYDROGEN EUROPE). In addition to the deployment of one hydrogen-powered train in Europe (see **section 5.2.2, p. 161**), the deployment of hydrogen trains is also being considered an option in Canada and expected to be trialled in 2021 in Japan (ACTNews, 2019).

[60] Although in principle the mass of N1 vehicles should not exceed 3.5 tonnes, an exception for battery electric commercial vehicles is applicable in Germany.

**Box 9. FLAGSHIPS project (2019-2022)**

The objective of the 'Clean waterborne transport in Europe' (FLAGSHIPS) project is to demonstrate two hydrogen fuel cell vessels under commercial operation.

Expected outcome for IWWs:

New build demo vessel powered by gaseous hydrogen in Lyon (France).

Expected outcome for maritime transport:

Retrofitted demo vessel powered by liquid hydrogen in Stavanger (Norway).

Funding / coordination: €6.8 million (€5 million EU funding) / coordinated by Teknologian tutkimuskeskus VTT Oy

Source: (FLAGSHIPS, 2019)

(LR/UMAS, 2017) also identified hybrid hydrogen, hydrogen fuel cell and hydrogen plus internal combustion engine as technology options for zero carbon vessels in inland waterway transport. To (Moirangthem, 2016), hydrogen was in 2016 still a future option. In terms of IWWs, the demonstration vessel 'Hydroville', with capacity for 16 passengers, is currently testing the use of hydrogen mixed with diesel in a combustion engine (EIBIP, 2019). CCNR asserts that hydrogen and methanol fuel cells are still under development for inland navigation and that their maturity to be reached in a decade (personal communication). See also **Box 9**.

**Box 10. HySeas III project (2018-2021)**

The objective of the third phase of the research programme initiated in 2013 will be the deployment of the world's first sea-going ferry powered by renewable $H_2$.

Expected outcomes:

Construction of a prototype version.

Testing real-world operation in the Orkney Islands.

Supporting replication.

Funding / coordination: €12.6 million (€9.2 million EU funding) / coordinated by the University Court of the University of St. Andrews

Source: (HySeasIII, 2019)

(T&E, 2018b) concluded that liquid hydrogen, in combination with other fuels, is the best option to decarbonise the European maritime transport system. For passenger ferries and maritime transport, the technology is not mature yet (projects considering the use of fuel cells for auxiliary power are in the design phase) (personal communication by HYDROGEN EUROPE). The in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction considered that further research is needed for the use of hydrogen in maritime transport (EC, 2018c) (see also **Box 10**). To (DNV-GL, 2018b), however, hydrogen already represents a realistic option. The world's first commercial fuel cell ferry is expected to be launched this year in the US (WGR, 2019).

**Box 11. HYCARUS project (2013-2018)**

The objective of the HYdrogen Cells for AiRborne USage (HYCARUS) project was design a generic fuel cell system and test it a TRL 6 level for non-essential aircraft applications.

An expected outcome of the project is the accomplishment of test flights on a Dassault Falcon.

Funding / coordination: €12 million (€5 million EU funding) / coordinated by Zodiac Aerotechnics SAS

Source: (HYCARUS, 2019)

The hydrogen technology for aviation is not yet mature. Airplanes using $H_2$ are being trialled (see **Boxes 11 and 12**), with fuel cell technologies currently under development for regional flights (personal communication by HYDROGEN EUROPE). For instance, flight tests on a 20-seat fuel cell aircraft are taking place in the US (ZeroAvia, 2019). (Kandaramath Hari, Yaakob, & Binitha, 2015) identified several challenges to the use of liquid $H_2$ in aviation (see **section 5.2.3, p. 165**).

**Box 12. FLHYSAFE project (2018-2020)**

The objective of the Fuel CelL HYdrogen System for AircraFt Emergency operation (FLHYSAFE) project is to prove that a cost-effective fuel cell system may be used as an emergency power unit (EPU) aboard commercial aircraft, shifting from demonstrator (e.g. HYCARUS) to ready-to-certify product level.

Funding / coordination: €7.4 million (€5 million EU funding) / coordinated by Safra Power Units

Source: (FLHYSAFE, 2019)

### 5.2.2 DATA ON VEHICLES AND INFRASTRUCTURE

Fuel cell car model availability remains low to date: five models (Hyundai ix35, Hyundai NEXO, Mercedes-Benz GLC F-Cell and Toyota Mirai) are listed in (H2M, 2018b), of which one (Honda Clarity Fuel Cell) is not available in the European market yet. Despite this, the stock of fuel cell cars, though modest, has increased in recent years, from 218 units in 2015 to almost 600 in 2018 (see **Figure 5-40**).

For leisure travel, (Daimler, 2019g) has presented a fuel cell plug-in hybrid motorhome (Concept Sprinter F-CELL) with a driving range of 300-530 km, depending on the $H_2$ storage tank capacity.

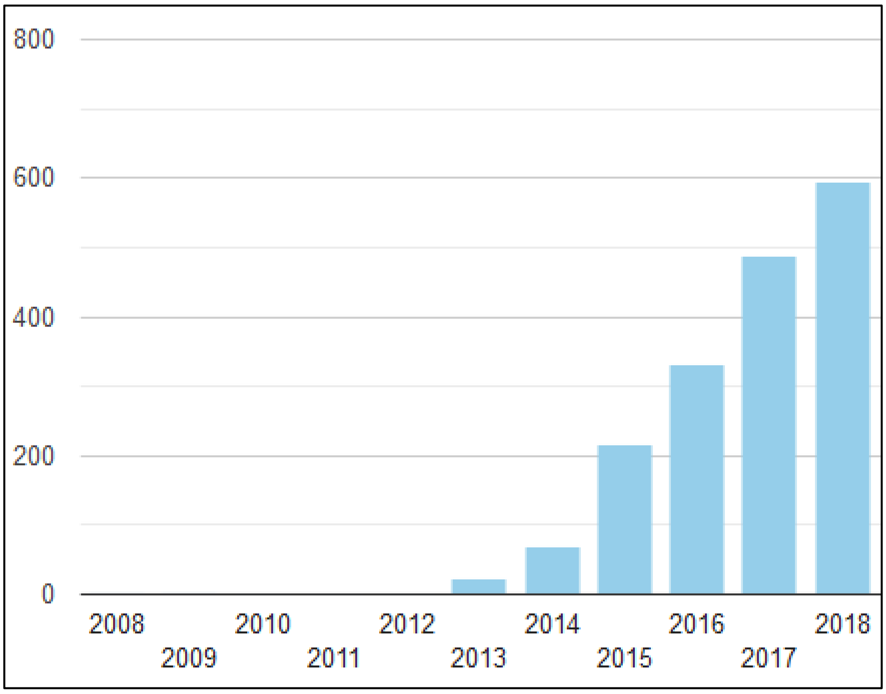



**Figure 5-40. Fuel cell car stock in the EU28**
**Source: EAFO, 2019**

It seems that there is currently only one fuel cell LCV model in the EU market (H2M, 2018b) (EAFO, 2019): the Kangoo ZE $H_2$. Over 50 of these vehicles are in operation in the UK (Symbio, 2018). **Figure 5-41** shows the stock of fuel cell LCV in the EU28 (most of them in France), which is on the rise at very low volumes (303 units in 2018, compared to 174 in the previous year (EAFO, 2019)).

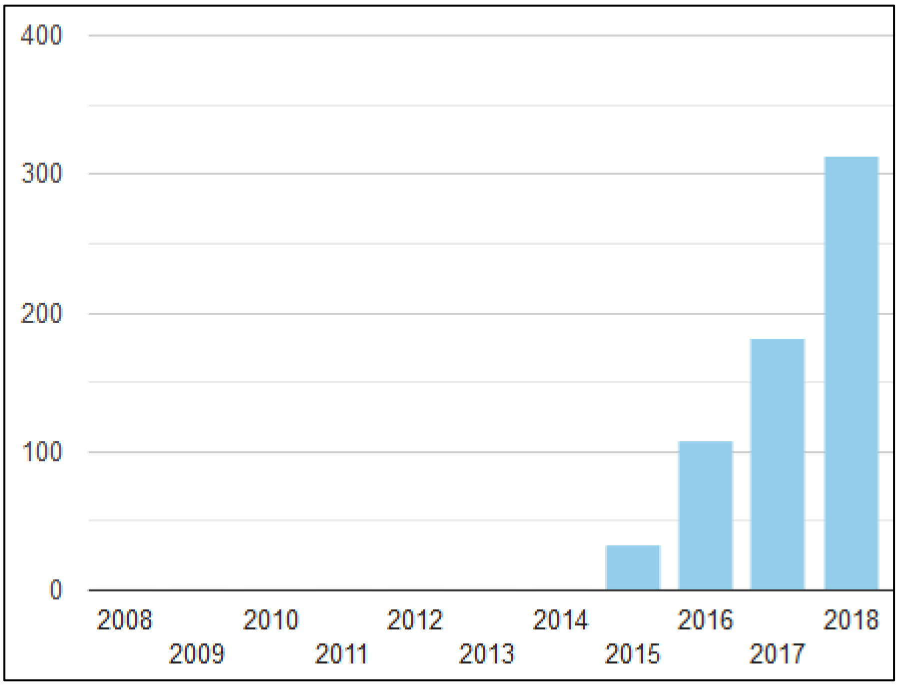



**Figure 5-41. Fuel cell LCV stock in the EU28**
**Source: EAFO, 2019**

In 2014, five bus manufacturers (EvoBus (Daimler), MAN, Solaris, Van Hool and APTS/VDL) anticipated that 500-1,000 fuel cell urban buses could enter service over 2017-2020 (JFC-JU, 2014). However, less than 100 hydrogen buses are currently in operation in the EU. Hydrogen buses have travelled in excess of 10 million km as of end 2018, most of them in London, Aberdeen, Aargau and Bolzano (FCEB, 2019). Part of this driving experience has been made on Citaro FuelCELL buses (Daimler, n.d.). One of the fuel cell buses available in the market, the Urbino 12, provides a range of 350 km (Solaris, 2019), while another model is the Enviro400 (ADL, 2018a). In 2019, the first bus corridor (13km) served only by fuel cell buses was inaugurated in France (LBA, 2019). (EAFO, 2019) reports an EU fuel cell bus stock of almost 50 units in 2018 (see **Figure 5-42**). Neither fuel cell minibuses nor fuel cell coaches are presently available in the market (HE, 2018).

Over 22,400 km have been driven by Class 8 fuel cell trucks in the US since 2017 (Toyota, 2019a). The key specifications of a 34-tonne fuel cell truck developed in Switzerland are: 100 kW fuel cell system, 120 kWh battery (LFP), 34.5 kg $H_2$ tank (gross), fuel consumption ranging from 7.5 to 8 kg $H_2$ per 100 km and 375-400 km of driving range (H2energy, 2017). In the EU, no sales of fuel cell HCVs are reported to date by (EAFO, 2019).

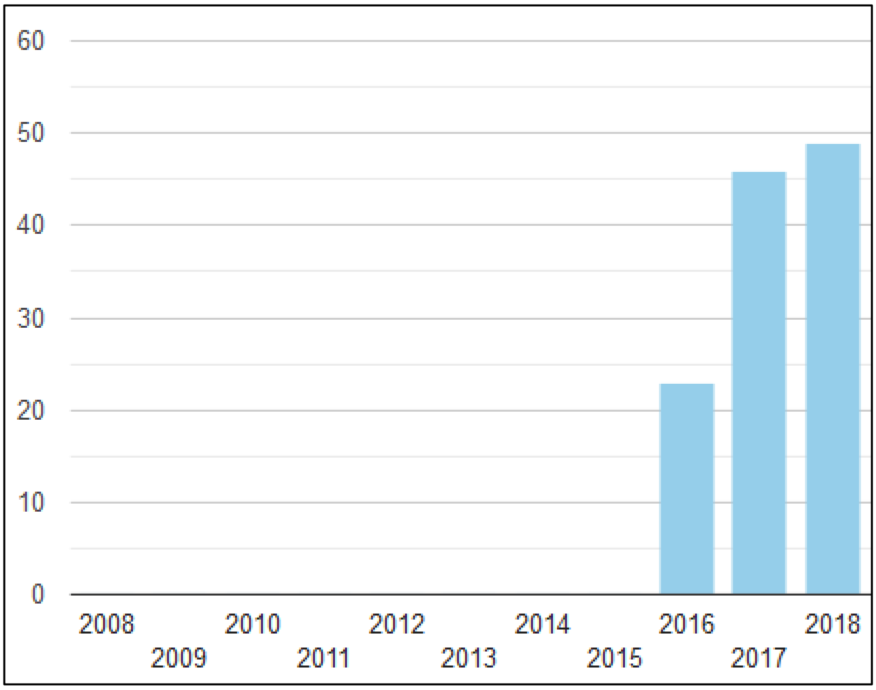



**Figure 5-42. Fuel cell bus/coach stock in the EU28**
**Source: EAFO, 2019**

The world's first $H_2$ train was deployed for regional passenger services in Germany in 2018, with a range of 1,000 km (Alstom, 2018). As reported by (TR, 2018), this train features two 200 kW fuel cell systems and two batteries with a total capacity of 110 kWh.

The number of vessels powered by hydrogen is extremely low. The European Commission funded the recent retrofit of the inland freight vessel 'Emeli', which features a diesel-electric powertrain and can be powered by hydrogen (a 30 kW fuel cell, 12 kg $H_2$ tank and 60 kWh battery allow 10 hours of zero emission operation) (EIBIP, 2019). For maritime transport, there are vessels featuring fuel cell systems (not only PEMFC) that are powered not only by $H_2$ but also methanol, LNG or diesel, as surveyed by (DNV-GL, 2017b). The same authors credited PEMFC as the fuel cell system with the highest score. By the end of 2019, a fuel cell system manufacturing site with an expected capacity of 15 MW per year to support vessels will become operational in Europe (Ballard, 2019). There are three hydrogen vessels in operation and on order, according to (DNV-GL, 2019a).

The use of hydrogen for air transport was not considered an option in the 2011 and 2015 reports. At the time of writing, no data on aircraft powered by hydrogen is available.

**Infrastructure**: Currently the hydrogen refuelling network is in an early stage of development. Two types of hydrogen refuelling stations are developed: 350 bar pressure stations for forklifts, buses, range-extender type road vehicles in the 20 – 200 kg/hour capacity range and 700 bar pressure stations for road vehicles in the 80 – 1000 kg/day capacity range (FCEVs can be refuelled in 3 to 5 minutes).

The Commission has funded 11 hydrogen refuelling infrastructure projects through the CEF, corresponding to 122 refuelling points (other 9 hydrogen refuelling points were funded as part of road actions focusing on electricity infrastructure; see **section 5.1.2, p. 131**).

**Figure 5-43** shows the growing global stock of hydrogen refuelling stations between 2003 and 2017. According to (LBST, 2019b), at the end of 2018 there are 369 hydrogen refuelling stations available worldwide (273 being publicly accessible) of which 48 hydrogen refuelling stations were opened during 2018.

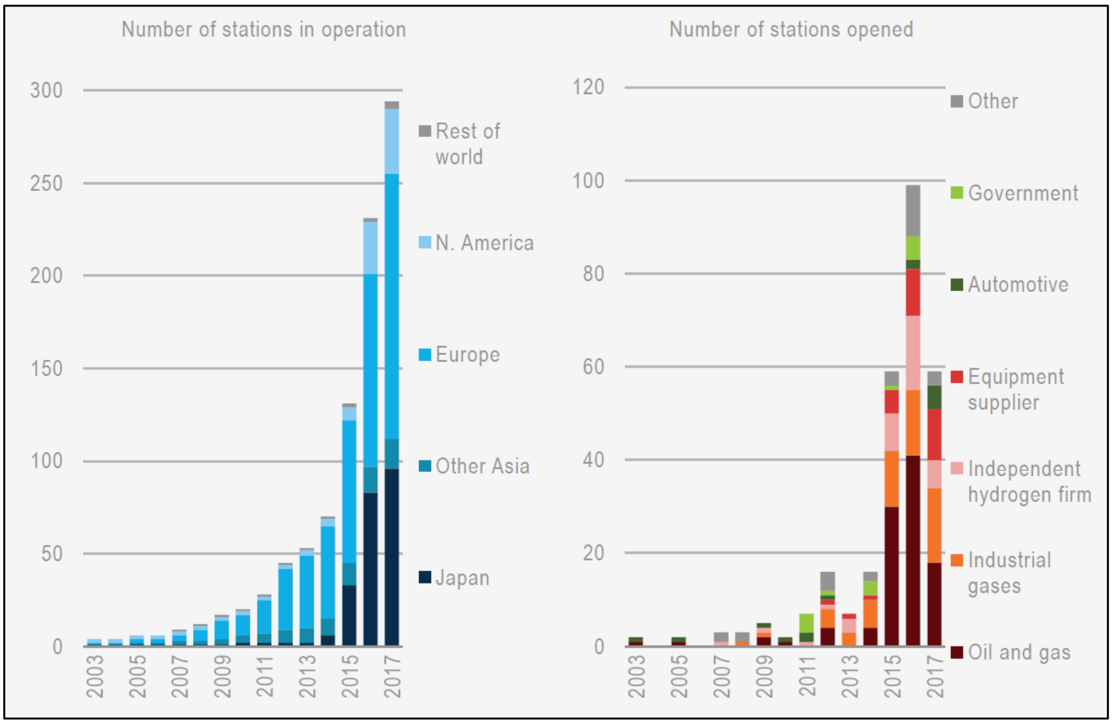



**Figure 5-43. H2 refuelling stations, by world region and ownership**
**Source: IEA, 2018b**

(FCH2JU, 2019) mentions that about 120 hydrogen refuelling stations are in operation in Europe, mostly in and around urban centres at the end of 2018. Based on the aforementioned information from the CEF, it can be reasoned that some of these stations have more than one refuelling point. In EU, (LBST, 2019b) lists 113 publicly accessible hydrogen stations and Germany is leading with 59 stations (globally second place after Japan with 96 stations). According to (EAFO, 2019), the top five EU countries contains also UK (14 stations), Denmark (10), France (7) and Austria (5).

<u>Standards for hydrogen refuelling points for motor vehicles</u>

Following the mandate M/533 given by the Commission to the European Standardisation Organizations CEN-Cenelec, the ESOs recommended to the Commission the standards to be applied to supplement or to amend the technical specifications established in Annex II of Directive 2014/94 /EU for hydrogen refuelling points for motor vehicles:

- The standard EN 17127 'Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols' which covers the interoperability of design, construction, operation, inspection and maintenance of stations for fuelling gaseous hydrogen to vehicles and the relevant filling protocols

- The standard EN 17124 'Hydrogen fuel - Product specification and quality assurance - Proton exchange membrane (PEM) fuel cell applications for road vehicles', which covers the quality characteristics of hydrogen fuel and the corresponding quality assurance in order to ensure uniformity of the hydrogen product as dispensed for utilization in proton exchange membrane fuel cell road vehicle systems.

- The standard EN ISO 17268 'Gaseous hydrogen land vehicle refuelling connection devices'

These three standards have been included in Directive 2014/94/EU through the Commission Delegated Regulation (EU) 2019/1745.

### 5.2.3 COST OF VEHICLES AND INFRASTRUCTURE

FCH JU estimates that the fuel cell system cost might decrease to below €50 per kW by 2030 (personal communication). A scenario of plausible future cost evolutions of the fuel cell system and the $H_2$ storage tank is shown in **Figure 5-44**. The hydrogen tank of current car models range from 4.4 kg to 6.33 kg (H2M, 2018b).

**Figure 5-45** shows fuel cell car prices for five models. Note that the aforementioned Mercedes-Benz GLC F-Cell, featuring a LIB with a capacity of 13.8 kWh, is offered via leasing (a period of 8 years is assumed to derive the price shown in the figure) and the Honda Clarity Fuel Cell is available only in Japan and California (H2M, 2018b).

The conversion efficiency of FCEVs is 26% (Leopoldina, 2017). Currently, hydrogen is sold at a price of e.g. €9.5 per kg in Germany (NeuePresse, 2019) and €11.3 plus VAT per kg in Italy (H2-SuedTirol, 2019). Thus, the fuel cost of fuel cell cars is currently similar to those of diesel cars. The cost of hydrogen fuel is expected to go down in the future (personal communication by ALSTOM), including the one produced via electrolysis: by 2030, a cost of €5 per kg of $H_2$ is expected by HYDROGEN EUROPE (personal communication) (see also (Schmidt et al., 2017)).

The only fuel cell LCV price found at the time of writing corresponds to the aforementioned Renault Kangoo ZE $H_2$, priced at €52,550-€58,250 (H2M, 2018b).

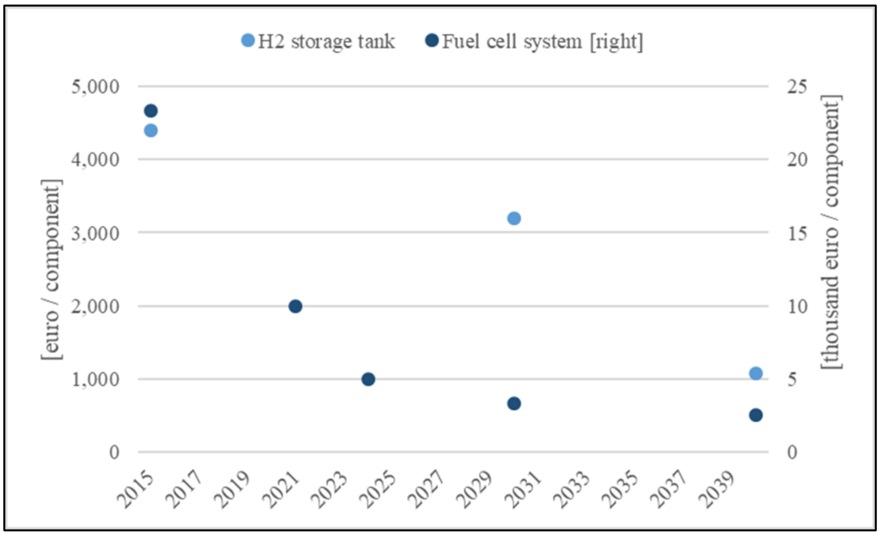



**Figure 5-44. Key powertrain components cost**
**Source: own work based on (HC, 2018) (E4tech, 2017) (Morrison, Stevens, & Joseck, 2018)**

The price of fuel cell buses recently exceeded one million euro (E4tech, 2017) (HE, 2018). In 2016, (Ballard, 2016) expected that the price of 12-metre fuel cell buses would drop to below half a million euro by 2020. However, other sources more recently postponed this number to 2023 (see the Appendix 1). The JIVE2 project (see **Box 13**) had the objective of reaching a purchase price of up to €625,000 for a standard fuel cell bus (JIVE2, 2019).

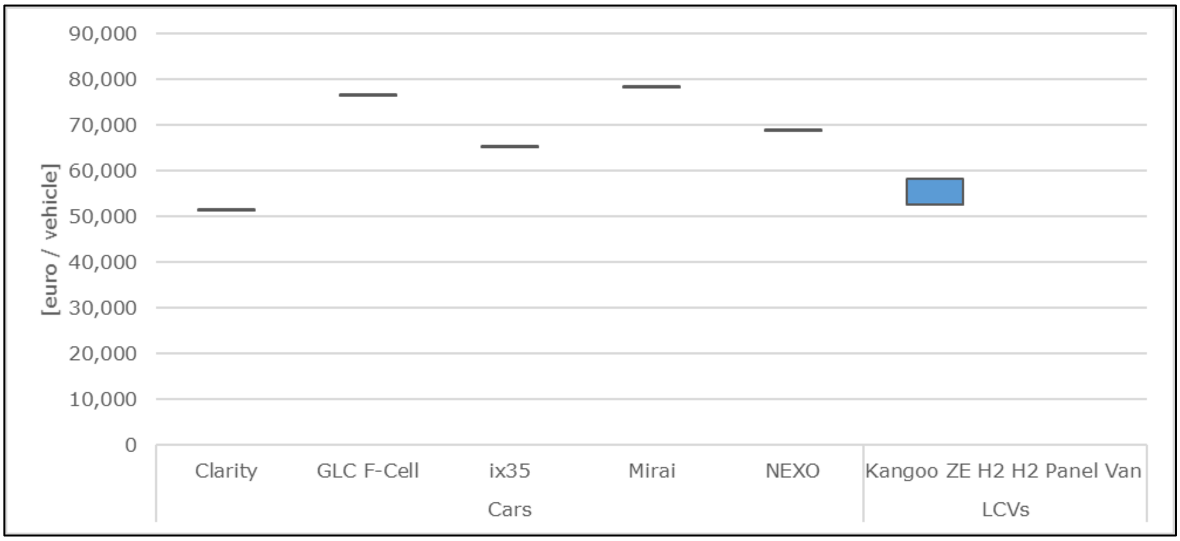



**Figure 5-45. Current prices of fuel cell LDVs**
**Note: the price of the StreetScooter $H_2$ Panel Van is currently not available (see (NOW, 2019)).**
**Source: own work based on (ADAC, 2019b) (H2M, 2018b)**

For fuel cell HCVs, (LBST, 2019a) assumed a hydrogen fuel consumption of 7.33 kg per 100 km. According to (Hyundai, 2018a), the TCO of fuel cell trucks is similar to that of diesel, at least for Swiss operators, because the higher purchase price and fuel consumption is offset by the lower maintenance costs and road taxes. In 2017, (ICCT, 2017c) estimated that the 2015 real capital cost of fuel cell HCVs (tractor-trailer) in Europe would be €244,000 in 2020 and €217,000 in 2025. Available information indicates that current prices are still substantially higher.

(Isaac & Fulton, 2016) calculated that the cost of a $H_2$ locomotive for passenger rail ranges from around 7 to 8.7 million euro per unit in the US, including the tank and the fuel cell system. More recently and in the EU context, (S2R, 2019) calculated that the

TCO of a fuel cell train was higher than the diesel train under their base case scenario and lower under their optimistic case scenario (applicable in Scandinavia, according to the authors). The cost of manufacturing hydrogen railway vehicles, while still high, is expected to decrease in the future (personal communication by ALSTOM).

The survey did not help elicit the current production costs of hydrogen powered and fuel cell vessels.

Liquid hydrogen requires the modification of the aircraft engine (Kandaramath Hari et al., 2015) and this entails additional cost. This option is in any case not yet technologically mature.

**Infrastructure**: The cost of a hydrogen refuelling station depends on several parameters like the scale/capacity and the hydrogen distribution and storage mechanisms. The initial hydrogen stations were generally deployed from €1,700,000 to €2,700,000 per station according to (ICCT, 2017a) and from €1,500,000 to €2,500,000 per station according to (SDG, 2017). A cost per station of €1,400,000 is reported by UPEI (personal communication) and by (RB, 2016). (Hydrogen Europe, 2018) mentions the cost of a hydrogen refuelling station is ranging from €1,000,000 (for a station for cars refuelling at 700 bars with a capacity of 200 kg/day) to €3,200,000 (for a large-scale station for buses refuelling at 350 bars with a capacity of more than 20 buses/day). According to (SDG, 2017), the cost of a hydrogen refuelling station is ranging from around €600,000 (for a station with a capacity of 100 kg/day) to around €1,700,000 (for a station with a capacity of 1000kg/day).

The need to build the hydrogen refuelling infrastructure for the rail transport system was highlighted as a main challenge by ALSTOM (personal communication).

In ports for large-scale shipping, HYDROGEN EUROPE considers that the cost initially ranges between €10 to €20 million but then falls to less than €5 million (personal communication).

### 5.2.4 PERSPECTIVES FOR MARKET DEVELOPMENT

Based on the presently high cost of components leading to a high purchase price and relatively high hydrogen prices, in the near future fuel cell cars do not seem to be an attractive option (in economic terms and compared to alternatives). As indicated above, only three FCEV models are currently commercially available in the EU (a fourth one for leasing) and all of them in the executive segment, which accounted for less than 14% of new registrations in Western Europe in 2017 (ACEA, 2017b). This, together with the low expected number of model offerings in the near future (one example for cars is (Audi, 2018); a second fuel cell LCV model (the $H_2$ Panel Van) is scheduled to enter service in Germany in 2020 (DPDHL, 2019)), are not encouraging signs of rapid growth in the EU LDV stock for this powertrain. In the longer term, this may however change. For instance, the BMW i Hydrogen NEXT has been recently unveiled and (BMW, 2019b) plans to offer more fuel cell vehicles from 2025. Hyundai has pledged to invest 5.8 billion euro in fuel cell vehicle technology through 2030 (Bloomberg, 2018).

The market perspectives for fuel cell road vehicles, with the exception of buses, in the EU based on (EC, 2018c) under two scenarios are shown in **Figure 5-46**. The perspectives in 2030 seem to be in line with the information from the previous paragraph.

The in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction concluded that fuel cells and hydrogen may play an important role for the coach and long-haul HCV markets (EC, 2018c). (EASAC, 2019) considers the HCV sub-system to be a major transport market for $H_2$, at least for long-haul operations. According to (HE, 2018), the most promising HCV segments for fuel cell technology are long-haul 26-40t and refuse collection. Development of fuel cell electric trucks with a driving range of ca. 480 km is underway (Toyota, 2019b). It is expected that two fleets of 1,000 FC trucks will be deployed in Norway and Switzerland in the near future (VR, 2018). A new hydrogen-electric truck has been recently presented (Bosch, 2019).

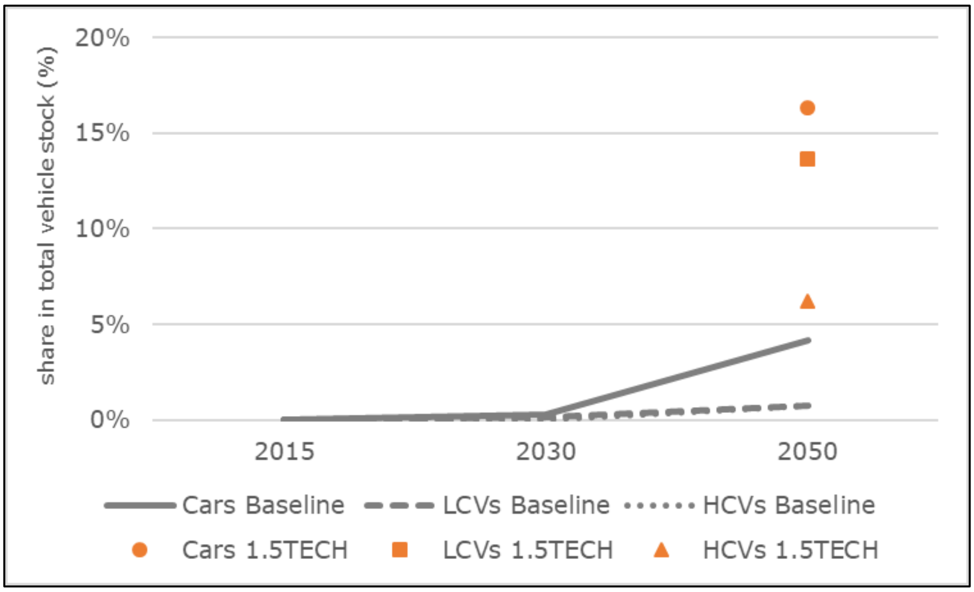



**Figure 5-46. Fuel cell vehicle shares in total car, LCV and HCV stocks in the Baseline and 1.5TECH scenarios**
**Source: own work based on (EC, 2018c)**

Two stakeholders representing the hydrogen industry have shared their perspectives on fuel cell market development: FCH JU and HYDROGEN EUROPE. The former considers that over 4 million fuel cell cars might be on the EU roads by 2030 (personal communication), but these might be of Asian origin since few EU manufacturers seem currently committed. It should be noted that the perspectives expressed by both stakeholders are substantially more optimistic than the scenarios derived from the in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction.

(EASAC, 2019) considers the bus transport sub-system to be a main transport market for $H_2$. In addition to the ca. 300 fuel cell buses being deployed in the context of the JIVE projects (see **Box 13**), the H2Bus project aims to deploy 605 additional fuel cell buses (FCB, 2018a), in part thanks to 39.6 million euro of EU funding (EC, 2018d). **Figure 5-47** shows where the further deployment of fuel cell buses is planned. Furthermore, according to HYDROGEN EUROPE there are plans for future fuel cell coach projects (personal communication by HYDROGEN EUROPE). FCH JU considers that almost half of the EU total bus sales in 2030 might be fuel cell buses (personal communication). This seems to be significantly more optimistic than the 5.9% figure for city buses provided by HYDROGEN EUROPE under their Ambitious scenario, and both figures are substantially higher than estimates from the in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction.

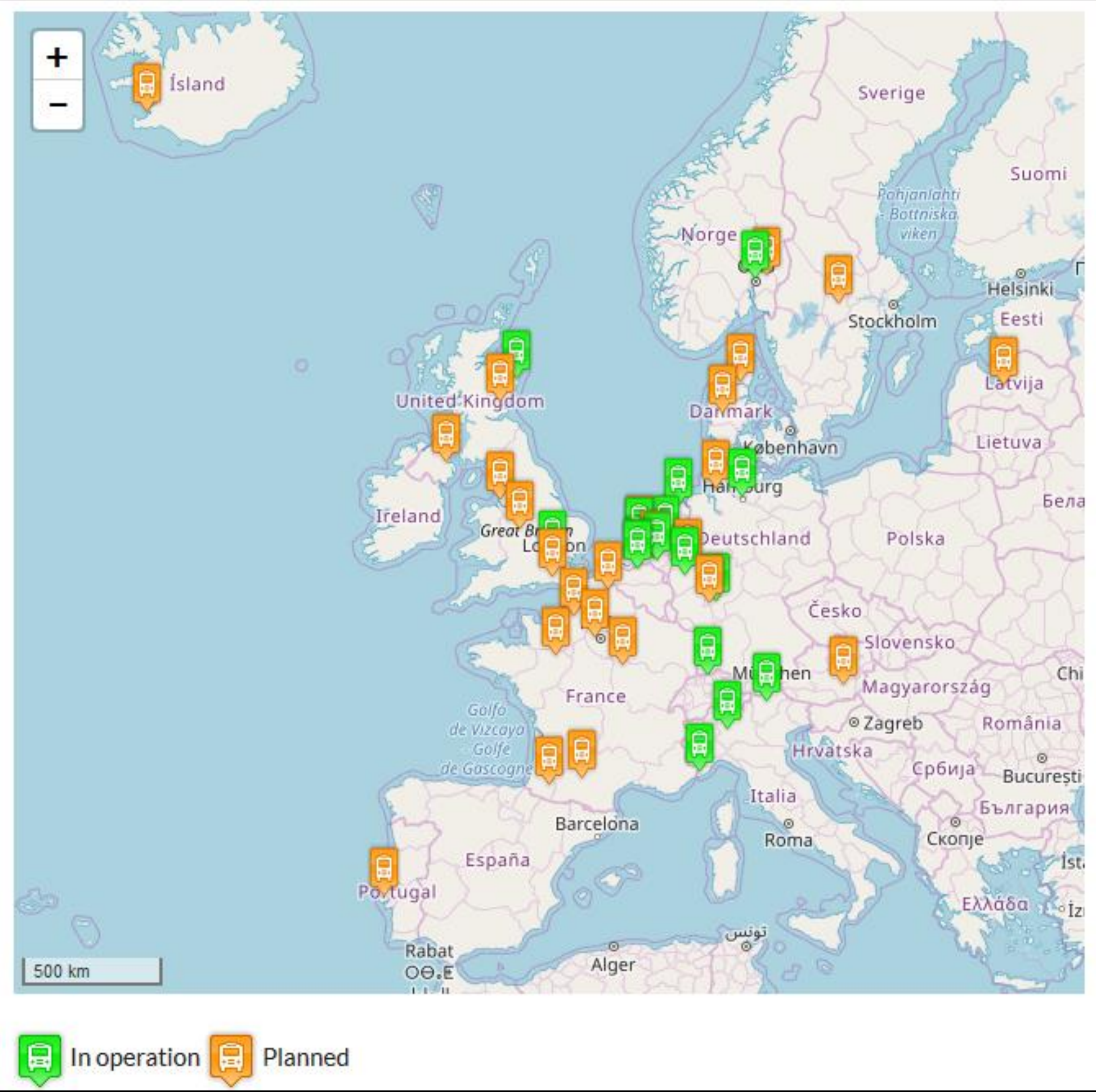



**Figure 5-47. Fuel cell electric buses in operation and planned in Europe**
**Source: FCEB, 2019**

**Box 13. JIVE projects (2017-2022)**

The objective of the Joint Initiative for hydrogen Vehicles across Europe (JIVE) project is to address the high ownership costs of fuel cell buses relative to conventional buses by exploiting the potential for economies of scale. The aim is to pave the way to commercialisation of these zero emission buses.

Main expected outcomes of the two projects:

JIVE (2017-2022): deploying 142 fuel cell buses in 9 locations;

JIVE2 (2018-2022): deploying 152 fuel cell buses in 14 cities.

Funding / coordination: €110.4 million (€32 million EU funding) / coordinated by Element Energy. For JIVE2: €25 million EU funding.

Source: (JIVE, 2019)

Manufacturing of fuel cell engines for deployment in $H_2$ trains, termed Hydrail, is happening (Hydrogenics, 2018). In those routes where railway lines continue to be non-electrified, the uptake of hydrogen is foreseen at a pace that will be influenced by policy developments and the speed of fuel cell system cost reduction. In 2020, a stock of at least 14 $H_2$ trains are expected to be in operation in Germany (FuW, 2019). In addition to the $H_2$ train model currently available, the deployment of another $H_2$ train model with a 200 kW fuel cell engine developed by competitors is expected by 2021 (FCB, 2018b). By means of conversion of existing trains to a hydrogen multiple unit, $H_2$ trains might be in operation in the UK starting in 2022, according to (Alstom, 2019). France's state-owned railway operator has pledged to order fifteen hydrogen trains for 2022 (SNCF, 2019). Thus, this technology will be introduced into three of Europe's largest railway markets.

EICB consider that the first inland waterway vessels powered by hydrogen will be based on hybrid propulsion (personal communication). EFIP expects that the number of fuel cell inland waterway vessels powered by hydrogen will increase in the future, provided that significant investments that lead to reduced hydrogen prices and increased fuel availability on-shore are made. The challenge of vessel certification is also mentioned by this stakeholder (personal communication). The storage and transhipment of hydrogen is also challenging for inland waterway transport. Fuel cell power ramp-up is limited and use of batteries is and will be required for at least the next 5 years (personal communication by EIBIP).

HYDROGEN EUROPE expects hydrogen to play a crucial role in the decarbonisation of shipping in the future (personal communication).

The market projections on the demand for hydrogen in the EU international maritime sector based on (EC, 2018c) under four scenarios[61] are shown in the in-depth analysis accompanying the "Clean Planet for all" long term strategy. Demand for hydrogen in 2050 for the three decarbonisation scenarios would represent between 2 Mtoe in the 1.5LIFEMar scenario and 7.7-7.8 Mtoe in the H2Mar70 and 1.5LIFEMar scenarios.

A firm working on an air taxi powered by hydrogen expects to receive certification from the US Federal Aviation Administration by the end of 2020 (NewAtlas, 2019). But overall, further research and testing is needed to bring this technology to a higher TRL for the purpose of commercial aviation. Aircrafts powered by cryogenic $H_2$ are thus still in an early development stage, and are unlikely to be commercially deployed before 2030 (EASA, 2019a) or even 2050 (IRENA, 2017a).

The perspectives for $H_2$ market development are highly dependent on the exploitation of economies of scale (personal communication by HYDROGEN EUROPE), which will depend on intra- as well as inter-sectoral developments, also in non-EU markets, as highlighted in **section 5.1.4, p. 149**. If realised, these economies of scale are expected to lead to substantial cost reductions in fuel cell vehicle technology. Countries that are pushing in this direction are Japan, South Korea and, recently, China (IEA, 2019d).

[61] For maritime transport, (EC, 2018c) considered a Baseline and three alternative scenarios referred to as decarbonisation variants. The three stylised variants for the EU international maritime are based on the H2 and 1.5LIFE scenarios. The variants drawing on the H2 scenario are assumed to achieve 50% and 70% reductions in the GHG emissions relative to 2008 (H2Mar50 and H2Mar70, respectively). In the 1.5LIFEMar scenario, international maritime is assumed to be part of an economy wide net zero GHG emissions target and reduces its emissions by about 88% by 2050 compared to 2008.

Besides infrastructure deployment, considered next, other challenges include the need to reduce the amount of expensive platinum used in a FCEV and to secure the supply of this material.

**Infrastructure:** If deployed at large-scale, the hydrogen infrastructure could balance the grid by producing hydrogen from surplus electricity and could provide a technical solution for seasonal storage of variable renewable energy (FCH2JU, 2019).

Hydrogen was included in 15 NPFs (Austria, Belgium, Bulgaria, the Czech Republic, Germany, Estonia, Spain, Finland, France, Hungary, Italy, the Netherlands, Sweden, Slovenia and the UK) and the map in **Figure 5-48** shows the distribution of the 765 hydrogen refuelling points targeted by these Member States for 2025 ((EC, 2019d), (de Miguel, Acosta, Thiel, Moretto, & Julea, 2018)).

In Germany, the consortium H2 Mobility (H2M, 2018a) presented plans to operate 100 hydrogen refuelling stations by the end of 2019 in seven German metropolitan areas (Hamburg, Berlin, Rhine-Ruhr, Frankfurt, Nuremberg, Stuttgart and Munich), and along the connecting arterial roads and motorways (mid-2019, there were 74 stations opened (H2M, 2019). This will be followed from 2020 by other 300 stations in line with regional demand.

According to (Hydrogen Europe, 2018), by 2025 across Europe 1,000 public hydrogen refuelling points will be deployed and by 2030 continent-wide coverage will be achieved through 4,500 stations out of which more than 500 will be high capacity ones (>1000kg/day) for heavy-duty vehicles, trains and vessels.

An increasing number of projects show the importance of hydrogen for the energy transition. The Hydrogen Mobility Europe initiative (2015-2022) is a flagship European project (H2ME, 2019a) co-funded by EU's Horizon 2020 programme through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). It is deploying 49 hydrogen refuelling stations across 8 countries in Europe (Denmark, France, Germany, Iceland, the Netherlands, Norway, Sweden and the UK) and it will create the first pan-European network, and the world's largest network of hydrogen refuelling stations. One of these stations is the first in the world off-grid solar-powered hydrogen producing and refuelling station and was inaugurated in Mariestad (Sweden) in May 2019 (H2ME, 2019b).

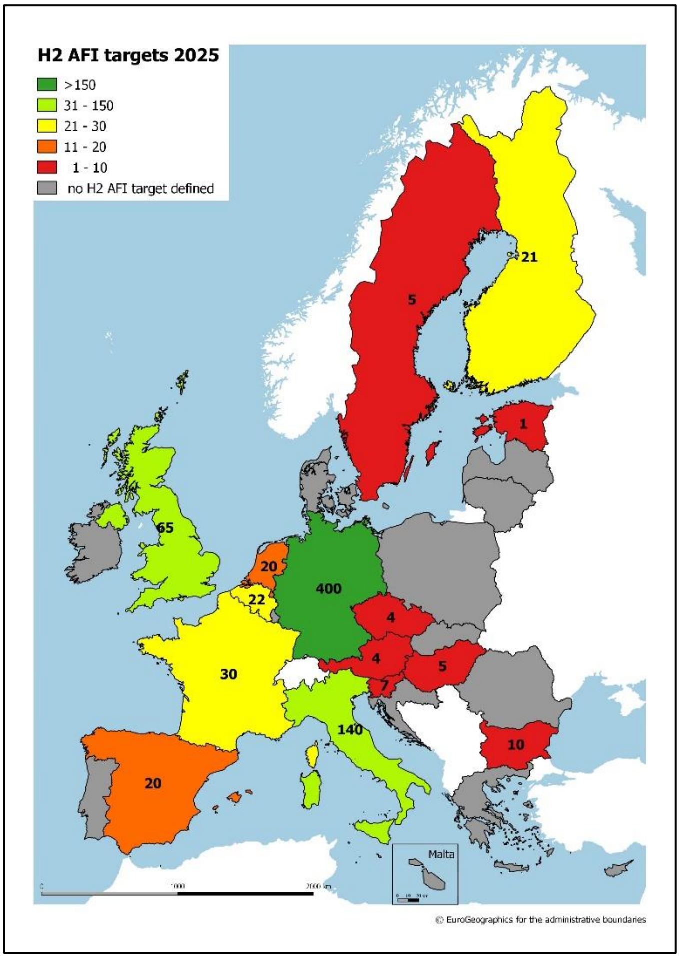



**Figure 5-48. NPF targets for hydrogen refuelling stations for 2025**
**Source: EC, 2019d**

In Northern Germany, three hydrogen refuelling stations are to be supplied by hydrogen generated in nearby wind farms by electrolysis while on the Scottish Orkney Islands, hydrogen is generated by tidal and wind power plants and used, inter alia, for ten fuel cell vehicles (LBST, 2019b). The Interreg North-West Europe project H2SHIPS (2019-2022) will develop and test a hydrogen refuelling system suitable for open sea operation in Belgium (H2SHIPS, 2019).

Nowadays, hydrogen is mainly used as a resource in the chemical industry and because chemical plants need a good transport connection for bulk cargo, they are often located directly next to waterways. Even if there is nearly no dedicated infrastructure, the major hydrogen production sites in Germany and the Benelux are located along the major inland waterways routes according to (MariGreen, 2018), thus the availability of hydrogen is given already and will be ensured for the future for inland waterway transportation.

According to (ICCT, 2017a), most government and industry consortium estimates indicate that average cost will reduce in the future from €1.7 to €2.6 million to around €900,000 per hydrogen refuelling station and eventually even lower. (Hydrogen Europe, 2018) also predicts that new hydrogen refuelling station designs with novel components and system architecture will be developed for improvements in their reliability, cost, footprint and capacity, and that the cost of a station will decrease by at least 50% by 2030 compared to the 2018 cost range of €1 to €3.2 million. According to (SDG, 2017), the range of the cost for a hydrogen refuelling station will be at the end of 2020 from €600,000 to €1,6 million.

## 5.3 BIOFUELS

### 5.3.1 MATURITY OF TECHNOLOGY

Liquid biofuels such as ethanol and FAME are currently used in EU as component of the transport fuels (E10 and B7). In 2020, about 95% of the (petrol) passenger cars and vans will be compatible with E10, and all diesel vehicles are compatible with B7 since model year 2000 (TNO, 2013). This use of biofuels cannot be considered as 'alternative fuels'. In the following paragraphs, we will therefore focus mostly on alternative biofuels and/or on the use of biofuels exclusively or in very high percentage as transport fuel.

**Table 5-10** summarises the information available on research funding for the fuels classified as alcohol, esters and ethers.

**Table 5-10. Summary on research funding (2007-2020) for alcohol, ester and ether fuels**
**Source: JRC, 2019b**

| *Fuel type* | *Total project value* | *Total EU contribution* | *Number of projects* | *Average project value* |
|---|---|---|---|---|
| Alcohol | € 159,765,867 | € 119,617,002 | 26 | € 6,144,841.02 |
| Ester | € 47,845,959 | € 20,593,930 | 6 | € 7,974,326.50 |
| Ether | € 10,653,988 | € 10,277,769 | 2 | € 5,326,994.00 |
| Other | € 211,352,709 | € 131,243,582 | 43 | € 4,915,179.28 |
| **Total** | **€ 429,618,523** | **€ 281,732,283** | **77** | **€ 5,579,461.33** |

Vehicles powered by high blends of ethanol are a mature technology, both with gasoline (E85) and diesel (ED95) (personal communication by SEKAB).

For LCVs, ePURE and ART FUELS consider that the most mature liquid biofuel is FAME (personal communication).

ED95 was authorised in Sweden years ago and in France in early 2016 (JORF, 2016). ED95 vehicle technology is available in the market for buses and HCVs (personal communication by CLARIANT; see also (Scania, 2017b)). For the maturity of biogas in these markets, see **section 5.4.1, p. 183**.

Biodiesel for railway vehicles is also mature.

Moirangthem (2016) considered biodiesel as a most common alternative fuel for inland waterway transport and mentioned hydrogenation-derived renewable diesel as a future option. (LR/UMAS, 2017) also considered biofuels as an option for low carbon vessels in inland waterway transport.

In a review of ca. 150 studies, (Bouman, Lindstad, Rialland, & Strømman, 2017) identified biofuels as the alternative fuel with the greatest potential to reduce $CO_2$ emissions from maritime transport. The most promising biofuel is FAME (DNV-GL, 2018a), particularly for passenger vessels and ferries (personal communication by ART FUELS). No information was provided in the questionnaire on biofuels for deep-sea maritime transport. Concerning advanced biofuels, tests with algae-based biofuel on the 'Maersk Kalmar' container vessels were performed in 2011 (WMN, 2011). (DNV-

GL, 2018c) considers that these fuels are currently at the R&D phase. The in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reductions considered advanced biofuels as one of the options for maritime transport (EC, 2018c).

The in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction identified advanced biofuels as an option for air transport (EC, 2018c). The 2011 and 2015 reports focused only on biofuels and synthetic fuels for aviation. (Kandaramath Hari et al., 2015) reviewed alternative fuels, including the following biofuels: hydro processed renewable jet fuels, Fischer Tropsch fuels, biodiesel, liquid bio hydrogen and biomethane and bio-alcohols. The problem with bio-alcohols and biodiesel lies in their relatively poor fuel properties (Yilmaz & Atmanli, 2017). The most mature biofuel is hydro processed esters and fatty acids (HEFA) (personal communication by ART FUELS). In addition to HEFA(-SPK), the following fuel conversion pathways are considered: alcohol-to-jet synthesised paraffinic kerosene (ATJ-SPK), power-to-liquids Fischer-Tropsch synthesised paraffinic kerosene (PtL or FT-SPK), synthesis gas Fischer-Tropsch synthesised paraffinic kerosene (FT-SPK) and synthesised isoparaffins (SIP). A sixth certified pathway is co-processing biocrude up to 5% by volume of lipidic feedstock in petroleum refinery processes ('co-processing') while additional ones are currently in the certification process (EASA, 2019a).

### 5.3.2 DATA ON VEHICLES AND INFRASTRUCTURE

The amount of biofuels, expressed in ktoe, used by the different EU transport systems in 2016 can be seen in **Table 5-11**. Two main remarks can be made: (i) the vast majority of bioenergy used in this sector corresponds to liquid biofuels; and (ii) of all the transport systems, road is by far the largest consumer of biofuels.

**Table 5-11. Final liquid biofuels and biogas use in EU transport in 2016 [ktoe]**
**Source: EC, 2019b**

| | **Biogas** | ***Biogasoline*** | ***Biodiesel*** | ***Other liquid biofuels*** | ***Bio jet kerosene*** | **Total Liquid biofuels** | **Total** |
|---|---|---|---|---|---|---|---|
| Road | 131 | *2,619* | *11,041* | *4.5* | - | 13,664 | **13,796** |
| Rail | 0.0 | | *32.9* | *0.0* | - | 32.9 | **33.1** |
| International aviation | - | *0.0* | *0.0* | *0.0* | *0.0* | 0.0 | **0** |
| Domestic aviation | - | *0.0* | *0.0* | *0.0* | *0.0* | 0.0 | **0** |
| Domestic Navigation | 0.0 | *1.4* | *3.5* | *0.0* | - | 5.0 | **5.0** |
| Non-specified transport | 0.5 | *0.0* | *6.2* | *0.0* | *0.0* | 6.2 | **6.7** |
| **Total** | **132** | ***2,620*** | ***11,083*** | ***4.5*** | ***0.0*** | **13,708** | **13,840** |

Sales data on vehicles powered by biofuels is available in (EEA, 2018b) but not in (EAFO, 2019). No recent information showing model availability in the EU for flexible-fuel vehicles powered by E85 was found. Based on data from (EEA, 2018b), cars registrations for this powertrain took place only in France and Sweden in 2017 for three models, which represents a reduction in model availability compared to the twenty models on the market in 2015 (EEA, 2018b) and the twenty OEMs offering flexible-fuel vehicles (E85) ten years ago (BEST, 2009a).

No new LCVs powered by biofuels sold in the EU could be found in (TRACCS, 2017) (EAFO, 2019) and (EEA, 2018c). Based on the e-NV200 model, which has a payload of 4.2 $m^3$, Nissan showcased in 2016 a concept vehicle that can run via bioethanol electric power. The vehicle prototype features a solid oxide fuel cell and delivers a range of 600 km (Nissan, 2016).

In 2013, 10% of the European bus stock was powered by biodiesel (ZeEUS, 2016). In Sweden, almost 60% of the public bus fleet (9,898 units) in 2014 was powered by renewable energy, with biodiesel accounting for 34% and ethanol for 7% (Xylia & Silveira, 2017). As can be seen in **Table 5-11**, 80% of the biofuels used in road transport in 2016 was biodiesel. The 2015 report indicated that high-blend biodiesel was available for captive fleets in some Member States: B20 in Poland and B30 in the Czech Republic and France.

Data on the stock of biofuel trucks is neither available in (TRACCS, 2017) nor in (EAFO, 2019). However, it is known that biofuel trucks have been introduced in the EU market. For instance, Scania delivered its first bioethanol truck (ED95) in 2018 (Scania, 2018a). At present, HCVs powered by biodiesel (FAME) and ethanol are commercially available in the EU (see e.g. (Scania, 2019)). According to (IEA, 2017), commercialisation of ED95 in the European truck market is low.

In 2007, (UIC, 2007) found that experience with the use of biodiesel in the European railway system was rather scarce, with some trials in France, Germany and the UK. Some years later, biodiesel was still not used in European railways (EC, 2017a). As can be seen in **Table 5-11**, the European railways used almost 33 ktoe of biodiesel in 2016.

In the waterborne sector, the volume is very limited (personal communication by TOTAL). A 30% biofuel blend is available for vessels in the Rotterdam-Rijnmond region (GoodFuels, 2019).

**Table 5-11** shows that the aviation sector is completely deprived of supply of biofuels at commercial scale. In 2016, no biofuel was used in commercial flights taking place in the EU. This comes in stark contrast with the urgent need of the aviation to find alternative energy sources than crude oil, in order to operate more sustainably.

At this stage, and looking at the global picture, the use of biofuel in aviation is rather anecdotal or experimental. Since the first test flight on biofuel took place in 2008, more than 180,000 commercial flights operated on biofuels have been made (as of June 2019) (IATA, 2019); however, this only represents a very small fraction of the total number of flights which took place over the same period. The worlds' first 100% biofuel flight was accomplished on a civil jet in 2012 (NRC, 2012) and on a commercial aircraft in 2018 (Boeing, 2018). Whereas the former was powered solely by carinata (Agrisoma, 2019), the latter used sustainable aviation fuel made from plant oils and residual animal fats (Boeing, 2019). Furthermore, the world's first passenger flight powered by a blend of biofuel made from steel mill waste gases and conventional fuel took place in late 2018 and the world's first passenger aircraft using biofuel made from seawater-irrigated desert plants flew in early 2019 (Boeing, 2019). As can be seen in **Table 5-11**, no biojet kerosene was used in EU domestic and international aviation in 2016. For a landmark EU project, see **Box 14**.

**Box 14. ITAKA project (2012-2016)**

The objective of the Initiative Towards sustAinable Kerosene for Aviation (ITAKA) project was to develop a full value-chain in Europe to produce sustainable Synthetic Paraffinic Kerosene (SPK).

Main milestones of biojet fuel use demonstration:

In 2014-2015: 18 long haul flights from Amsterdam to Aruba and Bonaire islands (Dutch Caribbean; about 10 hours-duration flights) on an Airbus A330-200, transporting ca. 4,500 passengers. Whereas one wing was fuelled with jet A-1, the other with the 47% UCO-based (a HEFA fuel from UCO) biojet fuel blend;

In 2016: 80 short haul flights from Oslo to Amsterdam on an Embraer 190 powered by a HEFA fuel from camelina sativa oil, transporting ca. 8,000 passengers.

Funding / coordination: 15.9 million euro (9.4 million euro EU funding) / coordinated by SENASA

Source: (ITAKA, 2016)

**Infrastructure**: High bioethanol blends (E85, E100 and ED95) require adaptation of refuelling infrastructure, whereas low blends (e.g. E5, E10) do not.

According to (ePURE, 2019), the five EU countries with most E85 refuelling stations in 2015 were Sweden (1700), France (600), Hungary (403), Germany (355) and Czechia (140).

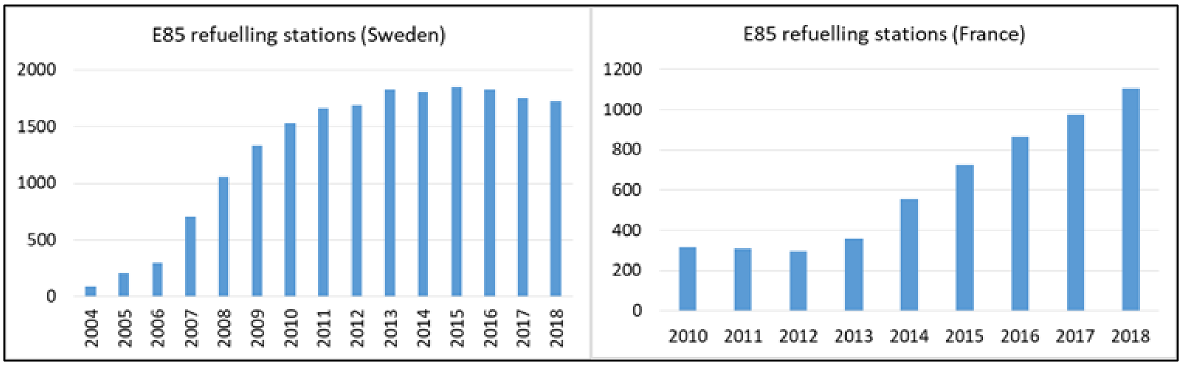



**Figure 5-49. Development of the E85 refuelling infrastructure in Sweden and France**
**Source: own elaboration based on data from (SPBI, 2019) and (SNPAA, 2019)**

The development of the E85 refuelling infrastructure in the last years is displayed in **Figure 5-49** for Sweden and France.

In France, 14% of the total refuelling stations selling more than 500 $m^3$ of fuels yearly offer E85 and all the departments have at least one station providing E85 in June 2019 according to (CBF, 2019).

The BioEthanol for Sustainable Transport project (BEST, 2009b) demonstrated 12 ED95 refuelling points at five sites in Europe (Stockholm, Madrid, La Spezia), Brazil (São Paulo) and China (Nanyang), between 2006 and 2009. According to (NPF Finland, 2017), two ED95 refuelling points were found in Finland in 2017 in the depot areas of private companies, thus not being publicly available. According to (E4tech, 2019), there is currently an emerging market for ED95 in Finland, France, Norway and Sweden.

According to (SPBI, 2019), there were 9 refuelling stations for rapeseed methyl ester (a type of FAME biodiesel).

In 2018, the average refinery output of kerosene in OECD Europe was 8.6%, with the EU systematically requiring in this century jet fuel net imports (17,651 ktonnes in 2017) (FuelsEurope, 2019).

Worldwide, HEFA facilities can supply 4.3 bn litres (IRENA, 2017a). In 2017, around 42 million litres of sustainable aviation fuels were produced (IATA, 2018). Usually, a bio-refinery can use up to 25% of its total capacity to produce biojet fuel (personal communication by UPM). In 2017, there were 224 bio refineries in Europe (BIC, 2017).

SAF can use the same supply infrastructure used for conventional jet fuel. A number of airports have agreed to supply SAF through their existing fuel systems (IATA, 2019) (in January 2016, Oslo Airport became the first hub in the world to receive regular deliveries of biojet fuel and offer it to all airlines - the first time an airport has used its normal supply mechanism for biofuels delivery).

### 5.3.3 COST OF VEHICLES AND INFRASTRUCTURE

The cost of the biofuel vehicles is not significantly different from gasoline or diesel vehicles. Except flexi-fuel cars running with E85, vehicles running with high blend biofuels are conventional vehicles with minor engine adaptations.

**Table 5-12** provides an overview of support schemes for biofuels, by Member State. As can be seen, only the Czech Republic, Germany, Hungary, Lithuania, Slovakia and Sweden applied tax exemptions and reductions to biofuels by 2018.

**Table 5-12. Support schemes for biofuels, by Member State**
**Source: European Commission**
**(draft Staff Working Document for the evaluation of the Energy Taxation Directive)**

| Member State | Period | Member State | Period |
|---|---|---|---|
| Belgium | 2007 - 2014 | Lithuania | 2006 - 2011; 2012; 2013 - 2017; 2018 - 2020 |
| Bulgaria | 2010 - 2012 | Luxembourg | - |
| Czechia | 2004 - 2007; 2009 - 2014; 2015 - 2020 | Hungary | 2005 - 2010; 2007 - 2012; 2008 - 2013; 2013 - 2018 |
| Denmark | - | Malta | - |
| Germany | 2004 - 2009; 2013 - 2023 (only biogas); 2018 - 2020 | Netherlands | 2006 |
| Estonia | 2005 - 2011 | Austria | 2005 - 2010 |
| Ireland | 2005 - 2007; 2006 - 2010 | Poland | 2007 - 2011; 2007 - 2014 |
| Greece | - | Portugal | - |
| Spain | 2004 - 2012 | Romania | - |
| France | - | Slovenia | - |
| Croatia | - | Slovakia | 2006 - 2010; 2018 - 2023 |
| Italy | 2004 - 2007; 2005 - 2007; 2008 - 2010 | Finland | 2009 - 2011 (only to St1 Oy for the ECO 100 pilot project); 2012 - 2013 (agriculture and greenhouse cultivation) |
| Cyprus | 2006 - 2010 | Sweden | 2003 - 2008; 2009 - 2013; 2011 - 2013; 2014; 2014 - 2015; 2018 - 2020 |
| Latvia | 2006 - 2012; 2009 - 2010; 2011 - 2013 | United Kingdom | - |

Flexible-fuel cars have been available in the French market at a price of €22,450 (VW, 2019a). The Ford Kuga flexifuel-E85 is being launched in 2019 in France, at an incremental cost of 100 euro, and in Sweden (FleetEurope, 2019). The potential for conversion of petrol cars into flexible-fuel cars was highlighted by (BEST, 2009a).

A decade ago, the purchase price of a bioethanol bus was 10% higher than the diesel counterpart (BEST, 2009a) The same authors reported more frequent maintenance service and thus higher maintenance costs for bioethanol buses than for diesel buses.

(Stockholm, 2015) estimated that the purchase price of a 26t ED95 HCV was in 2015 ca. 20% higher than that of a diesel equivalent.

Railway engine modifications are not required by most engine manufacturers for blends up to 5% (UIC, 2007). The same authors found that B20 might have minor effects on railway vehicle performance and reliability but higher blends might be problematic (this is unlikely to hold for advanced biofuels). More recently, (Isaac & Fulton, 2016) calculated that a new diesel locomotive for passenger service costs ca. 6.5 million euro per unit in the US, regardless of whether it is powered by diesel, biodiesel (FAME) or renewable diesel. As highlighted by (Stead, Wadud, Nash, & Li, 2019), the difference in maintenance costs between diesel and biodiesel use in rail operations is uncertain. For a recent cost analysis of six powertrain options for regional passenger rail under two scenarios, see (IEA, 2019e).

The difficulty of estimating investment costs for biofuels to be used in shipping, even after interviewing stakeholders, was highlighted by (Ecofys, 2012). According to ART FUELS (personal communication), FAME may be used in small vessels, not on other types for cost reasons.

The modification of the vessel engine is not necessary to operate using biofuels (PPMC, 2015). For maritime vessels, (EMSA, 2015) concluded that the new build and retrofit investment costs for ethanol are similar than scrubber installation costs. According to an economic assessment made by (LR/UMAS, 2017), biofuel is the most attractive low carbon vessel option, closely followed by ammonia plus internal combustion engine. However, none of these options is expected to be more profitable than the HFO reference ship in 2030 (see Figure 6 in (LR/UMAS, 2017) for an analysis of relative profitability in money terms, by vessel type and scenario). The same authors consider that the future internal combustion engine and biofuel storage costs are unlikely to change significantly.

There are plans to test the use of biofuel from agricultural waste (bio-oil from the by-product of nut processing in India and Tanzania) to propel Danish ships (DFDS, 2019).

As opposed to other transport modes, air travel is included in the EU Emissions Trading System (ETS), covering $CO_2$ emissions from civil aviation (EC, 2016). While the fourth phase will be in place for the period 2021-2030, the EU ETS will apply until the end of 2023 only to intra-European Economic Area flights (EC, 2019a). Importantly for the purpose of this report, airlines are required to report the use of alternative fuels under the EU ETS (see (T&E, 2016) for an analysis). It should be noted that this is without prejudice to the implementation of CORSIA in EU legislation through a revision of the ETS Directive, which will take place in 2020-2021.

**Figure 5-50** shows the evolution of EU emission allowances between mid-2015 and mid-2019. When burned, a tonne of conventional aviation fuel generates 3.15 tonnes of $CO_2$ (AEF, n.d.). With a carbon price of 25 €/tonne, this translates into €75.6 per tonne of jet fuel. In 2017, aviation operators had to purchase 26.7 million EUAAs to comply with the EU ETS emissions cap (EEA, 2018d).

(Zschocke, 2019) asserts that kerosene generally accounts for 20-30% of the variable costs faced by an airline and further indicates that the price of kerosene can be basically decomposed into the crude oil price (75%) and the conversion cost (25%). In relation to crude oil prices, jet fuel prices exhibit two key features: (i) are systematically higher, and (ii) trend correlation (NREL, 2014). Airlines face different fuel prices at European airports. This incentivised 'fuel tankering', whereby airlines can reduce refuelling costs by carrying more fuel on a flight than necessary. (Eurocontrol, 2019a) estimated that this practice saves airlines €265 million annually but has an environmental impact of 901,000 tonnes of $CO_2$ being emitted annually in the European Civil Aviation Conference airspace. In terms of aircraft fuel efficiency, average fuel consumption has improved from 4.4 litres per 100 passenger-km in 2005 to 3.4 litres in 2017 (Eurocontrol, 2019b).


**Figure 5-50. Price [€] of EU emission allowances (secondary market)**
**Source: EEX, 2019**

The profits of producing road biofuel are higher than those of aviation biofuel (ICCT, 2019a). As can be seen in **Figure 5-51**, HEFA currently has the lowest production costs of all the alternative jet fuels, but remains well above the baseline jet price. Based on responses to the survey, the following jet fuel prices could be defined (see **Figure 5-52**).

(Kandaramath Hari et al., 2015) consider that biodiesel has "deprived economics" for aviation.

The price of aviation biofuel from UCO is currently in the range of 950-1,015 €/tonne (EASA, 2019a). Over the next decade, UPM expects conventional fuel prices to be half the price of advanced biofuels (personal communication). Lufthansa considers feedback availability to remain a crucial constraint to biojet fuel price reduction through economies of scale (personal communication).

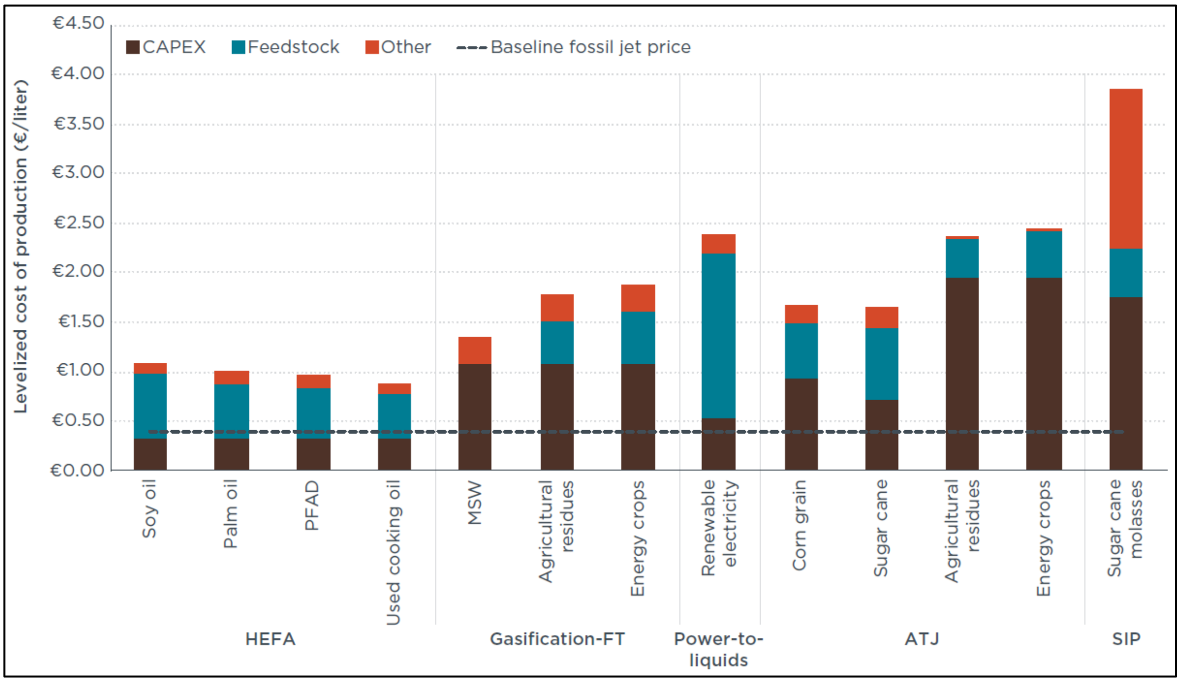



**Figure 5-51. Production cost of alternative jet fuel, by conversion pathway**
**Source: ICCT, 2019b**

A key advantage of biodiesel and HEFA is that it requires no modification of the aircraft engines (Kandaramath Hari et al., 2015).

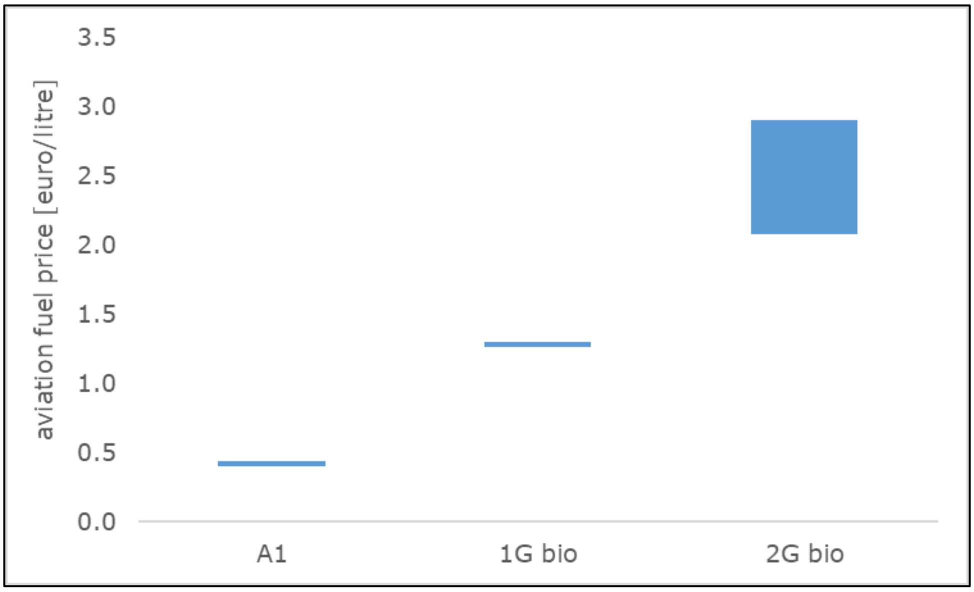



**Figure 5-52. Jet fuel prices**
**Source: own work based on information provided by Lufthansa (personal communication)**

**Infrastructure**: According to UPEI (personal communication), the current cost (euro/point) of fitting an existing service station with one biofuel refuelling point "depends on the features, type and age of the existing station, as well as the blending ratio foreseen".

According to (BEST, 2005), in 2005, to establish a new complete station for E85 refuelling, the cost was around €42,000 including a 50 $m^3$ tank and around €32,000 including a 20 $m^3$ tank. According to (RB, 2016), the investment cost in 2015 for an average E85 refuelling station was around €100,000.

The ED95 refuelling points are similar to the diesel ones and cost around the same, although the materials in the tank and dispenser must be bioethanol resistant and the storage tank must be larger (BEST, 2009a).

The investment needed to build one bioDME refuelling station within the project BioDME (BioDME, 2012) was of €200,000.

According to TOTAL (personal communication), no extra distribution cost is required for biofuel use in waterborne transport.

### 5.3.4 PERSPECTIVES FOR MARKET DEVELOPMENT

VDA asserts that car manufacturers in Europe do not have flexible fuel cars in their agenda (personal communication). Over the next decade, the number of flexible fuel cars will likely remain low, according to UPM (personal communication). In view of the model availability and infrastructure deployment, this may seem a plausible scenario.

The perspectives for biofuel market development in the rail transport system are highly uncertain. (ETIP, 2019) considers that biodiesel is the most promising biofuel for rail transport.

By 2030, ART FUELS expect the blending of FAME or HVO in waterborne transport (personal communication).

The in-depth analysis accompanying the "Clean Planet for all" long-term strategy, shows the market projections on the demand for liquid biofuels in the EU international maritime sector (EC, 2018c). The demand for liquid biofuels is projected to range from 21.5 to 30.1 Mtoe in the decarbonisation variants (see **Figure 5-53**)[62].

(PPMC, 2015) estimated that biofuels could account for 5-10% of the global marine fuel mix by 2030. By then, marine HFO and diesel will be produced from renewable resources, according to TOTAL (personal communication). (DNV-GL, 2018c) has recently forecasted that 39% of global shipping energy demand will be served with carbon-neutral fuels by 2050. Of these, biodiesel is expected to play a role for deep-sea maritime transport. In the previous edition of their report, the same authors had projected a share of 18% for biofuels.

[62] Recall that the three stylised variants for the EU international maritime are based on the H2 and 1.5LIFE scenarios. The variants drawing on the H2 scenario are assumed to achieve 50% and 70% reductions in the greenhouse gas emissions relative to 2008 (H2Mar50 and H2Mar70, respectively). In the 1.5LIFEMar scenario, international maritime is assumed to be part of an economy wide net zero greenhouse gas emissions target and reduces its emissions by about 88% by 2050 compared to 2008.

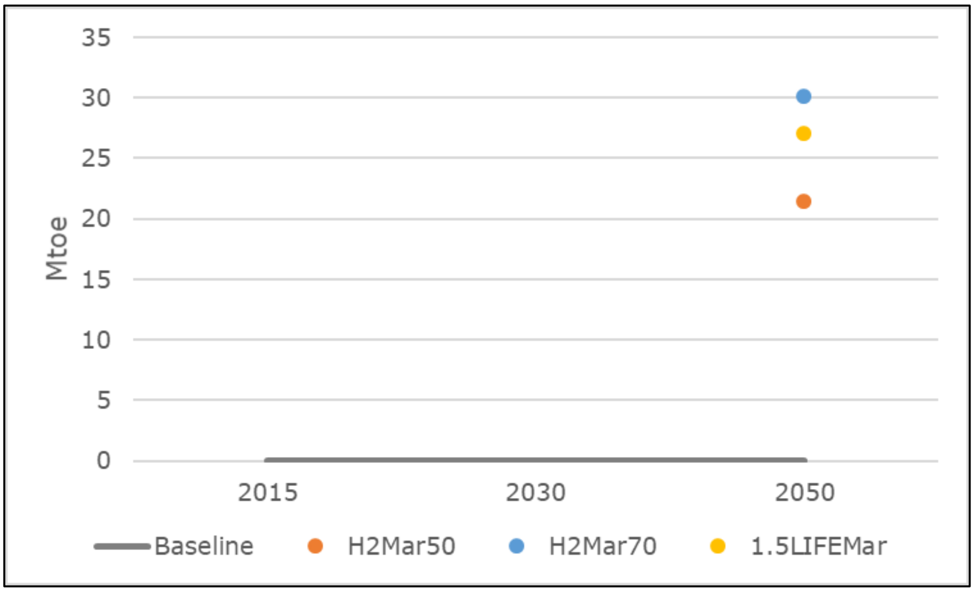



**Figure 5-53. EU international maritime demand for liquid biofuels in the Baseline and decarbonisation variants**
**Source: own work based on (EC, 2018c)**

The market perspectives for the demand of liquid biofuels in the EU aviation sector based on (EC, 2018c) under two scenarios are shown in **Figure 5-54**. As can be seen, the difference between demand in 2050 under the Baseline scenario and the 1.5TECH scenario is 12 Mtoe.

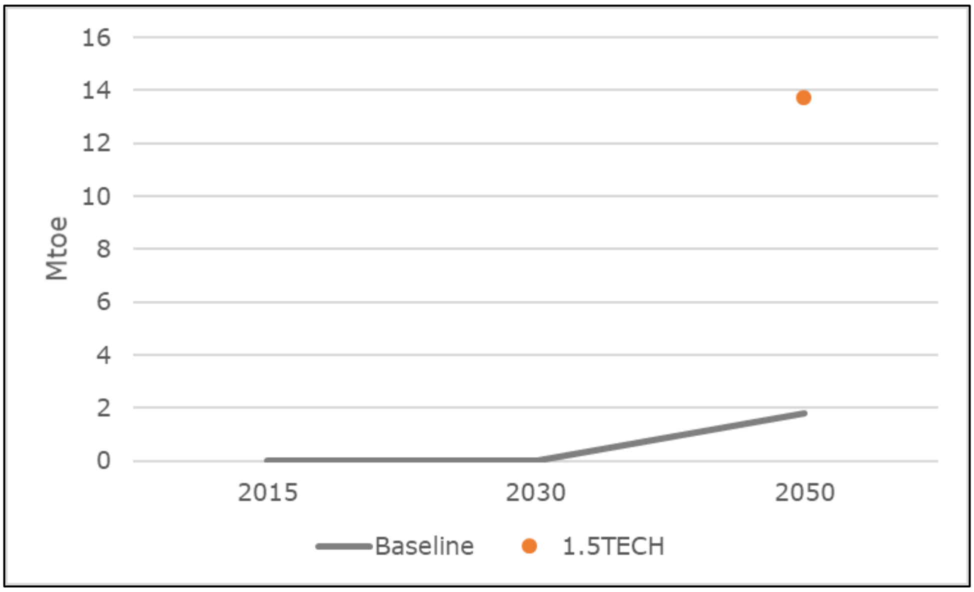



**Figure 5-54. Aviation liquid biofuels demand in the Baseline and 1.5TECH scenarios**
**Source: own work based on (EC, 2018c)**

The 'European Advanced Biofuels Flightpath' action launched in 2011 foresaw the use of 2 million tonnes of sustainable biofuel in the EU civil aviation sector by 2020 (EC, 2011). It is no longer likely that this target will be met (FlightPath, 2019). Notwithstanding the low volumes, (Airbus, 2018) asserts that sustainable aviation fuels are currently at the stage of market ramp-up and industrialisation. (SkyNRG, 2019) claims that the first European dedicated SAF production plant will supply 100,000 tonnes of SAF per year by 2022, with KLM Royal Dutch Airlines annually purchasing 75,000 tonnes.

According to (Deane, O Shea, & Ó Gallachóir, 2015), aviation biofuels will have to play an important role to meet the 2050 $CO_2$ emissions reduction target, as better air traffic management and aircraft efficiency will not be sufficient. (Zschocke, 2019) holds the view that sustainable kerosene will have to be used by the aviation industry over the medium term even if that entails additional costs. UPM is optimistic about biojet fuel growth (personal communication). (IEA, 2019a) anticipates that HEFA-SPK will be the main aviation biofuel in the short- and medium-term.

There is uncertainty as to whether CORSIA will have a sizeable impact on alternative fuel uptake or not. Lufthansa expects the implementation of CORSIA to have a positive impact on biofuel uptake (personal communication). In contrast, (ICCT, 2019a) and (Zschocke, 2019) regard this as unlikely due to the incentives structure. UPM expects that competition for the same feedstock will arise between the aviation and chemical industries (personal communication), implicitly revealing that biofuel demand from aviation will increase.

By 2025, 18 billion litres of SAF would be needed in the IEA's Sustainable Development Scenario (SDS). According to this scenario, around 10% and 20% of aviation energy demand in respectively 2030 and 2040 would have to be met by biofuels (IEA, 2019a). Lufthansa, however, considers that the estimated demand of biofuels in aviation by 2030 will be lower: maximum 5% (personal communication).

The Norwegian government aims at a *de facto* 30% biofuel mandate for airlines by 2030 (Reuters, 2018b).

**Infrastructure:** Only Finland mentioned specific targets for the biofuel refuelling infrastructure in its NPF (NPF Finland, 2017) corresponding to 2030, planning to increase the number of refuelling points: for E85 from 100 in 2016 to around one half of all refuelling stations and for ED95 to 250.

## 5.4 NATURAL GAS AND BIOMETHANE

### 5.4.1 MATURITY OF TECHNOLOGY

Natural gas vehicles and all components are mature and fully OEM-developed. While 48-volt mild hybrid cars powered by CNG are a possibility, mild hybrid CNG urban buses are available at the commercial level (personal communication by Westport). LNG vehicles differ slightly from CNG vehicles by possessing different storage tanks and a vaporiser to convert LNG to gas for use in the engine. Thanks to LNG tanks fitted on HCVs, the energy density of natural gas and storage capacity is five times higher than for CNG. All these qualities apply also to liquid biomethane (bio-LNG) or mixtures thereof with natural gas. Biomethane is a renewable version of natural gas and completely interchangeable with natural gas in an engine designed to burn methane. The technology to power not only road vehicles but also vessels with natural gas is mature. **Table 5-13** gives key information on research funding in natural gas in Europe.

**Table 5-13. Summary on research funding (2007-2020) for methane-based alternative fuel Source: JRC, 2019b**

| *Fuel type* | *Total project value* | *Total EU contribution* | *Number of projects* | *Average project value* |
|---|---|---|---|---|
| LNG | € 132,977,259 | € 77,562,709 | 20 | € 6,648,862.95 |
| CNG | € 43,158,792 | € 28,148,549 | 6 | € 7,193,132.00 |
| LNG/CNG | € 142,858 | € 100,000 | 2 | € 71,429.00 |
| Biomethane | € 33,070,429 | € 24,262,830 | 10 | € 3,307,042.85 |
| Not specified / mixture of fuels | € 295,180,623 | € 185,770,194 | 52 | € 5,676,550.44 |
| **Total** | **€ 504,529,961** | **€ 315,844,282** | **90** | **€ 5,605,888.45** |

Further efficiency gains are expected for light, medium and especially for heavy-duty vehicles in the next engine generations and years to come (see also **Box 15**). The most advanced high-pressure direct injection (HPDI) dual-fuel engine, achieving up to 20% improvement in fuel efficiency, is expected to become widely available in the LNG truck market only after 2025 (EC, 2018a).

Both CNG and LNG are mature technologies and CNG and LNG road vehicles are available in the EU market, although the number of brands providing CNG vehicles has contracted in recent years. According to ePURE, biogas is the most mature biofuel for buses and HCVs (personal communication). This means, recalling **section 5.3.1, p. 173**, that different biofuels stakeholders consider that different biofuel options are the most mature for HDVs.

**Box 15. HDGAS project (2015-2018)**

The objective of the Heavy Duty GAS engines integrated into vehicles (HDGAS) project was to provide breakthroughs in LNG vehicle fuel systems, natural gas and dual fuel engine technologies as well as after-treatment systems.

Key outcome:

All key technologies developed up to TRL6 and TRL7

Funding / coordination: €27.8 million (€19.9 million EU funding) / coordinated by AVL LIST

Source: (HDGAS, 2019)

As in the 2011 and 2015 reports, the use of CNG in European railways is not considered an option. Since 2018, LNG railway vehicles are being trialled on a 20km stretch in Spain (Renfe, 2018).

As in the 2011 and 2015 reports, the use of CNG in the European water transport system is not considered an option. (Moirangthem, 2016) considered LNG and biomethane, respectively, as a present and future option for waterborne transport. According to GIE and IOGP, LNG is a mature alternative fuel for waterborne transport (personal communication). But as pointed out by (Gandossi & Calisto, 2018), the maturity of the LNG technology depends on the segment of the vessel fleet under consideration. According to (DNV-GL, 2018a), liquid biogas is also a promising alternative fuel for maritime transport, with biomethane already representing a realistic option (DNV-GL, 2018b).

As in the 2011 and 2015 reports, the use of natural gas for air transport is not considered an option.

### 5.4.2 DATA ON VEHICLES AND INFRASTRUCTURE

Data on natural gas use, expressed in ktoe, in the EU road transport system is shown in **Figure 5-55**. As can be seen, the volume more than doubled between 2008 and 2015 and has remained at a level of around 1,700 ktoe since then.

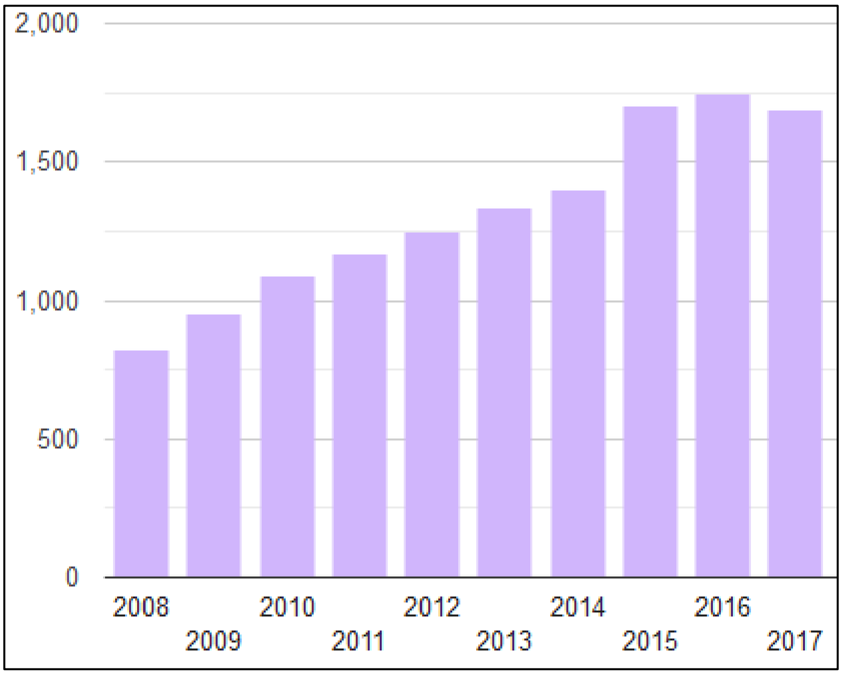



**Figure 5-55. EU road transport natural gas use [ktoe]**
**Source: EAFO, 2019**

The 2015 report claimed that natural gas was the preferred alternative fuel by European OEMs, with more than 30 CNG cars and LCV options available in that year. (NGVA, 2017) listed a total of 61 natural gas vehicle models in 2017, which increased in 2019 to 68 models (including cars, LCVs, trucks and buses) (NGVA, 2019).

Between 2017 and 2019, CNG model availability for cars in Europe decreased from 26 to 23 models (NGVA, 2017) (NGVA, 2019). Less than 67,000 new CNG cars were registered in the EU in 2018, which represents a 55% fall compared to the series' peak in 2009 (EAFO, 2019). CNG car stock has grown annually since 2011 (see **Figure 5-56**).

Between 2017 and 2019, CNG model availability for LCVs in Europe decreased from 15 to 11 models (NGVA, 2017) (NGVA, 2019). According to (EAFO, 2019), most sales of alternative fuel LCVs between 2008 and 2011 were CNG. **Figure 5-57** shows the increasing stock of CNG LCVs in the EU, with a levelling-off and contraction in recent years.

Between 2017 and 2019, natural gas model availability for buses and coaches in Europe increased from 15 models (of which two were LNG and the rest CNG) to 21 models (of which three were LNG) (NGVA, 2017) (NGVA, 2019). The uptake of these vehicles is shown in **Figure 5-58**. As can be seen, the number of CNG buses in use grew rapidly in 2012 and increased steadily to almost 18,000 vehicles in 2018. The stock of LNG buses is currently lower. (Xylia & Silveira, 2017) reported that 12% of the Swedish public bus fleet in 2014 was powered by biogas. It is estimated that around 40% of the 428 CNG urban buses in Lille are powered by biomethane (SustainableBUS, 2018) (Le-Gaz, 2018). The technology maturity of coaches powered by bio-LNG is currently low (IRU, 2019).

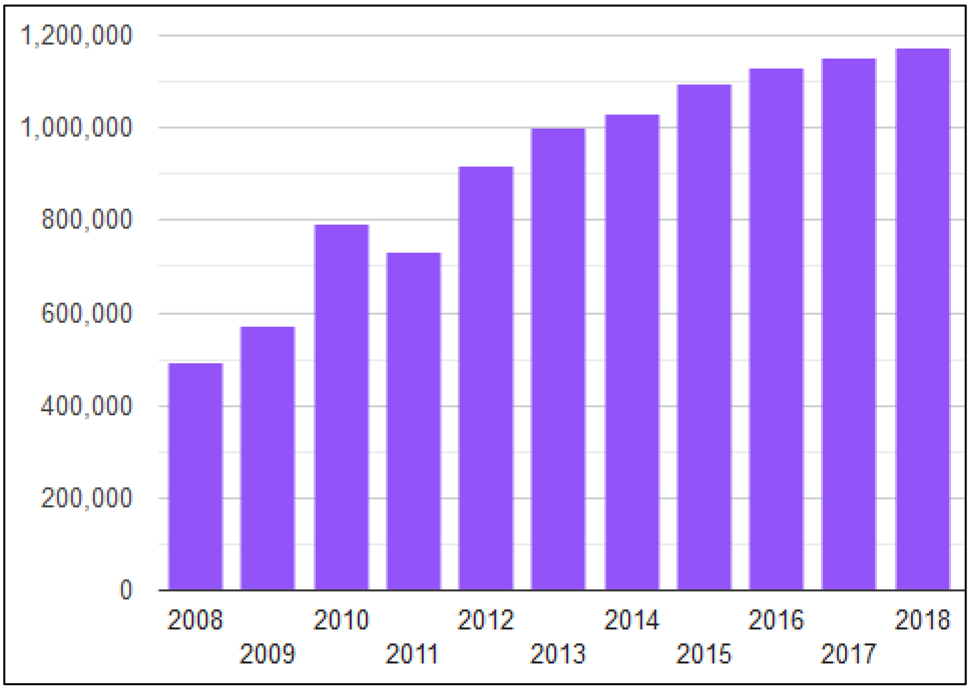



**Figure 5-56. CNG car stock in the EU28**
**Source: EAFO, 2019**

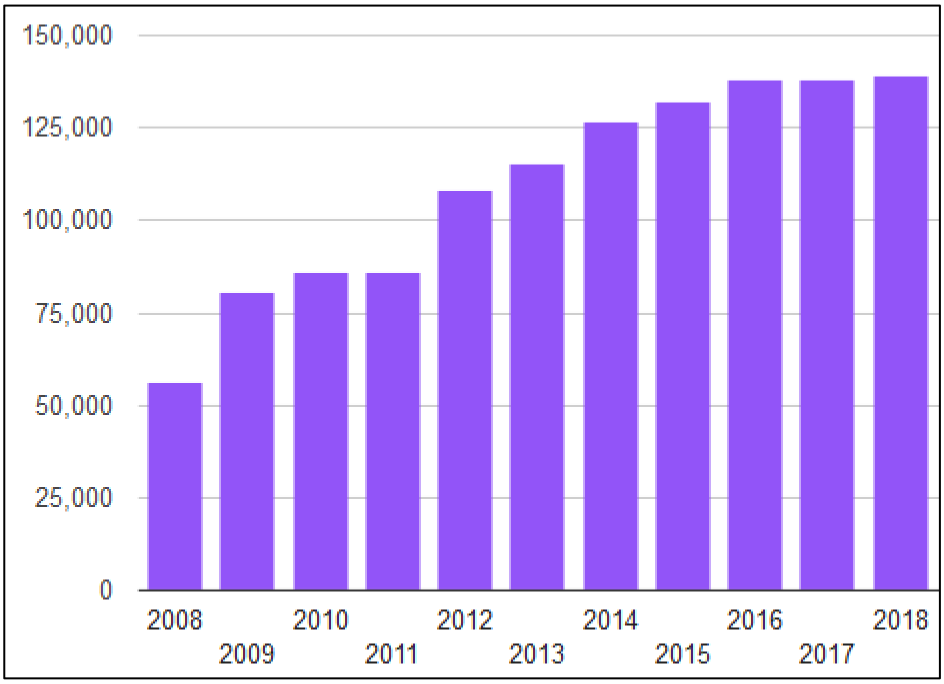



**Figure 5-57. CNG LCV stock in the EU28**
**Source: EAFO, 2019**

Between 2017 and 2019, natural gas model availability for HCVs in Europe increased from nine models (of which three were LNG and the rest CNG) to 13 models (of which five were LNG) (NGVA, 2017) (NGVA, 2019). Currently, three OEMs manufacture LNG trucks for sale in the European market (see e.g. (IVECO, 2017) (Scania, 2017a) (Volvo, 2019b)). As can be seen in **Figure 5-59**, the stock of HCVs powered by natural gas in the EU is approaching 20,000 units (of which around 1,500 HCVs were powered by LNG in 2018).

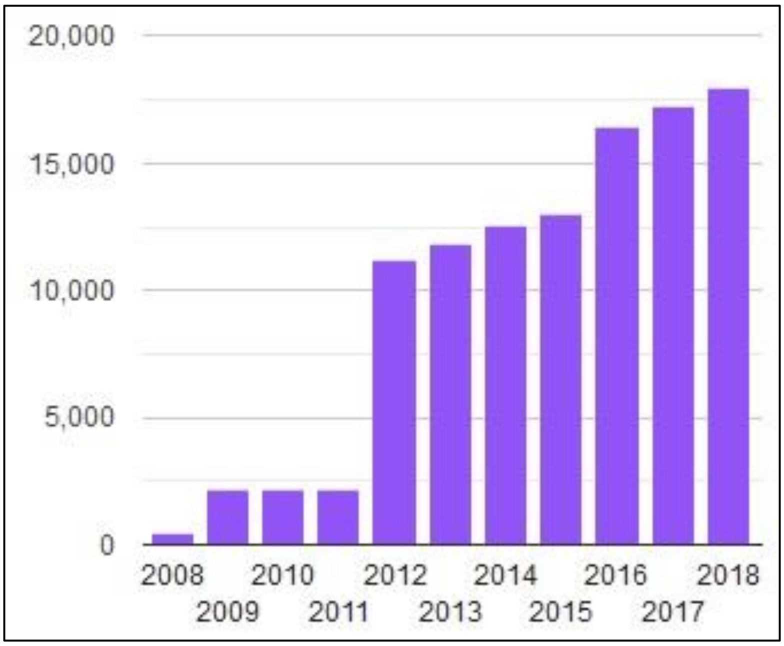



**Figure 5-58. Natural gas bus/coach stock in the EU28, by type**
**Source: EAFO, 2019**

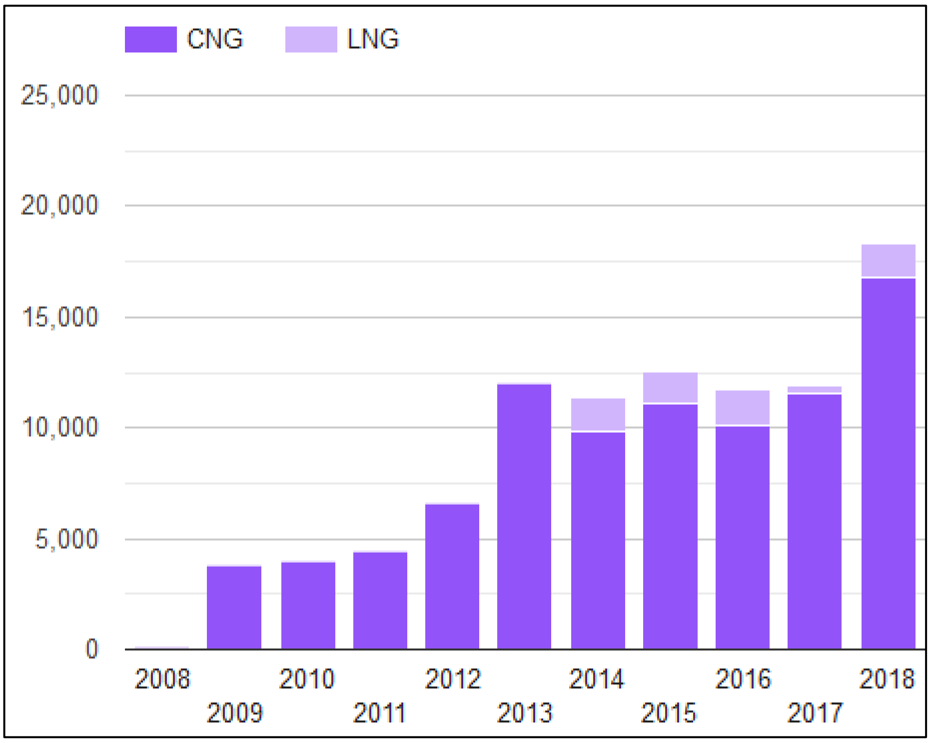



**Figure 5-59. Natural Gas HCV stock in the EU28, by type**
**Source: EAFO, 2019**

LNG railway vehicles have not been deployed in the EU yet.

The number of inland waterway vessels powered by LNG is extremely low, according to EFIP (personal communication). CCNR estimates that there are seven tanker vessels (Argonon, Ecotanker II, Ecotanker III, Sirocco, RPG Bristol, RPG Stuttgart and RPG Stockholm) and one container vessel (Eiger Nordwand) in use in the EU inland waterway transport system (personal communication). More recently, (EICB, 2019) reports three additional vessels powered by LNG: two tankers (Ecoliner and Somtrans LNG) and a crane vessel (De Werkendam). Shell had signed a charter agreement for fifteen 110-metre inland barges powered mainly by LNG (Shell, 2019b). However, only three of them seem to have been delivered, according to CCNR (personal communication), while the same source suggested that twelve appear to have been cancelled. The first inland waterway LNG bunker vessel in Europe, the 'LNG London', entered service in 2019 (Shell, 2019c).

The number of maritime vessels powered by LNG in use is increasing (see **Figure 5-60**). In 2019, there are 159 LNG vessels in operation and 159 on order (ca. 26% of those 318 LNG vessels in Norway and ca. 29% in the rest of Europe) (DNV-GL, 2019a).

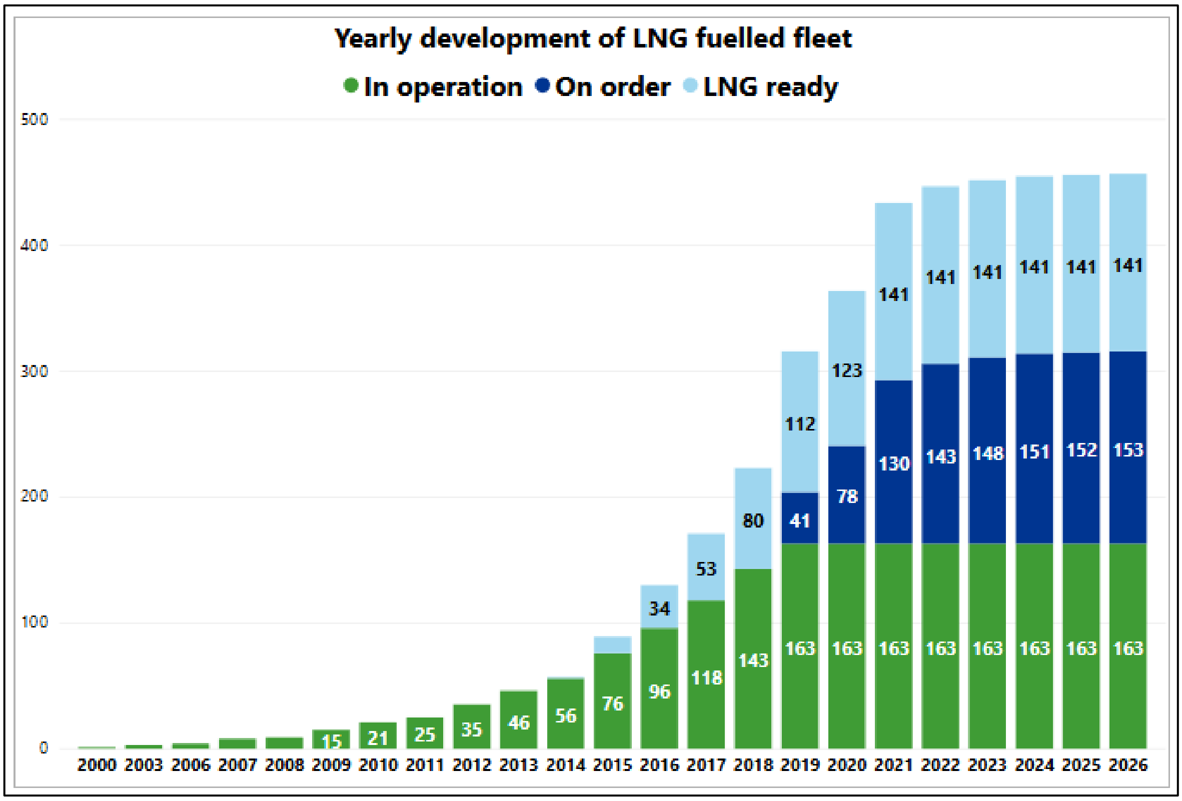



**Figure 5-60. Global stock of LNG-powered vessels, by status**
**Source: DNV-GL, 2019a (reproduced with permission from DNV GL)**

**Infrastructure**: For a landmark EU project, see **Box 16**. The Commission has in addition funded 38 CNG/LNG road infrastructure projects through the CEF, which have delivered 170 CNG refuelling points and 275 LNG refuelling points (158 CNG refuelling points and 10 LNG refuelling points were also added as part of road actions focusing on electricity infrastructure; see **section 5.1.2, p. 131**). Moreover, nine projects targeting only CNG road infrastructure were funded by the CEF for a total of 254 refuelling points. Furthermore, 27 maritime infrastructure projects have received funding from the CEF.

**Box 16. LNG-BC project (2013-2017)**

The objective of the LNG Blue Corridor (LNG-BC) project was to roll out LNG refuelling infrastructure along pre-defined European corridors and demonstrate the feasibility of LNG HCV operation.

Key figures:

13 new LNG or L-CNG stations built, connecting 12 Member States;

156 LNG HCV: 32,591,501 km travelled, 115,424 refuellings, 14,922,338 kg of LNG.

Funding / coordination: €14.3 million (ca. €8 million EU funding) / coordinated by IDIADA

Source: (LNG-BC, 2019)

**Figure 5-61** presents the slow increase of the CNG refuelling point's number in the EU during the period 2014 - 2018. The top five EU countries with the most CNG refuelling points in 2018 are Italy (1,211), Germany (861), Sweden (177), Czechia (174) and Netherlands (172).

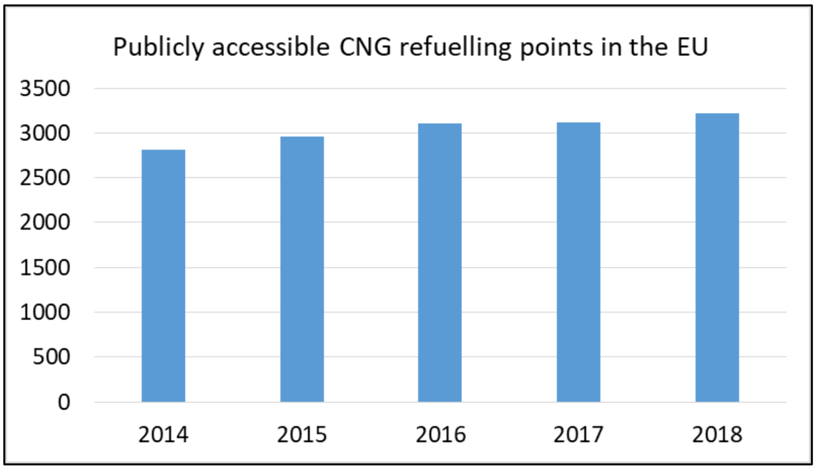



**Figure 5-61. Situation of the CNG refuelling points in EU in the period 2014 – 2018**
**Source: own elaboration based on data from (EAFO, 2019)**

**Figure 5-62** presents the development of LNG road refuelling point's number in the EU during the period 2014 - 2018. The number of existing LNG points in the EU is relatively small and amounts to 146 at the end of 2018, according to data provided by (EAFO, 2019). Spain, where the number of LNG refuelling points amounts to 29, is the leading Member State in this respect, followed by Italy (28), Netherlands (25), France (20) and United Kingdom (13). These stations are publicly accessible and can provide fuel for any LNG vehicle and in some cases can also provide CNG.

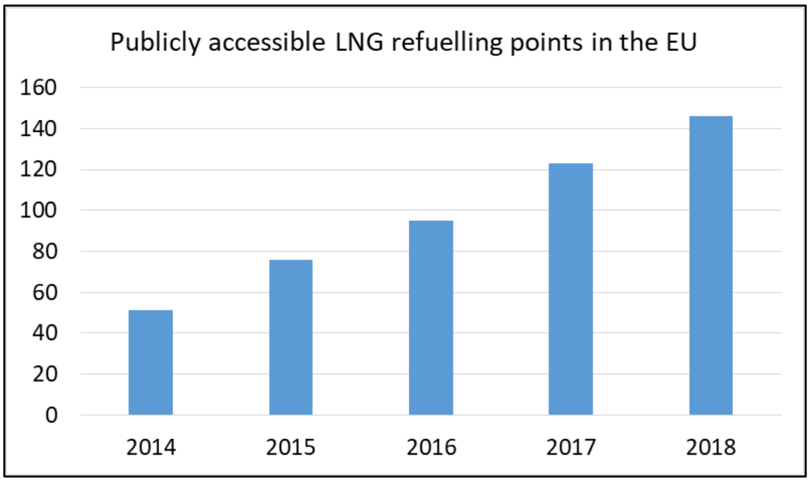



**Figure 5-62. Situation of the LNG refuelling points in EU in the period 2014 – 2018**
**Source: own elaboration based on data from (EAFO, 2019)**

According to GIE (personal communication), there are 16 maritime ports in Europe that have LNG refuelling points in operation in 2018. Most of them are located in Belgium, Spain, France, Lithuania, Netherlands, Portugal, and UK.

The EU maritime and inland ports with LNG infrastructure in 2017 are displayed in **Figure 5-68** (EC, 2019d). While still limited, the dedicated LNG bunkering infrastructure for ships is improving quite rapidly. A large share of LNG bunkering as well as LNG distribution to bunkering locations is still taking place by road.

At the beginning of 2019, there were 85 large-scale operational LNG tanks installed in 35 ports in EU (GIE, 2019); the front runners were Spain with 29 tanks (in 9 ports), UK with 15 tanks (in 3 ports) and Italy with 8 tanks (in 3 ports).

According to EFIP (personal communication), within European inland waterways there is sufficient LNG bunkering in 2018 to meet the demand from the very low number of LNG vessels in use.

The global LNG market reached 293 million tonnes in 2017 (personal communication by IOGP). For some operators, LNG bunker fuel availability remains an issue, though it is being addressed via the AFI Directive 2014/94/EU. For instance, in the Port of Rotterdam, Europe's largest bunker port, LNG sales grew from 1,500 to 9,483 metric tonnes between 2017 and 2018 (HR, 2019). We attribute this growth to the presence of the 'Cardissa' LNG bunker vessel, constructed in 2017 (Shell, 2019d).

**Standards for natural gas refuelling points for road and waterborne transport**

Following the mandate M/533 given by the Commission to the European Standardisation Organizations CEN-Cenelec, the ESOs recommended to the Commission the standards to be applied to supplement or to amend the technical specifications established in Annex II of Directive 2014/94/EU for natural gas refuelling points for road and waterborne transport.

- The European standard EN ISO 16923 'Natural gas fuelling stations – CNG stations for fuelling vehicles', covers the design, construction, operation, inspection and maintenance of stations for fuelling CNG to vehicles, including equipment, safety and control devices. This European standard also applies to portions of a refuelling station where natural gas is in a gaseous state and dispensing CNG derived from liquefied natural gas (L-CNG) according to EN ISO 16924. It also applies to biomethane, upgraded coal-bed methane (CBM) and gas supplies coming from LNG vaporization (on-site or off-site). The elements of the standard EN ISO 16923 ensuring the interoperability of the CNG refuelling stations and the vehicles should apply to CNG refuelling points.

- The European standard EN ISO 16924 'Natural gas fuelling stations – LNG stations for fuelling vehicles', in its current version, covers the design, construction, operation, maintenance and inspection of stations for refuelling liquefied natural gas (LNG) to vehicles, including equipment, safety and control devices. This European standard also specifies the design, construction, operation, maintenance and inspection of refuelling stations for using LNG as an onsite source for refuelling CNG to vehicles (L-CNG refuelling stations), including safety and control devices of the station and specific L-CNG refuelling station equipment. The European standard covers refuelling stations having the following characteristics: private access; public access (self-service or assisted); metered dispensing and non-metered dispensing; refuelling stations with fixed LNG storage; refuelling stations with mobile LNG. The elements of the standard EN ISO 16924 ensuring the interoperability of the LNG refuelling stations and the vehicles should apply to LNG refuelling points.

- The European standard EN ISO 12617 'Road vehicles – Liquefied natural gas (LNG) refuelling connector – 3,1 MPa connector' in its current version, specifies liquefied natural gas (LNG) refuelling nozzles and receptacles constructed entirely of new and unused parts and materials for road vehicles powered by LNG. An LNG refuelling connector consists of, as applicable, the receptacle and its protective cap (mounted on the vehicle) and the nozzle. This European standard is applicable only to such devices designed for a maximum working pressure of 3.4 MPa (34 bar) to those using LNG as vehicle fuel and having standardised mating components.

- The European standard EN-ISO14469 specifies CNG refuelling nozzles and receptacles constructed entirely of new and unused parts and materials, for road vehicles powered by compressed natural gas. A CNG refuelling connector consists of, as applicable, the receptacle and its protective cap (mounted on the vehicle) and the nozzle. It is applicable only to such devices designed for a service pressure of 20 MPa (200 bar) and 25 MPa (250 bar), to those using CNG according to ISO 15403-1 and ISO 15403-2 and having standardised mating components, and to connectors that prevent natural gas vehicles from being fuelled by dispensers with service pressures higher than that of the vehicle, while allowing them to be fuelled by dispensers with service pressures less than or equal to the vehicle fuel system service pressure.

- The standard EN ISO 20519 'Ships and marine technology – Specification for bunkering of liquefied natural gas fuelled vessels'

The elements of the standard EN ISO 16923 and EN ISO 16924 ensuring the interoperability of the CNG and LNG refuelling stations and the standards EN ISO14469 and EN ISO 12617 defining the specifications for CNG and LNG connectors respectively, the standard EN ISO 20519 for refuelling points for seagoing ships and the same European standard (parts 5.3 to 5.7) for refuelling points for inland waterway vessels have been included in Directive 2014/94/EU through the Commission Delegated Regulation (EU) 2019/1745.

### 5.4.3 COST OF VEHICLES AND INFRASTRUCTURE

The cost of a CNG car is similar to that of a diesel. A new bi-fuel CNG/gasoline car may represent an incremental cost of €2,000, mainly due to the gas cylinders (IRENA, 2017b). It is also possible to retrofit spark ignited (bi-fuel) and compression ignition engines (dual fuel) to run on natural gas. Natural gas does not corrode an engine as much as petrol and so provides a longer engine life. The cost of a CNG LCV is similar to that of a diesel.

Based on Spanish public procurement data from (EMT, 2018), we estimate the purchase price of CNG buses at €300,000. The biogas and electric hybrid trambus 'Exqui.City 24' reportedly cost in 2016 one million euro (BlogActiv, 2016).

The additional cost of a HCV powered by CNG, with respect to diesel, is estimated at €19,100 (IEA, 2017). The fuel consumption, refuelling time, range and performance of LNG trucks are similar to that of diesel but with tailpipe $CO_2$ emissions reductions that range from 20% to 100% if bio-LNG is used (Volvo, 2019b). In addition to higher maintenance costs, LNG trucks are estimated to be €25,000-€35,000 more expensive than a diesel counterpart (Vos, n.d.). (UBA, 2015) estimated the additional cost of an LNG engine for a 40-tonne semi-trailer truck to be €40,000.

(Isaac & Fulton, 2016) calculated that CNG and LNG locomotives for passenger rail cost ca. 7 million euro per unit, including the tank and engine retrofit in the US.

With traditional gasoil being cheaper, the structure of incentives needs to change for uptake of alternative fuels in inland navigation, according to CCNR (personal communication). The same stakeholder asserted that twelve of the fifteen inland navigation LNG vessels ordered by Shell in 2015 were cancelled.

**Box 17. PROMINENT project (2015-2018)**

The objective of the Promoting Innovation in the Inland Waterways Transport Sector (PROMINENT) was to make inland navigation as competitive as road transport and to promote the massive transition towards clean and efficient and vessels.

Key targets:

Developing cost-effective solutions applicable to 70% of the inland fleet;

Reducing implementation costs by 30%.

Conclusions:

Investing 1.05 billion euro would might make the complete European inland waterway fleet compliant with Stage V emission limits;

A stable price gap between LNG and gasoil of at least 0.35 €/litre might lead to a 40% LNG penetration in the inland fleet.

Funding / coordination: 6.6 million euro (6.3 million euro EU funding) / coordinated by STICHTING STC-GROUP

Source: (PROMINENT, 2019)

(EMSA, 2015) concluded that in 2015 the new build and retrofit investment costs for LNG were higher than alternatives such as ethanol, methanol and scrubber installation costs. The cost of LNG fuel has traditionally been similar to HFO (HEC, 2018). More recently, the price of MGO, IFO and LNG is respectively: €530 per tonne, €388 per tonne and €270 per tonne (as of February 2019 and calculated from (DNV-GL, 2019c); see also **Box 17**). However, the efficiency of LNG vessels is 13% lower than ICE vessels (Navigant, 2019).

**Box 18.Breakthrough LNG deployment in Inland Waterway Transport action (2016-2018)**

The objective of the Breakthrough LNG deployment in Inland Waterway Transport action is to facilitate the market penetration of LNG in the European inland waterway system by lowering investment requirements faced by ship owners.

Key outcomes:

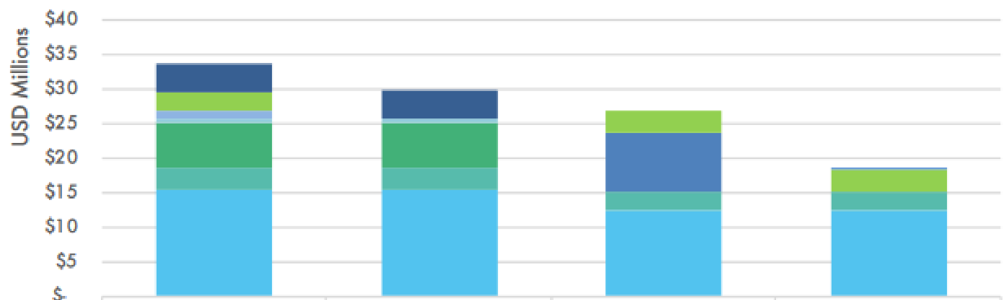
First pilot LNG vessel, 'The Werkendam', commissioned in 2018;

Second pilot LNG vessel, 'Somtrans LNG' (one of the largest European inland vessels), taken into operation in 2019.

Funding / coordination: Funded through the CEF / coordinated by Stichting Projecten Binnenvaart

Source: (TRIMIS, 2019) (LNGbinnenvaart, 2019)

Notwithstanding potentially lower operating costs, LNG vessels require higher upfront costs (see **Box 18** and **Figure 5-63**). In 2011, (TNO, 2011) estimated that the cost of an LNG engine and fuel tank system was double the cost of the diesel counterpart, but that excluded scrubber and fuel treatment costs. (Burel, Taccani, & Zuliani, 2013) estimated that the installation of a diesel solution was ca. 3 million euro, compared to 13 million euro for an LNG propulsive system. In 2014, (Wang & Notteboom, 2014) reported the incremental cost of an LNG vessel to be 20-25% that of the diesel equivalent. Currently, the incremental cost of newly built LNG vessels is around 15% higher than diesel vessels (personal communication by GIE).




| | 2-s HP DF | 2-s LP DF | Open Loop Scrubber | Conventional |
|---|---|---|---|---|
| Fuel Chiller | $- | $- | $- | $118,000 |
| LNG Yard Work | $4,230,000 | $4,230,000 | $- | $- |
| SCR | $2,495,700 | $- | $3,260,340 | $3,260,340 |
| Scrubber (inc. yard work) | $- | $- | $8,620,560 | $- |
| HP gas supply | $1,190,621 | $- | $- | $- |
| LP gas supply | $708,654 | $708,654 | $- | $- |
| LNG tanks | $6,382,837 | $6,382,837 | $- | $- |
| Auxiliaries | $3,327,600 | $3,327,600 | $2,662,080 | $2,662,080 |
| Main Engine | $15,396,552 | $15,396,552 | $12,317,241 | $12,317,241 |
| Total | $33,731,963 | $30,045,642 | $26,860,221 | $18,357,661 |
| Delta (vs Conventional) | $15,374,301 | $11,687,981 | $8,502,560 | $- |

**Figure 5-63. CAPEX vessel by powertrain option**
**Source: SEA\LNG, 2019**

Retrofitting of a large vessel with a HFO-burning engine to a dual fuel engine supporting LNG is also feasible. This will be the case for a 15,000 TEU container ship (Hapag-Lloyd, 2019).

**Infrastructure**: A CNG station will have capital costs relating to connection to the gas grid, storage and compression of the gas, refuelling hardware and civil works. According to Ionity (personal communication), the cost of a CNG refuelling point can vary between €100,000 and €500,000 depending on the type and capacity.

According to (SDG, 2017), the total costs for a 1,000kg/day CNG station can vary from less than €400,000 in Brownfield, to more than €500,000 in Greenfield, if the gas supply is nearby. One km connection to a network costs in the range €300,000 - €600,000. CNG stations may have additional operating costs for the warranty and maintenance of the infrastructure along with additional operational costs to compress natural gas, of about €40,000/year for a 1,000kg CNG station.

The capital costs include civil costs that are common across fuelling stations and specific costs for the storage and dispensing of the fuel. The LNG would arrive by tanker, so does not require a grid connection, and is already compressed meaning that there are lower capital costs, but there will be higher operating costs.

The LNG Blue Corridors project (LNG-BC, 2016) reported a range of the total capital cost for LNG stations in between €500,000 and €1,150,000 (that can peak up to €1,800,000 in some cases), depending on various factors that include the type of technology and whether the station also provides CNG.

According to (SDG, 2017), gas equipment capital costs depend of LNG station size, from €120,000 for 1,000kg/day to around €500,000 for 10,000kg/day, and the costs can rise depending on quality of service provision. As the industry becomes mature, station costs may fall, but there is a high level of uncertainty around capital costs in this developing market. An LNG refuelling station may have additional operating costs for the warranty and maintenance of infrastructure, such as, cryogenic pump and ancillary equipment servicing and emergency breakdown cover, of about €25,000/year for a 2,000 kg/day point.

For inland navigation, a major challenge is the availability of alternative fuels infrastructure according to EFIP (personal communication).

The capex requirements for bunkering are estimated by (pwc, 2017) at €30 - 60 million for a port storage facility with a capacity of 6,000 to 15,000 m$^3$, and €30 – 40 million for a bunkering vessel with a capacity of 3,000 to 10,000 m$^3$. In (DMA, 2012), the capital cost for a small terminal (700 m$^3$ tank storage capacity) is estimated around €7.7 million and for a medium terminal (50,000 m$^3$ tank storage capacity) around €118 million. This may restrict smaller ports from providing marine bunkering facilities though road-based refuelling would remain an option.

### 5.4.4 PERSPECTIVES FOR MARKET DEVELOPMENT

The market perspectives for gas-fuelled vehicles[63] in the EU based on (EC, 2018c) under two scenarios are shown in **Figure 5-64**. As can be seen, the projections for gas-fuelled vehicles are higher in the HCV market, where fewer options are available. However, the blending of biomethane and e-gas can reduce the carbon emissions of gas-fuelled HCVs. Thus, low carbon fuels reduce the GHG emissions of trucks, even when used in conventional drivetrains.

[63] (EC, 2018c) in fact reports ICE gaseous vehicles, without further splitting the figures into CNG and LNG vehicles.

For cars, the perspectives for LNG are non-existent and for CNG uncertain. Westport expects the 'Clean Vehicle' Directive and the $CO_2$ emission standards for HDVs to lead to the uptake of CNG and LNG buses, coaches and trucks (personal communication). According to NGVA Europe (personal communication), the following number of vehicles powered by natural gas might be in use in the EU by 2030: 12.6 million CNG cars (12% of the assumed car stock), 190,000 CNG LCVs (25% of the assumed LCV stock), 110,000 CNG buses (33% of the assumed bus stock) and 280,000 LNG HCVs (25% of the assumed HCV stock) (see also (NGVA, 2018)). It should be noted that these figures are substantially higher than the estimates in the in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction, presented in **Figure 5-64**.

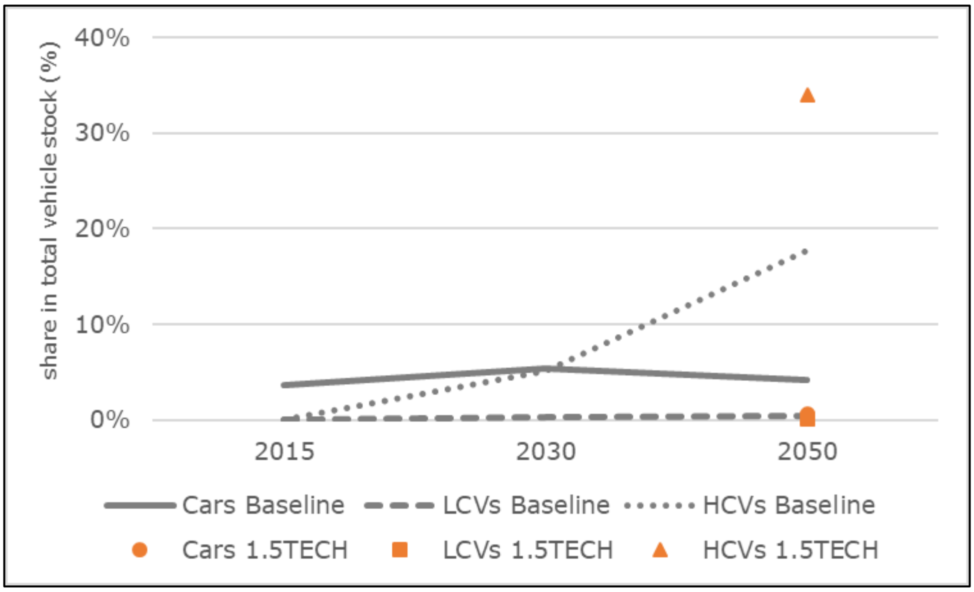



**Figure 5-64. Gas-fuelled vehicle shares in total car, LCV and HCV stocks in the Baseline and 1.5TECH scenarios**
**Source: own work based on (EC, 2018c)[64]**

Other powertrain options limit the prospects for the use of natural gas for rail transport in the EU. Notwithstanding this, (Dincer & Zamfirescu, 2016) identified LNG as a very promising option for the railways.

For inland navigation in the EU, the prospects of LNG uptake are uncertain. According to CCNR, these prospects are not bright due to economic and environmental reasons, at least in the Rhine (personal communication). The same stakeholder indicates that the current strategy of various operators is to wait for the uptake of battery, methanol and hydrogen-related technology. Other stakeholders remain more optimistic. Westport forecasts growing LNG demand from inland navigation (personal communication). EICB considers the possibility of a fleet of up to 300 LNG vessels in 2030 (personal communication). It remains to be seen whether the LNG Master Plan for the Rhine-Main-Danube (LNG-MP, 2018) will lead to greater LNG vessel uptake in the Danube river.

Compared to CNG and compressed biomethane, its higher energy density makes (bio)LNG particularly relevant for long-distance trucking and navigation (dena, 2019). (IRENA, 2017b) considers bio-LNG to be a particularly promising option for future heavy-duty transport. LNG road vehicle and vessel uptake is taking place in

[64] The blending of biomethane and e-gas reduces the carbon emissions of gas-fuelled HCVs. Thus, low carbon fuels reduce the GHG emissions of trucks, even when used in conventional drivetrains.

respectively the road freight and maritime transport markets. However, that does not guarantee rapid growth of bio-LNG. For that to happen, incentives are needed (personal communication by Ørsted).

The market projections on the demand for natural gas in the EU international maritime sector based on (EC, 2018c) under four scenarios are shown in **Figure 5-65**. As can be seen, the demand for natural gas is shown to increase to over 5 Mtoe by 2030 in the Baseline scenario and reach 7-8 Mtoe by 2050 under three decarbonisation variants. The demand for natural gas in 2050 is projected to be lower under the 1.5LIFEMar scenario (around 5 Mtoe) whereas an additional 5 Mtoe would be provided by e-gas.

In Norway, six vessels partially powered by liquefied biogas are expected to come into operation in 2020 (Reuters, 2019c). Globally, (DNV-GL, 2018c) forecasts that LNG demand from international shipping will reach around 2 Mtoe by 2030 and 60 Mtoe by 2050, respectively accounting for ca. 15% and 23% of energy demand. These percentages are forecasted to be similar for short-sea and deep-sea operations.

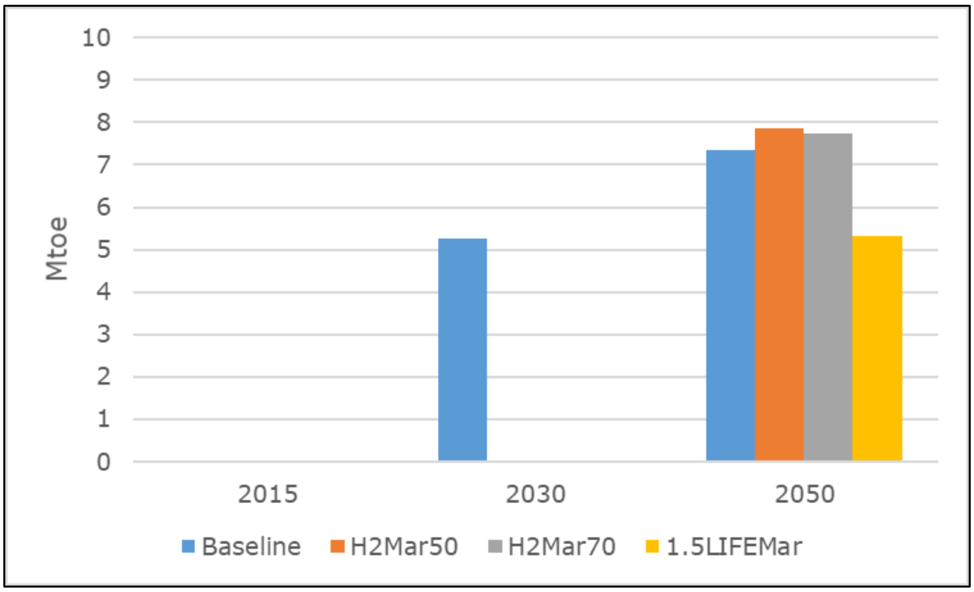



**Figure 5-65. EU international maritime demand for natural gas in the Baseline and decarbonisation variants**
**Source: own work based on (EC, 2018c)**

**Infrastructure:** A number of 24 Member States provided 2020 targets in their NPFs regarding the CNG refuelling infrastructure which would signify an increase of 25% of the infrastructure available at the end of 2018 (EC, 2019d). Some NPFs (Germany, Luxembourg, and the Netherlands) express a pessimistic view on the viability of CNG for road, while others (Belgium, the Czech Republic, Hungary, and Italy) consider this as a priority.

**Figure 5-66** gives an overview of the 2020 CNG refuelling points targets per NPF and the level of target achievement at the end of 2018 (Bulgaria, Cyprus, Malta and Sweden, that didn't provide targets are displayed in light blue).

According to (NGVA, 2018), the number of CNG refuelling stations would increase by 2030 around three times, up to 10,000.

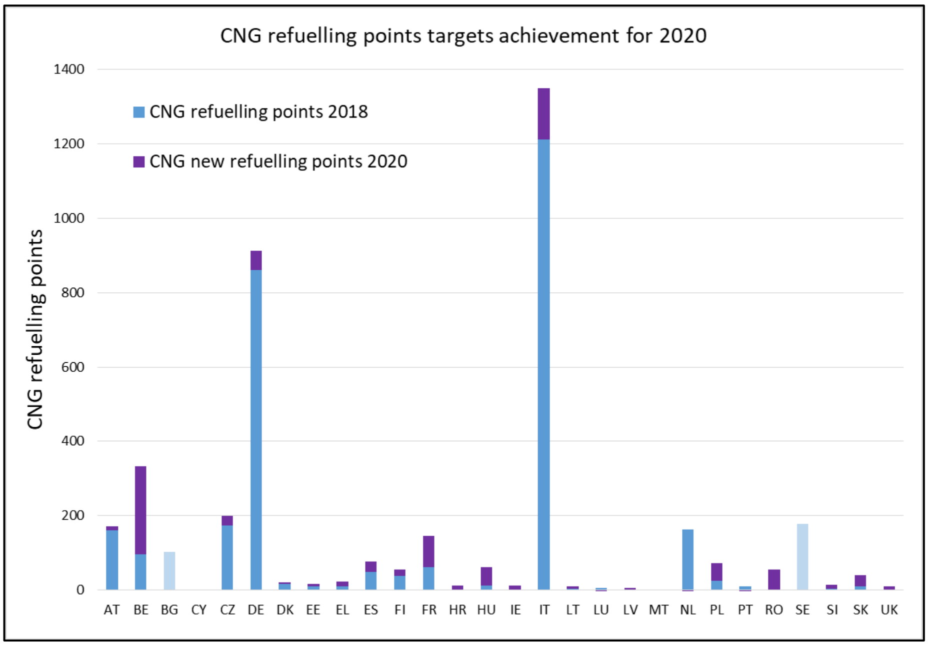



**Figure 5-66. Overview of the level of achievement for CNG refuelling points targets across EU**
**Source: own elaboration based on data from (EAFO, 2019) and (EC, 2019d)**

21 NPFs provided targets for 2025 related to LNG refuelling infrastructure for heavy-duty vehicles along the road TEN-T Core Network (EC, 2019d). A number of 384 LNG refuelling points are planned to be deployed across EU, with Hungary (83), Italy (80) and Spain (44) being the most ambitious countries.

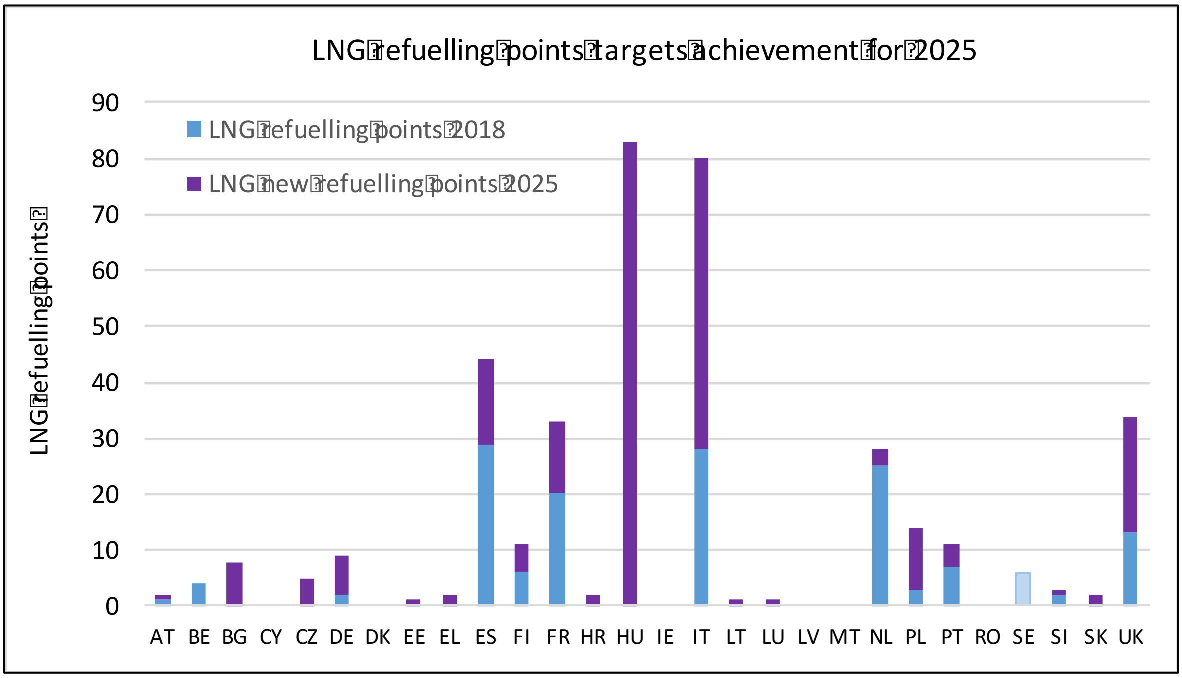



**Figure 5-67. Overview of the level of achievement for LNG refuelling points targets across EU**
**Source: own elaboration based on data from (EAFO, 2019) and (EC, 2019d)**

According to IOGP (personal communication), nine of the world's Top 10 bunkering ports either already offer LNG bunkering or have firm plans to do so by 2020.

**Figure 5-67** gives an overview of the 2025 LNG refuelling points targets per NPF and the level of target achievement at the end of 2018 (the countries that didn't provide targets are displayed in light blue).

(NGVA, 2018) estimates that the number of LNG refuelling stations would increase in 2030 to about 2,000 across the EU.

The plans to deploy LNG in maritime and inland ports vary between high ambition (Finland, Hungary, and Italy) and no consideration, leaving a number of TEN-T Core Network ports without any solution for LNG refuelling (see **Figure 5-68**). For most of the inland waterway corridors, the coverage of LNG refuelling will likely be inadequate according to the targets of the NPFs (EC, 2019d).

According to GIE (personal communication), by 2020, the number of maritime ports in Europe providing LNG refuelling solutions is expected to double compared to the value in 2018.

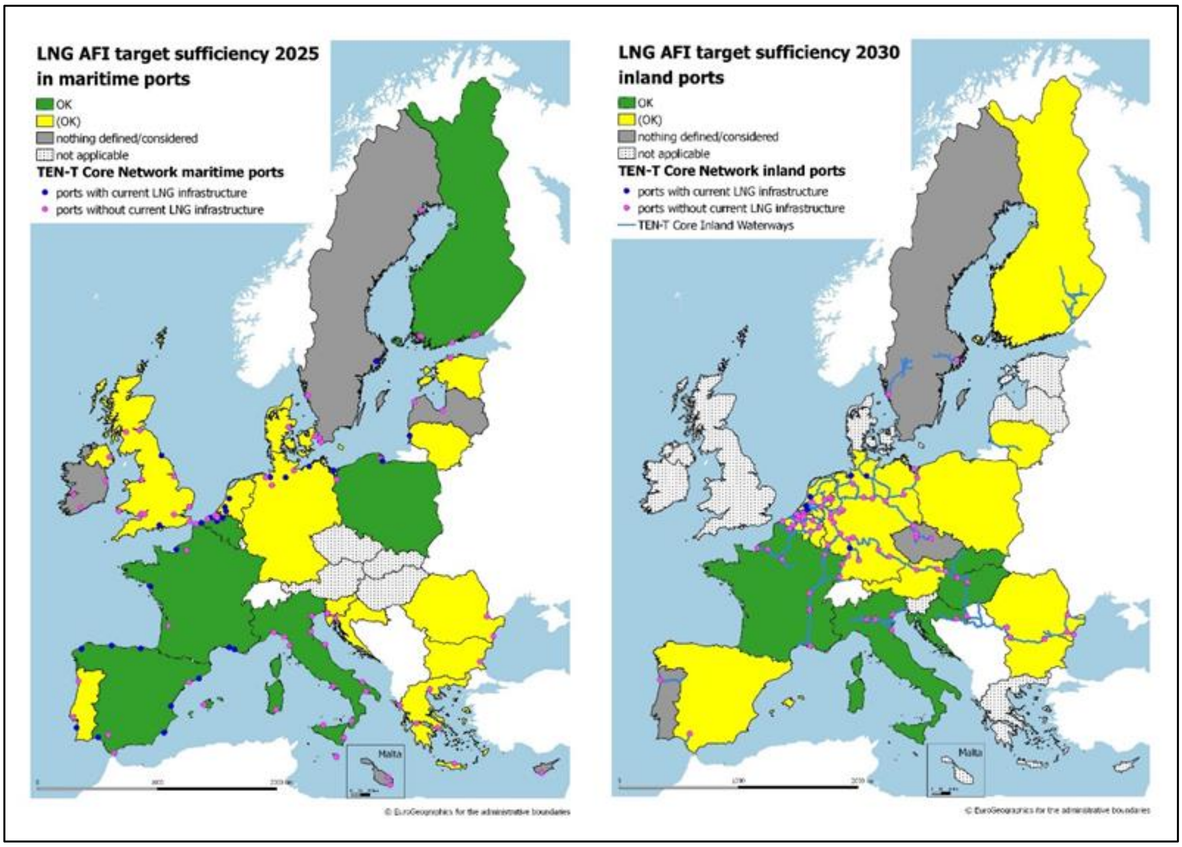



**Figure 5-68. Results of the assessment for the sufficiency of LNG refuelling points in TEN-T Core Network maritime ports (left map) and LNG refuelling points in TEN-T Core Network inland ports (right map) Source: EC, 2019d**

## 5.5 SYNTHETIC FUELS AND PARAFFINIC FUELS

### 5.5.1 MATURITY OF TECHNOLOGY

Synthetic and paraffinic fuels are a class of high quality alternative fuels that can be used directly in diesel engines and/or blended with diesel, and are defined by CEN EN 15940. In principle, electrofuels or synthetic fuels are an interesting option for all transport modes (Brynolf, Taljegard, Grahn, & Hansson, 2018).

The 2015 report indicated that bioDME had been successfully tested in Sweden and GTL and HVO were at an early stage of commercial use in Europe. In 2016, the PSA Group became the first European OEM to accept HVO in its cars and LCVs, after DAF, MAN, Mercedes, Scania and Volvo had done the same for HCVs (Neste, 2016). Though theoretically mature , the technology needs further development in terms of efficiency and scale (personal communication by Ørsted). With regards to the electrolyser technology for synthetic fuels, the same stakeholder expects that it will mature in the next five to ten years. WESTPORT expects synthetic methane production to become more mature towards the year 2030 (personal communication).

**Table 5-14** summarises the information available on research funding for synthetic and paraffinic fuels.

**Table 5-14. Summary on research funding (2007-2020) for synthetic and paraffinic fuels Source: JRC, 2019b**

| *Fuel type* | *Total project value* | *Total EU contribution* | *Number of projects* | *Average project value* |
|---|---|---|---|---|
| HVO | € 52,046,473 | € 19,055,766 | 5 | € 10,409,295 |
| FT | € 30,261,185 | € 13,109,990 | 6 | € 5,043,531 |
| HTL | € 10,935,331 | € 10,935,331 | 2 | € 5,467,666 |
| Other / all types | € 405,260,594 | € 276,547,602 | 71 | € 5,707,896 |
| **Total** | **€ 498,503,583** | **€ 319,648,689** | **84** | **€ 5,934,566** |

HVO is considered the most mature paraffinic fuel for cars, LCVs, buses and HCVs (personal communication by ART FUELS and UPEI). The technology maturity of coaches powered by HVO is however currently low, according to (IRU, 2019). In addition to HVO, (Volvo, n.d.) regards DME as a promising alternative fuel for HCVs. This manufacturer announced tests with trucks powered by DME in the US (Volvo, 2017). The engines of Daimler trucks can be powered by HVO, BTL, GTL and CTL (Daimler, 2019b).

The most mature paraffinic fuel for rail transport is HVO, according to ART FUELS and UPEI (personal communication). (Shell, n.d.) reported tests in which Deutsche Bahn (DB) Schenker locomotive engines were powered by GTL.

For inland waterway transport, (Moirangthem, 2016) considered methanol as a present option and DME and pyrolysis oil as future alternatives. Methanol is a mature fuel to power inland waterway vessels. (LR/UMAS, 2017) also identified ammonia fuel cell and ammonia plus internal combustion engine as technology options for low carbon vessels in inland waterway transport. According to EICB, the most mature paraffinic fuel is HVO (personal communication). ART FUELS reported that HVO is the most mature paraffinic fuel for passenger vessels and ferries as well as for short-sea (in addition to bio-methanol) waterborne transport (personal communication).

For maritime transport, ammonia represents an attractive option according to (T&E, 2018b). It is, however, still at a research and development stage for use as a marine fuel (ITF, 2018). Ammonia and hydrogen from renewable sources are considered by (DNV-GL, 2019b) to be, of all the realistic alternative fuel options for deep-sea operation, at the lowest levels of commercial readiness, in part due to low bunkering availability. According to ASFE, GTL should be mainly used as fuel in maritime vessels, as well as in heavy-duty vehicles (personal communication). (DNV-GL, 2018b) regards synthetic fuels as an alternative for the future. The most promising paraffinic fuel for vessels is considered HVO, while BTL is seen as a promising alternative (DNV-GL, 2018a). The same authors indicate that market interest in methanol is also increasing. The in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction considered that further research is needed for the use of ammonia in maritime transport (EC, 2018c). The 1.5LIFEMar decarbonisation variant projects a share of 17% for e-liquids by 2050 and 10% for e-gas. The 2015 report indicated that the use of methanol in refurbished ships was being tested. Since then, methanol maritime vessels have become a mature technology. The marine engine developed by MAN (see **section 5.6.1, p. 203**) can also run on DME and methanol (MAN, 2019a). Researchers have concluded that methanol is a suitable fuel to power cruise vessels (Bundesregierung, 2018).

For most aviation operations, the use of GTL kerosene blended (maximum 50%) with jet A1 has been approved (Shell, 2019a). The in-depth analysis accompanying the EU Long-Term Strategy for GHG emissions reduction identified e-liquids as an option for air transport (EC, 2018c). Electrofuels are currently at a development phase (personal communication by Lufthansa). Currently, there are a few demonstration projects for e-fuels (EASA, 2019a). Synthetic fuels may have a role to play as drop-in fuels in the air transport system (Malins, 2017). (Goldmann et al., 2018) compared jet A-1 fuel with five electrofuels: n-octane, methanol, methane, $H_2$ and ammonia. These authors identified n-octane as the most attractive substitute and highlighted the need for further research on another promising option: $H_2$/ammonia mix.

### 5.5.2 DATA ON VEHICLES AND INFRASTRUCTURE

Passenger vehicles powered by synthetic and paraffinic fuels were in use in the past. For instance, ammonia buses were deployed in Belgium in the 1940s and ammonia cars in South Korea and the US (Barret, 2015). In Europe, an ammonia-gasoline hybrid car was shown in 2013 (AEA, 2013). Renewable diesel (HVO) for road transport is being used in at least the Baltic countries, Sweden and Finland (personal communication by Neste). In the latter, it is used in blends with concentrations of 30–50% by volume (Jääskeläinen, 2017b). About 30,000 buses and HCVs (27% of the Finnish bus and HCV market) are compatible with 100% renewable diesel (Jääskeläinen, 2017a).

GTL can be used in existing diesel HDVs without modifications, and according to Shell is currently in use in some commercial fleets in Germany and the Netherlands (Shell, 2019a). Commercialisation of bio-DME in the European truck market is low (IEA, 2017).

According to available information, two inland waterway vessels powered by methanol have been deployed. One of them is the MS Innogy in Germany, with capacity for 160 passengers (WF, 2019).

The 2015 report indicated that the ‘Stena Germanica’ would begin to operate using methanol. This large maritime vessel, which currently links Germany and Sweden and has capacity for 1,300 passengers and 300 cars, continues to be powered by methanol (StenaLine, 2019). According to (DNV-GL, 2019a), there are twelve methanol maritime vessels in operation and on order, of which one is a RoPax vessel (presumably the Stena Germanica) and the rest oil/chemical tankers. No vessel powered by ammonia is reported by (ITF, 2018).

**Infrastructure**: Having very similar properties to their fossil fuels counterparts, the paraffinic fuels can be used neat or blended in existing diesel engines, distribution and refuelling infrastructure and therefore no additional upfront investment is required for dedicated infrastructure.

Since physical properties of DME resemble those of LPG, the refuelling and storage requirements of these fuels are similar. In principle, transport and distribution of DME could use the existing LPG infrastructure with some modifications. There was no DME infrastructure in the EU in 2017 (EC, 2017a).

According to ASFE (personal communication), GTL is sold in Belgium, Denmark, Germany, France, Netherlands, Finland and United Kingdom. In Finland, GTL is blended with diesel by the fuel suppliers and sold in the refuelling stations as diesel.

A Finnish fuel sector operator, Neste has launched a renewable diesel (HVO100) made entirely from waste and residues at selected refuelling stations in Finland at the beginning of 2017 (Neste, 2017). In 2019, there are more than 50 refuelling stations providing this fuel in Finland, and the fuel is being marketed also in Sweden, the Baltic countries and Netherlands according to Neste (personal communication). There were 162 HVO100 refuelling stations in Sweden in 2018 (SPBI, 2019).

### 5.5.3 COST OF VEHICLES AND INFRASTRUCTURE

As mentioned in the 2015 report, synthetic fuels can be used with today's vehicle technology or with minor adaptations implying no substantial additional costs. More recently, (EC, 2018c) indicated that neither powertrain nor infrastructure adaptation would be required for the use of e-fuels

So far, the literature seems to be divided on the economics of synthetic fuel use for road transport. (T&E, 2017) concluded that electrofuels have no role to play in the light-duty and partially in the heavy-duty sector due to their inefficiency and cost. The conversion efficiency of electrofuels used in ICEs is only 13% (Leopoldina, 2017). (Hänggi et al., 2019) recently reviewed synthetic fuels for passenger vehicles and found that, in terms of energy consumption, DME and methanol are at disadvantage when compared to fuel cell vehicles.

GTL can be used in diesel engines and does not require modifications for heavy-duty vehicles (Shell, 2019a). DB Schenker reported that the higher costs of GTL, relative to diesel, can be offset by lower maintenance costs (Shell, n.d.).

In addition to technical, legal and supply chain barriers, (EIBIP, 2017) identified the fuel cost (5-10% higher than the benchmark fuel) as a hurdle for the use of GTL in IWWs. According to ART FUELS (personal communication), HVO may be used in small vessels, not on other types for cost reasons. This conclusion seems to be supported by the analysis on energy costs made by (DNV-GL, 2019b) for large vessels.

Although ammonia is not explicitly mentioned in Directive 2014/94/EU and Directive 2018/2001 (EU, 2014) (EU, 2018), it is a relevant alternative fuel in the maritime transport system (see e.g. (T&E, 2018b)). (LR/UMAS, 2017) examined synthetic fuels (ammonia and hydrogen) and concluded that their use in combination with the internal combustion engine tends to outcompete their use in combination with the fuel cell. The same authors consider that the future ammonia storage costs are unlikely to change significantly. The high energy cost of ammonia and hydrogen from renewable sources is considered by (DNV-GL, 2019b) a major barrier in this sector.

The 2015 report included a claim made by marine engine manufacturers that the conversion of an existing engine to burn methanol would bear less costs than an LNG retrofit work, since there are no dead volumes and no insulation requirements. Also in 2015, (EMSA, 2015) concluded that the new build and retrofit investment costs for methanol were similar to scrubber installation costs. (FCBI, 2015) mentioned costs of 270 €/kW for newly built vessels and conversion costs, with caveats, of 350 €/kW and expected these to go down. According to (Methanex, 2017), methanol represents an affordable way of complying with the emissions regulations due to its cost competitiveness with MGO and relatively low cost of enabling vessel engines to be powered by this fuel. In terms of fuel price, the spot average price of methanol free on board in Rotterdam oscillated from €276 per metric tonne in December 2016 to €286 per metric tonne in December 2018 (MI, 2019).

For aviation, (Kandaramath Hari et al., 2015) conclude that the FT process is expensive. (Dimitriou, Goldingay, & Bridgwater, 2018) estimated that the most economic BTL system, the circulating fluidised bed Fischer-Tropsch (CFB-FT), would require a subsidy of around €12 per tonne of dried wood to compete in price with conventional fuel. Lufthansa estimates that, under the current policy framework, the production cost of liquid e-fuels for aviation in 2030 will be around €4,000-€5,000 per tonne (personal communication).

**Infrastructure**: No specific infrastructure is needed for drop in fuels. Compared with the cost of a typical LPG refuelling point, a difference of 10-15% extra cost is estimated by (IDA, 2019) for a typical DME refuelling point.

### 5.5.4 PERSPECTIVES FOR MARKET DEVELOPMENT

The perspectives for market development of e-fuels in the EU transport systems are highly uncertain. Two studies claimed that the potential of electrofuels for transport GHG emission reductions in the EU until 2030 is rather limited (Christensen & Petrenko, 2017) (ICCT, 2018a).

It is expected that 'Flirtino' trains fitted with a HVO engine will be deployed in 2020 (Arriva, 2017). Nevertheless, other powertrain options limit the prospects for the use of expensive e-fuels for rail transport in the EU.

In the 2015 report, it was asserted that the Dutch Energy Vision estimated penetration for GTL as a fuel in the inland shipping sector of 11% by 2030 and 19% by 2050, and in recreational vessels of 19% in 2030 and 31% in 2050. CCNR expects e-fuels to play an important for in inland waterway transport (personal communication). EICB considers that, depending on the policy framework, half of the fleet of inland waterway vessels might be powered by HVO in 2030 (personal communication).

For EU international maritime transport, e-fuels projected in 2050 under the 1.5LIFEMar scenario: 13.5 Mtoe, with a split of 62% for e-liquids and 38% for e-gas (EC, 2018c).

The MethaShip research project concluded that methanol can be used as a vessel fuel for passenger operations, though some technical and financial aspects require further examination (MeyerWerft, 2018).

The potential of synthetic methane for vessels was identified by EFIP (personal communication). Research on the cost of methanol use in different types of vessels is underway under the Green Maritime Methanol consortium (MARIN, 2019).

(EC, 2018c) projects that, for aviation, the demand for e-liquids in 2050 is zero under the Baseline scenario and 19.8 Mtoe under the 1.5TECH scenario.

Lufthansa expects that the availability of liquid e-fuels for aviation will be one million tonnes in 2030, which is regarded as extremely limited (personal communication).

**Infrastructure:** Only Finland mentioned specific targets for the paraffinic refuelling infrastructure in its NPF (NPF Finland, 2017) corresponding to 2030, planning to increase the number of HVO100 supply to around one half of all refuelling stations.

## 5.6 LIQUEFIED PETROLEUM GAS

### 5.6.1 MATURITY OF TECHNOLOGY

LPG is fuelled in a slightly modified spark ignited internal combustion engine. Hybrid LPG technology is also being deployed (personal communication by AEGPL). **Table 5-15** summarises the funding on LPG research, including bio-LPG.

**Table 5-15. Summary on research funding (2007-2020) for LPG**
**Source: JRC, 2019b**

| *Fuel type* | *Total project value* | *Total EU contribution* | *Number of projects* |
|---|---|---|---|
| LPG and bio-LPG fuels | € 158,150,578 | € 104,696,963 | 38 |

The LPG technology is mature for road transport, as it has been commercialised for many years.

In the aforementioned review of alternative fuel options for rail transport, (Isaac & Fulton, 2016) did not list LPG. No information on this was provided in the questionnaire by AEGPL either.

So far, there is no demonstration with LPG in inland waterway transport (personal communication by EICB).

According to (DNV-GL, 2018b), LPG can be considered a realistic option for maritime transport. Marine engine manufacturers like MAN offer dual fuel engines that can be operated with LPG as well as marine fuel oil. The technology is mature, as its reliability has been confirmed by service experience and its performance verified on engines in service before market launch (MAN, 2018b).

The 2015 report mentioned that experiments with recreational aircraft powered by LPG were successfully conducted but not pursued further. As in the 2011 and 2015 reports, the use of LPG for air transport is not considered an option.

### 5.6.2 DATA ON VEHICLES AND INFRASTRUCTURE

Because of the reality of after-sale LPG conversion, this market is more difficult to observe than other alternative fuel markets. For this reason, it is necessary to monitor LPG use. For the EU, this is shown in **Figure 5-69**, where consumption is expressed in ktoe. As can be seen, this market has grown from almost 5,000 ktoe in 2008 to almost 6,000 ktoe in 2017.

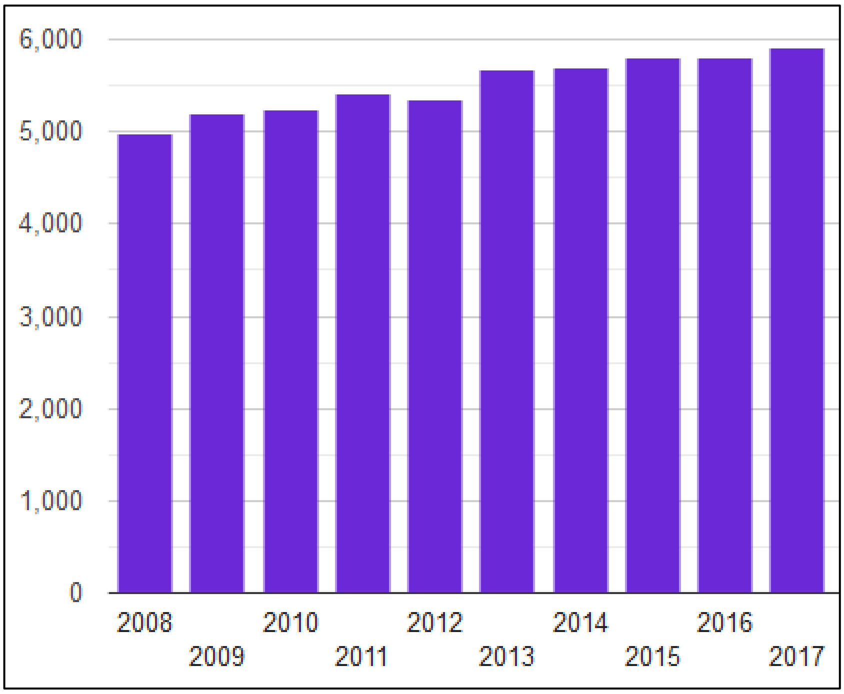



**Figure 5-69. EU road transport LPG use [ktoe]**
**Source: EAFO, 2019**

In terms of stock, LPG remains the most successful alternative fuel in the EU28 car market (see **Figure 5-70**). Almost 162,000 new LPG cars were sold in the EU in 2018, which represents a 78% decrease with respect to the series' peak in 2009 (EAFO, 2019).

The 2015 reported indicated that more than 50 different models of LPG vehicles, including passenger cars and vans, were available in the EU market. In 2017, there were 55 LPG car models and 4 LPG commercial vehicle models available in the European market (AEGPL, 2017). LPG vehicle model offerings in Europe increased from 59 to 69 models between 2017 and 2018 (WLPGA, 2018).

Five of the models reported as M1 in (WLPGA, 2018) could be identified as N1 (i.e. LCVs) (see (UNECE, 2014) for the definition of these vehicle categories). There were 110,000 LCVs powered by LPG in use in the EU in 2018 (EAFO, 2019).

The stock of LPG buses in the EU is less than 500 units (EAFO, 2019). Fleets of LPG buses exist in several EU cities. However, the prospects for new acquisitions or replacement of LPG buses are not encouraging (WLPGA, 2017a). For coaches, LPG is not discussed in (IRU, 2019).

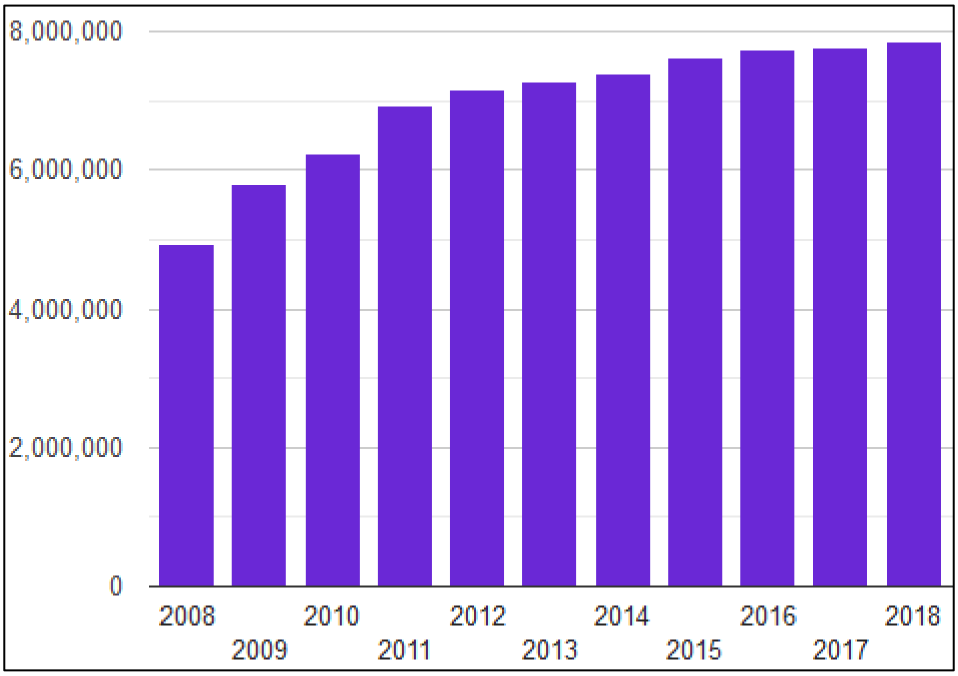



**Figure 5-70. LPG car stock in the EU28**
**Source: EAFO, 2019**

Though available in North America, heavy-duty models could not be found for Europe (WLPGA, 2018). The data on these vehicles available at (EAFO, 2019) is rather scarce.

In the 2011 and 2015 reports, the use of LPG for rail transport was not considered an option. (WLPGA, 2017a) mentions that two railway operators are testing CNG/LNG technologies, which can be powered by LPG after conversion.

There are seven LPG vessels in operation and on order, all of them gas tankers, according to (DNV-GL, 2019a).

**Infrastructure**: In road transport, the LPG refuelling infrastructure is well-developed in the EU and consists of 33,346 points at the end of 2018, according to (EAFO, 2019). The countries with the most LPG refuelling points in 2018 are Poland (7,432), Germany (7,100), Italy (4,120), Bulgaria (2,800) and France (1,902). However, some areas or countries (e.g. Austria, Sweden and Denmark) are not well covered by the LPG refuelling infrastructure. In Finland, LPG is not used as motor vehicle fuel, and consequently, it is not available (myLPG, 2019).

Since the publication of the 2015 report, the Commission has funded two LPG infrastructure projects through the CEF, which have delivered a total of 51 refuelling points in Portugal and Spain.

### 5.6.3 COST OF VEHICLES AND INFRASTRUCTURE

As indicated in the 2015 report, a significant advantage for the market uptake of LPG is that with only moderate excise duty reductions, the price of LPG can be maintained on average at about half the price of gasoline or diesel. Due to differences in the excise duty structure, the end-user price of LPG currently ranges from €489 per thousand litres in Bulgaria to €843 per thousand litres in France (personal communication by AEGPL using (EC, 2018b)). It is expected that the future retail price of LPG will follow a similar behaviour as conventional fuels and natural gas, according to AEGPL (personal communication).

As pointed out in the 2015 report, LPG vehicles were being offered either as bi-fuelled OEM vehicles (mono-fuelled only outside of the EU) or as after-market conversions.

The premium for an OEM LPG version ranges from €800 up to €2,000 while it costs between €1,400 and €3,000 to perform a conversion.

The cost of an LPG van usually lies between that of a gasoline and diesel counterpart. For instance, the purchase price of the Dacia Dokker in the German market is as follows: €10,174 for the gasoline version, €11,186 for the LPG version and €11,483 for the diesel version (Dacia, 2019).

No information was found on the purchase price of LPG buses and coaches in the EU. Though lower LPG prices offset energy costs, the operating expenses of LPG buses are unlikely to be significantly lower than for diesel, as the fuel consumption of LPG buses almost doubles (Civitas, 2011).

The estimated cost of a HCV powered by LPG is unknown to the authors at the time of writing.

The estimated cost of a railway vehicle powered by LPG is unknown to the authors at the time of writing.

LPG, traditionally cheaper than MGO, complies with the maritime emissions regulations and can power a dual-fuel marine engine available (retrofitting may also be possible) in the market (MAN, 2018b) (see also (WLPGA, 2017b)). While new LPG vessels are competitive, the economics of LPG retrofits are less compelling (DNV-GL, 2017a).

**Infrastructure**: According to AEGPL (personal communication), the cost of installing a public LPG refuelling point is estimated between €50,000 to €150,000, depending on the scale of the project and the sophistication of the equipment included in the station. The cost is expected to remain stable by 2030 since the technology is mature.

### 5.6.4 PERSPECTIVES FOR MARKET DEVELOPMENT

Three OEMs are planning to launch LPG versions of their vehicles: Mazda is focusing on range extenders powered by LPG, Renault targets 16% LPG vehicle sales in 2020 by adding new vehicle versions and Suzuki is offering three hybrid LPG/gasoline-electric vehicles (personal communication by AEGPL). With policies that support LPG, LPG vehicle stock might reach ca. 24 million units in the EU by 2030, according to AEGPL (personal communication).

Given the emergence of natural gas options for HCVs, there are no convincing reasons to think that LPG will rapidly penetrate this market in the next years.

Other powertrain options limit the prospects for the use of LPG for rail transport in the EU.

(Moirangthem, 2016) considered LPG as a future option for inland waterway transport. However, it seems that, for safety reasons, LPG is presently not considered a sufficiently attractive option for this mode of transport.

According to marine engine manufacturer (MAN, 2018a), LPG vessel technology may be particularly attractive for very large gas carriers, for which orders have already been placed, and coastal vessels. It seems that (DNV-GL, 2018c) does not forecast significant growth in LPG demand from international shipping for the next three decades.

**Infrastructure:** According to AEGPL (personal communication), the 2018 infrastructure is considered sufficient to serve an estimated triple number of LPG vehicles in 2030.

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## 5.8 APPENDICES TO CHAPTER 5

### 5.8.1 QUESTIONNAIRE

In the context of this study, the following questionnaire was sent out to stakeholders:

**General questions**

1.1. Based on your information/data, how has the production capacity for different alternative fuels, and in particular of decarbonised alternative fuels, evolved since 2014?

1.2. Looking at 2030 and based on your information/data, what changes do you expect – if any – in the evolution pattern of the different alternative fuels, and in particular decarbonised alternative fuels?

1.3. Based on your information, which is the most mature alternative fuel, and in particular decarbonised alternative fuel, per transport mode and vehicle/vessel category?

- road (passenger cars)
- road (light duty vehicles/vans)
- road (heavy-duty vehicles/trucks)
- road (buses and coaches)
- rail
- air transport
- waterborne (short-sea)
- waterborne (deep-sea)
- waterborne (inland waterways)
- waterborne (passenger & ferries

1.4. Looking at 2030: how could the production capacity of alternative fuels, and in particular of decarbonised alternative fuels, evolve taking into account current policies?

- Electricity
- Renewable Hydrogen
- Biomethane
- Synthetic methane
- Natural gas
- First generation liquid biofuels
- Advanced liquid biofuels
- Liquid hydro carbon electro
- fuels
- Liquid non hydrocarbon electrofuels (e.g. Ammonia)
- Paraffinic fuels
- Liquefied petroleum gas

1.5. For electricity and electro fuels, what are the consequences for electrical energy generation capacity? What are the technologies for transport systems and alternative fuels, and in particular decarbonised fuels that are still in the development stage, but might have market impact by 2030 and beyond, taking into account the current policies? What is the current state of maturity of these technologies/fuels? *You may name more than one technology, but please rank them according to their importance (i.e. in terms of possible market impact); you may also identify and rank different alternative fuel technologies for different transport modes and vehicle/vessel categories. Please be specific (e.g. electric vehicles, hydrogen and fuel cells (H&FC) vehicles, gas vehicles.*

1.6. Based on your information/data, how would you quantify market uptake of these technologies/fuels in terms of market share in 2030?

1.7. Based on your information/data, for which technologies do you see constraints in terms of security of supply with rare materials/resources?

1.8. What are the main challenges facing the uptake of alternative fuels, and in particular decarbonised alternative fuels, in your area of interest?

1.9. What are the main overall trends affecting availability of alternative fuels, and in particular for decarbonised alternative fuels?

**Specific questions on road transport**

**Electricity**

2.1. Do you consider the shortage of supply of needed materials/resources as a risk for the rapid increase of demand for electrified vehicles? Can you qualify the risk?

2.2. To what extent is dependency on certain rare materials likely to be addressed through battery or motor technology innovation?

2.3. Based on your information/data, how will the production cost of batteries evolve in the coming years, taking into account also technological progress?

2.4. Based on your information/data, how much of the battery demand can be addressed by domestic (lithium-ion) battery manufacturing in the medium-term (by 2030), taking into account the current policies?

2.5. What is the current and expected realistic driving range of different battery electric vehicles by size class in 2030, taking into account current manufacturer plans and policies?

2.6. Based on your information/data, how many battery and plug-in hybrid electric cars and vans (by category) do you expect to be registered in the EU by 2030, taking into account the current policies? What would be their share in the total number of cars and vans by 2030?

2.7. How many battery electric buses (excluding trolley-buses) and how many battery electric trucks do you expect to be registered in the EU by 2030, taking into account the current policies? What would be their share in the in the total number of buses by 2030?

2.8. Based on your information/data, what is the average battery capacity (kWh) of the electric buses in use in the EU?

2.9. Based on your information/data, how is battery capacity expected to change by 2030, taking into account the current policies?

2.10. What is the current cost (euro/station, assuming each station has two recharging points) of installing a publicly accessible AC recharging station [please distinguish between different powers if possible]; please distinguish between project development cost (e.g. concession costs, permitting etc.) and recharging equipment purchase costs? How these costs could evolve by 2030, taking into account the current policies?

2.11. What is the current cost (euro/charging point) of installing a publicly accessible DC recharging station [please distinguish between different powers, e.g.: 50kW, 100kW and 350kW and above]? Please distinguish between project development cost (e.g. concession costs, permitting etc.) and recharging equipment purchase costs. How these costs could evolve by 2030, taking into account the current policies?

2.12. Based on your information/data, what time does it take to recharge a battery to achieve a 200km range increase, and how will this evolve by 2030?

2.13. Based on your information/data, which is the optimal ratio between the number of publicly accessible slow-medium speed recharging points and the number of circulating electric vehicles (i.e. including total plug-in hybrids and battery electric passenger cars) in at least the cases of large and low availability of private charging points (parking in owned or rented garages)?

2.14. Based on your information/data, which is the optimal ratio between the number of publicly accessible fast/ultra-fast recharging points and the number of circulating battery electric passenger cars) in an urban environment in at least the case of large and low availability of private charging points (parking in owned or rented garages)?

2.15. Based on your information/data, which is the optimal ratio between the number of publicly accessible fast/ultra-fast recharging points and the number of circulating battery electric passenger cars) in an extra-urban environment (main road, motorway)?

2.16. Based on your information/data, which is the current technological level of development of the European industry as regards the manufacturing of batteries and electric vehicles in comparison to manufacturers in non-EU world regions? Which is the current level of industrial deployment vis-à-vis the current situation in the same non-EU world regions?

2.17. Based on your information/data, by which year the price of electric vehicles, per vehicle category (including PHEV) may be at par to that of conventional vehicles, taking into account the current policies? Please consider the total price of electric vehicle, including the battery.

**Hydrogen & fuel cells**

2.18. What is the current average production cost (euro/kW) of a fuel cell vehicle's fuel cell system? What could be the cost by 2030, taking into account the current policies?

2.19. What is the average amount of platinum currently used in fuel cell vehicles? How is this expected to change thanks to technological progress by 2030?

2.20. What is the current cost (euro/refuelling point, please indicate also the refuelling capacity) of installing a publicly accessible hydrogen refuelling point? What could be the cost by 2030, taking into account the current policies?

2.21. What are the main challenges for the manufacturing of fuel cells and BoP to deliver FCH vehicles at competitive prices?

2.22. Based on your information/data, what is the current technological development of the European industry as regards the manufacturing of fuel cells and fuel cell vehicles in comparison to non-EU manufacturers? Which is the current level of industrial deployment vis-à-vis the current situation in the same non-EU world regions?

2.23. Based on your information/data, by which year the price of fuel cell vehicles may be at par with that of conventional vehicles, taking into account the current policies?

2.24. How many fuel cell cars, vans, buses and trucks do you expect to be sold in the EU in 2030, taking into account the current policies? What would be their respective share in the in the total number of sales by 2030?

2.25. Could you please indicate what should be the appropriate number of $H_2$ refuelling points per vehicle in urban areas and per km in the core and comprehensive TEN-T to ensure large-scale deployment of fuel cell cars, buses and trucks in the EU?

2.26. Based on your information/data, what is the number of fuel cell vehicle models/makes (if applicable and possible, distinguish between passenger cars, vans, buses and trucks) expected to be launched by vehicle manufacturers on the European market?

**Sustainable liquid biofuels**

2.27. Based on your information/data, what is the potentially affordable price for advanced biofuels in line with the definition in the Renewable Energy Directive (RED) Recast by 2030?

2.28. Based on your information/data, what is the potential for the production of sustainable liquid biofuels, separated for first generation and advanced biofuels? in the EU by 2030?

2.29. Do you expect different transport modes or non-transport applications to compete for available volumes of sustainable liquid fuels in the EU by 2030? With what final use share?

2.30. What are the most prominent technologies for the production of advanced biofuels and their respective production costs? What could be, by 2030, the production cost, of these fuels to replace petrol and diesel taking into account the current policies?

2.31. What is the current cost (euro/point) of fitting an existing service station with one biofuel refuelling point (please state the type of biofuel)?

2.32. Based on your information/data, what is the number of flexible-fuel passenger cars (split by models) expected to be launched by vehicle manufacturers on the European market by 2030?

2.33. What is the level of polluting emissions, including currently unregulated ones with the different sustainable biofuels?

2.34. Based on your information/data, what is the current share of imported sustainable liquid biofuels in the EU?

2.35. What are the relative costs of imported liquid biofuels and of liquid biofuels produced in Europe?

2.36. Based on your information/data, from the environmental perspective, which are the most appropriate blends of sustainable biofuels with petrol or diesel to be used in cars and trucks by 2030 taking into account the existing resources?

**Natural gas, biomethane and synthetic methane**

2.37. Based on your information/data, how many CNG vehicles (passenger cars, vans, buses and trucks) do you expect to be registered in the EU by 2030, taking into account the current policies? What would be their respective share in the total number in 2030?

2.38. How many LNG buses, coaches and trucks do you expect to be registered in the EU in 2030, taking into account the current policies? What would be their respective share in the total number by 2030 (please distinguish between buses, coaches and trucks)?

2.39. Based on your information/data, what is the current cost (euro/refuelling point), please indicate also the refuelling capacity) of installing a publicly accessible CNG refuelling point? What could be the cost in 2030, taking into account the current policies?

2.40. What is the current cost (euro/station, please indicate also the refuelling capacity) of installing a publicly accessible LNG refuelling point? What could be the cost in 2030?

2.41. Based on your information/data, what is the potential for the production of biomethane in the EU to be used in transport by 2030?

2.42. Do you expect different transport and non-transport applications to compete for available volumes of biomethane in the EU by 2030? With what final distribution share?

2.43. Based on your information/data, what is the potential for the production of synthetic methane in the EU to be used in transport by 2030?

2.44. Based on your information/data, what is the current and estimated production cost of biomethane and synthetic methane by 2030, taking into account the current policies?

2.45. What is the potential of high-pressure direct injection (HPDI) dual-fuel trucks and mono-fuel (spark ignited) trucks to reduce greenhouse gas (GHG) emissions in the combustion phase compared to diesel trucks?

2.46. What is the potential of fugitive methane emission from combustion and tanks?

2.47. What is the level of polluting emissions, including currently unregulated ones, in each application (light and heavy road, waterborne)?

2.48. Based on your information/data, from the environmental perspective, which are the most appropriate blends of biomethane/synthetic methane and natural gas to be used in cars and trucks by 2030 taking into account the existing resources?

2.49. Could you indicate what should be the appropriate number of CNG and LNG refuelling points in urban areas per vehicle registered and per number of km in the core and comprehensive TEN-T to produce a market development of these vehicles in the EU at the horizon 2025 and 2030?

**LPG**

2.50. Based on your information/data, what is the current cost (euro/station, please indicate also the refuelling capacity) of installing a publicly accessible LPG refuelling point? What could be the cost by 2030, taking into account the current policies?

2.51. Based on your information/data, what is the current and expected cost of (bio-) LPG fuel for road vehicles by 2030, taking into account the current policies?

2.52. Based on your information/data, what is the expected availability of LPG by 2030, given the possible reduction of refinery by-products?

2.53. Based on your information/data, what is the current state of the technology to produce bio-LPG?

2.54. Based on your information/data, what is the potential for the production of bio-LPG at affordable costs in the EU by 2030, taking into account the current policies?

2.55. Based on your information/data, what is the number of LPG vehicle models/makes (if applicable and possible, distinguish between passenger cars, vans, buses and trucks) expected to be launched by vehicle manufacturers on the European market?

**Synthetic fuels (paraffinic and liquid electrofuels (e-fuels))**

2.56. Based on your information/data, what is the potential for the production of synthetic paraffinic transport fuels in the EU by 2030?

2.57. Based on your information/data, what is the potential for the production of liquid electrofuels in the EU by 2030?

2.58. Based on your information/data, what is the potential of paraffinic fuels to reduce life cycle GHG emissions compared to petrol and diesel vehicles?

2.59. Based on your information/data, what is the potential of liquid electrofuels to reduce life cycle GHG emissions compared to petrol and diesel vehicles?

2.60. Based on your information/data, what is the current and estimated cost of paraffinic fuels for road vehicles in 2030, taking into account the current policies?

2.61. Based on your information/data, what is the current and estimated cost of liquid electrofuels for road vehicles in 2030, taking into account the current policies?

2.62. Based on your information/data, what will be the environmental impact of the production of liquid electrofuels, for instance on water resources? Where will carbon atoms be recovered from, and with what efficiency? Should other electrofuels be considered such as ammonia?

2.63. Do you expect different transport modes or non-transport applications to compete for available volumes of synthetic fuels in the EU by 2030? With what final use distribution share?

**Specific questions on rail transport**

**Electricity**

3.1. Please provide referenced information on the current and expected costs and technological developments of electric battery powered rail locomotives by 2030, taking into account the current policies.

**Hydrogen & fuel cells**

3.2. Please provide referenced information (indicating the capacity of the fuel cell system) on the expected production costs and costs to operators and technological developments of hydrogen fuel cell / electric – hydrogen fuel cell powered rail locomotives in 2030, taking into account the current policies.

**Natural gas, biomethane and synthetic methane**

3.3. Please provide referenced information on the expected production costs and cost to operators and technological developments of LNG-powered rail locomotives by 2030 and beyond, taking into account the current policies.

**Specific questions on waterborne transport**

**Electricity**

4.1. Based on your information/data, are there enough EU ports (please distinguish between maritime and inland) currently having shore-side electricity supply in operation? How many of these ports are core TEN-T ports?

4.2. Based on your information/data, what is the current cost (Euro/point) of fitting an existing small, medium and large ports with shore-side electricity supply facilities?

4.3. Based on your information/data, what is the average power installed for shore-side electricity supply in small, medium and large ports? Is it enough to meet vessels needs for:

- a) stay at berth?
- b) battery charging?

4.4. What is the average energy consumption of small, medium and large ships using shore-side electricity? (please differentiate between the different types of vessels e.g. deep-sea / short-sea / inland waterway)

4.5. Based on your information/data, please provide current production costs of hybrid-electric and fully electric vessels. How do you expect this cost to evolve by 2030?

4.6. Based on your information/data, how will the cost of batteries for waterborne applications evolve in the coming years, taking into account also technological progress?

4.7. Based on your information/data, what is the current battery capacity installed on fully electric/hybrid electric vessels? How do you expect this capacity to evolve by 2030? (please differentiate between the different types of vessels e.g. deep-sea / short-sea / inland waterway/ferries) and what are the consequences for port power supplies?

4.8. What is the current share of electric/hybrid vessels in the fleet? (please differentiate between the different types of vessels e.g. deep-sea / short-sea / inland waterway/ passenger)

4.9. Based on your information/data, how will this share evolve by 2030, taking into account the development of the technology and policies? (please differentiate by type of vessel e.g. deep-sea / shortsea / inland waterway)

4.10. Based on your information/data, what is the current and expected realistic sailing range and capacity of fully battery electric ships in 2030?

4.11. Based on your information/data, what is the average capacity utilisation of on-shore power supply infrastructure (share of port calls using on-shore power supply)? Could you estimate how this is expected to evolve by 2030?

4.12. Based on electrically synthesised shipping fuels (e.g. hydrogen, Ammonia, Methanol) what are the implications for electrical generation capacity to decarbonise shipping in this way?

**Hydrogen & fuel cells**

4.13. Based on your information/data, indicate the expected development / deployment of hydrogen fuel cell powered vessels (indicating the capacity of the fuel cell system) by 2030 (including, when hydrogen is used for instance for auxiliary power, etc.). In doing so, please differentiate by the type of vessels (e.g. deep-sea / short-sea / inland waterways); also indicate any technology pathways that you may expect, such as the development of large fuel cells that initially use alternate fuels before ultimately hydrogen.

4.14. Based on your information/data, what is the expected share of hydrogen fuel cell vessels (including, when fuel cell is used for instance for auxiliary power, etc.) in the fleet by 2030, taking account the state of the technology, the needs of different sectors (freight, cruise, passenger etc.) and current policies?

4.15. Based on your information/data, please provide current production costs of hydrogen powered and Fuel Cell vessels. How do you expect this cost to evolve by 2030 and which fuel technologies would be employed?

4.16. Based on your information/data, what is the average hydrogen fuel consumption for different types of vessels powered with hydrogen?

4.17. Based on your information/data, what are the main challenges for deployment of hydrogen/Fuel Cell powered vessels?

4.18. What would be the cost of installing a hydrogen refuelling point in a port for large-scale shipping?

4.19. Based on your information/data, what could be the production cost of renewable hydrogen as a fuel by 2030? [If the cost cannot be provided, at least some indicative/comparative replies should be given, e.g. x-times the price of electricity or marine diesel oil, etc.]

**Natural gas, biomethane and synthetic methane**

4.20. Based on your information/data, how many LNG vessels are in use in the EU-flagged fleets? (please differentiate by type of vessels).

4.21. How many LNG vessels have been ordered by EU shipping companies and worldwide (new built or retrofits)? (please differentiate by type of vessels (e.g. deep-sea / short-sea / inland waterways)).

4.22. Based on your perception and information/data, is there enough capacity of LNG bunkering point in operation at EU ports?

4.23. How many ports worldwide have currently LNG refuelling points in operation? Based on your information/data, how would this worldwide situation evolve by 2030?

4.24. Based on your information/data, what is the average capacity of LNG refuelling points in European ports?

4.25. What is the current production cost of LNG fuel for vessels?

4.26. Based on your information/data, how will this production cost evolve by 2030?

4.27. Based on your information/data, what are the current production costs of LNG vessels (new built and retrofit)?

4.28. Based on your information/data, how would these production costs evolve by 2030? In doing so, please differentiate by the type of vessels (e.g. deep-sea / short-sea / inland waterways).

4.29. Based on your information/data, how would the share of LNG vessels in the EU-flagged fleet evolve by 2030, taking in account the state of the technology and current policies?

4.30. Which decarbonised alternate fuels should bunkered in ports, what should be the priority and what are the implications for port fuel infrastructure?

**Liquefied biofuels**

4.31. Based on your information/data, what is the share of biofuels currently used in the shipping sector? Which biofuels/blends, if any, are being used? (please differentiate by type of vessel e.g. deep-sea / shortsea / inland waterways)

4.32. Based on your information/data, how is the share of biofuels share likely to evolve by 2030?

4.33. Based on your information/data, which biofuels/blends of biofuels with conventional fuels are expected for use in vessels by 2030? (please differentiate, if necessary, by the type of vessel e.g. deep-sea / short-sea / inland waterways)

4.34. Based on your information/data, what could be the production cost of such biofuel/blends by 2030? [How would this compare with other type of fuels for the waterborne (maritime and inland waterway) sector? – if the cost cannot be provided, at least some indicative/comparative replies should be given, e.g. x-times the price of electricity or marine diesel oil etc.]

**Specific questions on air transport**

**Electricity / electrofuels (e-fuels)**

5.1. Based on your information/data, what is the current cost for fitting an existing airport with electricity supply for stationary airplanes (euro/point)?

5.2. Based on your information/data, how do you expect electric powering - e.g. hybrid vs. full-fledged electrical solutions - penetrating different segments of the aviation sector – (e.g. general aviation, short-haul /long-haul, passenger, cargo)?

5.3. Based on your information/data, please provide some information on expected Key Economic Indicators associated to the future use of electrical powering in aviation.

5.4. If the European aircraft fleet were fuelled with electricity, what would be the consequences for electrical generation capacity?

5.5. Please provide information on the expected costs and battery energy density of electric jets/airplanes (please state the seating capacity) flying less than 500 km by 2030 and beyond.

5.6. Based on your information/data, what is the production cost and availability of liquid electrofuels for aviation by 2030, taking into account the current policy framework?

5.7. Based on your information / data, how do you appraise the medium term potential of air transport (Hybrid-electric planes, drones) regarding urban e-mobility and services?

5.8. What could be the share of energy from electro fuels in relation to the total conventional energy used in air transport?

**Liquid biofuels**

5.9. Based on your information/data, what are the current production costs of sustainable aviation fuels (SAF) (euro/litre)? How do you expect these costs to evolve as a result of economies of scale / pathway optimisation?

5.10. Based on your information/data, what are the limiting factors or barriers (and why) to the future production of sustainable biofuels for aviation? How could these barriers be overcome?

5.11. Based on your information/data, what is the estimated demand of biofuels by 2030 in aviation in the EU?

5.12. Based on your information/data, which types of biofuel – using which feedstock(s) and which conversion process(es) - are competitive and sustainable for aviation?

5.13. Based on your information/data what percentage of EU commercial flights may be expected to use biofuel blends powered airplanes by 2030 taking into account the current policies? What could be the share of energy from biofuels in relation to the total conventional energy used in air transport?

5.14. How do you see developments in the international context in ICAO influencing the uptake in biofuels at a European level?

**Hydrogen & fuel cells**

5.15. Based on your information/data, what is the current state of hydrogen electric technology for auxiliary power of airplanes?

### 5.8.2 STAKEHOLDERS' INPUT TO THE QUESTIONNAIRE

**Table 5-16** summarises stakeholders' input to the questionnaire. In the table, X means that feedback for a specific question on that mode/fuel has been provided by the stakeholder.

**Table 5-16. Feedback from each stakeholder, by transport mode and alternative fuel**

| | Road | | | | | | Rail | | | Waterborne | | | | Air | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Electricity | H2 | Biofuels | Natural gas | LPG | E-fuels | Electricity | H2 | Natural gas | Electricity | H2 | Biofuels | Natural gas | Electricity | E-fuels | Biofuels | H2 |
| AEGPL | | | | | X | | | | | | | | | | | | |
| ALSTOM | X | | | | | | X | X | | | | | | | | | |
| AVERE | X | | | | | | | | | | | | | | | | |
| CCNR | | | | | | | | | | X | X | | X | | | | |
| CLARIANT | | | X | | | | | | | | | | | | | | |
| CLEPA | | | | | | | | | | | | | | | | | |
| EFIP | | | | | | | | | | X | X | | X | | | | |
| EICB | | | | | | | | | | X | X | X | X | | | | |
| ENERKEM | X | X | X | X | | X | | | | | | | | | | | |
| EXERGIA (ART FUELS) | | | X | X | | X | | | | | | X | | | | X | |
| ePURE | | | X | | | | | | | | | | | | | | |
| FCH JU | X | X | | | | | | | | | X | | | | | | X |
| FUELS EUROPE | X | | X | | | X | | | | | | | | | | | |
| GIE | | | | X | | | | | | | | | X | | | | |
| HYDROGEN EUROPE | | X | | | | | | X | | | X | | | | | | X |
| IOGP | | | | | | | | | | X | | | X | | | | |
| IONITY | X | | | | | | | | | | | | | | | | |
| LUFTHANSA (I) | | | | | | | | | | | | | | X | X | X | |
| LUFTHANSA (II) | | | | | | | | | | | | | | X | X | X | X |
| NGVA EUROPE | | | | X | | | | | | | | | | | | | |
| ORSTED | | | | | | | | | | | | | | | | | |
| RATP | X | | | | | | | | | | | | | | | | |
| SEKAB | | | | | | | | | | | | | | | | | |
| SOLARIS | X | X | | X | | | | | | | | | | | | | |
| TOTAL | | | X | | | X | | | | | | X | | X | X | X | |
| UPEI | X | X | X | X | X | X | | | | | | X | | X | X | X | |
| UPM | | | X | | | | | | | | | | | | | X | |
| VDA | X | X | X | X | | X | | | | | | | | | | | |
| WESTPORT | | | | X | | | | | | | | | | | | | |

# 6 SYNTHETIC PRESENTATION OF RESULTS

## 6.1 FUELS PRODUCTION MATURITY AND AVAILABILITY[65]

Among the alternative fuels for transport, electricity is expected to rapidly grow in importance. Electricity can be generated from a wide range of primary energy sources – some of which renewable. At EU level, approximately 30% of the electricity comes from renewable energy sources (Eurostat, 2019). According to the New Policies Scenario of the (IEA, 2017b), under current trends and adopted policies, the share of electricity generation from renewable energy sources will reach 45% by 2030. In this context, extending electricity use in the transport sector will contribute to the overall GHG emissions reduction, fuel diversification and improved air quality. The exact amount of GHG emission reductions from increasing electricity penetration will depend on the share of renewable energies used as primary sources, while air quality improvements are accrued with any energy source to produce electricity. According to the in-depth analysis accompanying the Commission proposal for a long-term climate strategy, the share of renewables in gross electricity generation is projected at 57% by 2030 and 73% in 2050 under current trends and adopted policies. The consumption of electricity as fuel in transport could be in the range of 31.4 to 55.8 Mtoe (depending on the scenario) in 2050 (EC, 2018b). Regarding the current cost of electricity production, the global weighted-average LCOE varies from 40 to 146 €/MWh for fossil fuel-fired power generation, whereas the respective cost for renewable electricity production ranges from 40 to 230 €/MWh (IRENA, 2019).

Regarding production of hydrogen, up to now, reforming of methane is still the dominant technology. There are three methods: steam methane reforming (using water as an oxidant and a source of hydrogen), partial oxidation (using oxygen in the air as the oxidant), or a combination of both called autothermal reforming (ATR). Steam methane reforming is the most widespread technology for hydrogen production while ATR is also in use. Carbon capture and storage (CCS) can be applied both to steam methane reforming and ATR hydrogen production. Using CCS with SMR plants can reduce the $CO_2$ emissions up to 90% if applied to both process and energy emission streams, thus making CCS crucial to decarbonising the large steam methane reforming production that exists today.

While steam reforming is associated with GHG emissions, hydrogen can also be produced from low carbon energy sources using electrolysis. Such "green hydrogen" would constitute an important form of energy storage from solar and wind sources. For the time being, however, the cost of producing "green" hydrogen (hydrogen from electrolysis) is significantly higher and explains why current production volumes of hydrogen from electrolysis are still low. Hydrogen from reforming of methane is already produced in large quantities for industrial applications, with the chemical industry accounting for 65% of the global $H_2$ demand. Industry demand is expected to increase. According to (IRENA, 2018), the potential hydrogen demand in 2050 will be 191 Mtoe, dedicated mostly to feedstock uses in industry (162 Mtoe) with transport accounting for 21.5 Mtoe. As far as EU is concerned, according to the long-term strategy of the EU mentioned above (EC, 2018b), the hydrogen consumption in transport in 2050 would range from 5.7 to 48.1 Mtoe in the different scenarios. The current cost of hydrogen production and energy efficiency can still be improved. Hydrogen production cost can range from below 5 to 10 €/kg$H_2$ at the nozzle (corresponding to 150-300 €/MWh) depending on where the hydrogen is produced and the volume (personal communication by Hydrogen Europe).

[65] The data from **Chapter 4 (p. 19)** are based on actual production capacity, costs and maturity. Nevertheless, the data on future projections are derived from a scenario-based approach.

The low energy density of hydrogen means that it can be very expensive to transport over long distances. Nonetheless, a number of possible options are available to overcome this hurdle, including compression, liquefaction or incorporation of the hydrogen into larger molecules that can be more readily transported as liquids. In many countries there is an extensive existing natural gas pipeline network that could be used to transport and distribute hydrogen. New infrastructure could also be developed, with dedicated pipeline and shipping networks potentially allowing large-scale overseas hydrogen transport.

Concerning gaseous fuels, for the time being, most of the CNG and LNG production and use in transport comes from fossil origin. Bio-based alternatives can be considered as a way to mitigate negative environmental impacts. A main advantage of the gaseous fuels is the possibility to exploit the existing well-developed infrastructure. After 2020, biogas and biomethane will be counted towards the 32% renewable energy share from EU energy consumption and towards a sub-target of minimum 14% of the energy consumed in the transport sector by 2030 (2018/2001, REDII). (NGVA, 2018) estimates a potential biomethane production in the range of 36–51 billion $m^3/y$ (32-46 Mtoe) at 2030. According to other studies (Prussi et al., 2019), the expected potential to 2030 is about 18 billion $m^3/y$ (16 Mtoe). Since all available estimates of the overall production potential are well below the current natural gas consumption in the EU economy, there are important uncertainties about the share of this potential which could be made available for the transport sector. This would depend on market conditions and national policy supports. The long-term climate strategy of the EU foresees a consumption of biomethane in the transport sector ranging from 0.3 to 7.4 Mtoe for the considered scenarios in 2050. Concerning production costs, biomethane produced from biogas costs between 40 to 120 €/MWh depending heavily on the feedstock used for its production (EC SGAB, 2017).

As far as liquid biofuels are concerned, their main advantages are the relatively high energy density and compatibility with existing vehicles and fuel distribution infrastructure (up to certain limits in concentration for non drop-in type biofuels). One important evolution concerning biofuels is the adoption of the REDII which has introduced, within the target of 14% of renewable energy on the final energy consumption in transport by 2030, a sub-target of 3.5% for biofuels coming from advanced feedstocks by 2030 (2018/2001, RED II). Moreover, RED II sets a cap on the amount of biofuels counting towards MS renewable energy targets, produced from food and feed crops in order to account for ILUC. MS must set a specific and gradually decreasing limit for biofuels, bioliquids and biomass fuels produced from food and feed crops for which a significant expansion of the production area into land with high-carbon stock is observed. The EU consumption of sustainable biofuels amounted to 13,840 ktoe with 80% biodiesel and 19% bioethanol in 2016 (Eurostat, 2019)[66]. According to the long-term strategy of the EU for a climate neutral economy (EC, 2018b), consumption of liquid biofuels (including synthetic and paraffinic fuels) is expected to be in the range of 15.7 to 48.6 Mtoe in the baseline and different scenarios. The production cost of conventional bioethanol is estimated to be in the range of 15-22 €/GJ (54-79 €/MWh), while biodiesel production cost is estimated to be around 16-21 €/GJ (58-76 €/MWh) (JEC-WTT, 2019). There are concerns that the availability of sustainable feedstocks can represent a limiting factor in the expansion of biofuels production.

Synthetic fuels, substituting diesel and jet fuel, can be produced from different feedstock, converting mainly biomass or gas. HVO, of a similar nature, can be produced by hydrotreating plant oils and animal fats. HVOs have been produced industrially in the EU (and elsewhere) at the scale of millions of tonnes for many

[66] In 2018, the EU consumption of sustainable biofuels amounted to 7,082 million litres of bioethanol and 16,854 million litres of biodiesel (FAME and HVO) (USDA, 2019).

years; approximately 2.2 million tonnes of HVO were produced in the EU in 2018. At the moment, the production costs of synthetic fuels (e.g. FT diesel or methanol and DME from woody biomass) are substantially higher than other biofuels and far from being competitive with fossil fuels (JEC-WTT, 2019). For FT-diesel, the production cost is estimated at 43-44 €/GJ whereas the relevant cost for HVO was in the range of 17 and 24 €/GJ (for the period 2014-2016) considering vegetable oils (rapeseed, sunflower, soya and palm oil but also including wastes feedstocks (UCO and tallow oil) (JEC-WTT, 2019). As in the case of biofuels, the availability of sustainable feedstocks can represent a limiting factor in the expansion of synthetic fuels production.

Renewable fuels of non-biological origin (REFUNOBIO), also called electrofuels, because of their main constituents (electricity, $CO_2$ and water) produce a gaseous or liquid fuel. For the time being, production scales are at the pilot plant level (in the 100's of tonnes per annum) although the sector is expected to increase; indeed the long-term strategy of the EU (EC, 2018b) estimates the future consumption of e-liquids for transport in 2050 in the range of 0 to 54.3 Mtoe depending on the considered scenario. E-gases, from power-to gas- technologies, are expected to contribute within a range of 0 to 16.3 Mtoe depending on the considered scenarios. Base-case production costs of electrofuels have been estimated at 200–280 €/MWh (55-78 €/GJ) in 2015 considering an electricity price of 50 €/MWh (Brynolf, Taljegard, Grahn, & Hansson, 2018) which is low compared to the EU28 average grid electricity price. Much higher production costs have been reported by other sources up to 451 €/MWh (or 125 €/GJ (LBST and Dena, 2017). Due to the high energy intensity of the production process for electrofuels, they will only result in GHG emission reductions if renewable electricity is used.

Other alternative fuels that could play a role in the future include bio-LPG, bio-methanol and ammonia. However, their current shares are very low. Indicatively, bio-LPG production is currently under 0.1% of all LPG.

## 6.2 MATURITY OF THE VEHICLES AND INFRASTRUCTURE

### 6.2.1 VEHICLES

#### 6.2.1.1 MARKET STATUS

**Chapter 5 (p. 113)** has provided an analysis of vehicle technology development and market maturity for each transport mode taken individually.

With reference to road transport, the number of alternative fuel vehicle models can be considered a leading indicator for market uptake at the initial stages of market development (see **Chapter 3, p. 10**). **Figure 6-1** shows the evolution of model availability for certain types of alternative fuels vehicles. For instance, electric car sales growth, as shown in **Figure 6-2**, can in part be explained by increased model availability. Compared to electric and LPG car model availability, CNG car model availability is lower, which also seems to translate into lower registrations (see **Figure 6-2**).

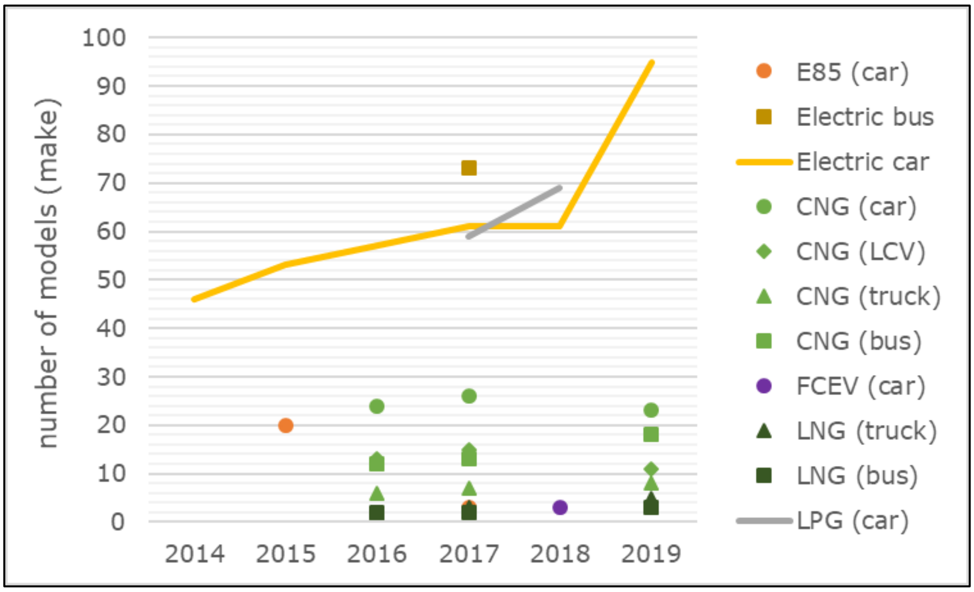


**Figure 6-1. Alternative fuels vehicle model availability**
**Source: own work based on (NGVA, 2016) (AEGPL, 2017) (NGVA, 2017) (ZeEUS, 2017) (EEA, 2018a) (H2M, 2018) (NGVA, 2019). Electric car values for 2014-2017 from (Tsakalidis & Thiel, 2018) (EAFO, 2019) and for 2018-2019 from (T&E, 2019)**

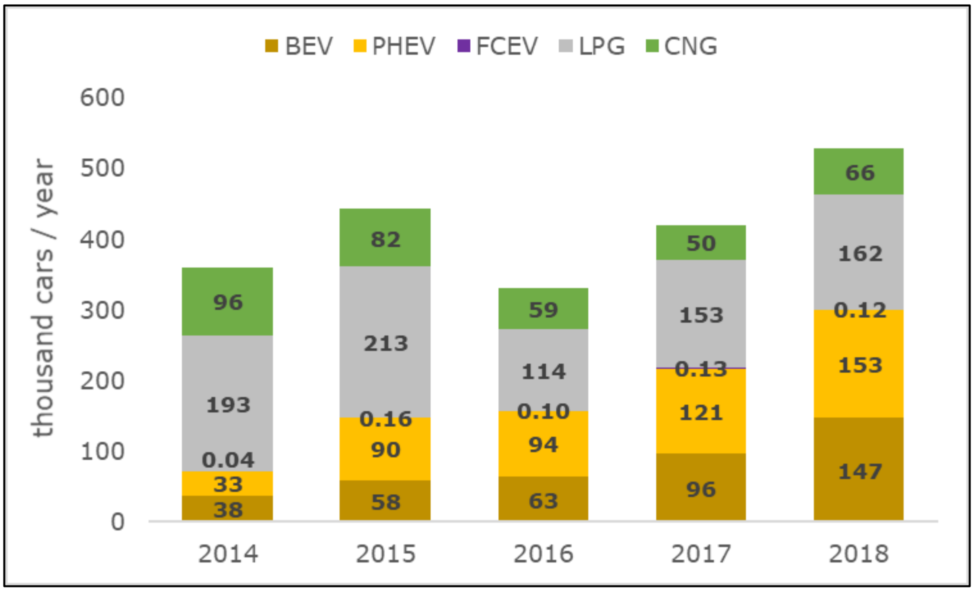


**Figure 6-2. Number of M1 sold in the EU, by powertrain**
**Source: adapted from (EAFO, 2019) (as of October 2019)**

**Figure 6-3** shows the share of alternative fuels car sales in the EU for the period 2014-2018, this time adding BEV and PHEV and showing E85 (together with LPG) as well as HEVs. As can be seen, the sales share of alternative fuels cars (thus excluding HEVs) increased from 2.6% to 3.6% over this period.

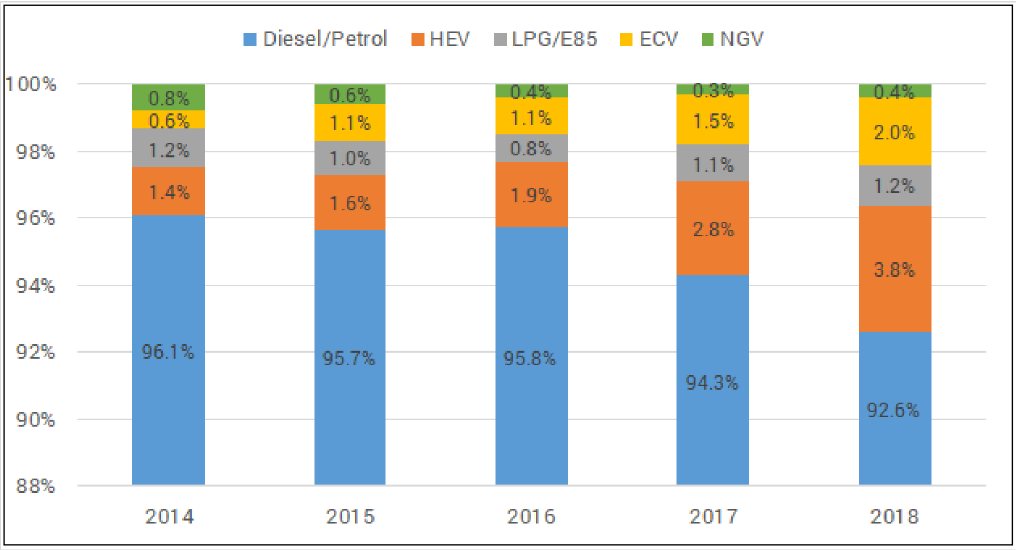


**Figure 6-3. New passenger cars sold in the EU [% share by fuel type]**
**Note: ECV = Electrically-chargeable vehicles (BEV+PHEV)**
**Source: ACEA (personal communication)**

Despite the growth in EU sales of cars powered by alternative energy sources, their market share remains rather low. The most recent data available at the time of writing shows that cars powered by alternative fuels accounted for 3.9% of the EU sales in the first quarter of 2019. Compared to the first quarter of 2018, electric car registrations grew by 40%, while the registrations of the remaining alternative fuels cars (E85, LPG and natural gas) declined by 7.2% (ACEA, 2019).

In 2016, the EU rail transport system used almost 33 ktoe of biodiesel. As shown in **Chapter 5 (p. 113)**, there is evidence on niche uptake of battery electric and hydrogen railway vehicles but the market for these alternative fuels is in its embryonic stage. Overall, it is expected that rail transport will continue to rely mainly on (non-battery) electricity, with an increase in the share of renewable electricity used.

As indicated in **Chapter 5**, there are examples of hybrid-electric inland waterway vessels in use. However, this technology currently represents less than 0.5% of the fleet. Vessels powered by hydrogen, liquid biofuels, LNG and methanol have also been deployed, but their shares remain also low.

**Figure 6-4** shows the global stock of maritime vessels powered by alternative fuels or featuring scrubbers currently in operation or on order. As can be seen, while 80% of this stock is represented by vessels with scrubbers, almost 11% consists of LNG ready and vessels powered by LNG, followed by battery-electric vessels (8%) (DNV-GL, 2019). When the global stock of maritime vessels is taken into account, these numbers are an indication of the low shares alternative fuels still hold in maritime transport.

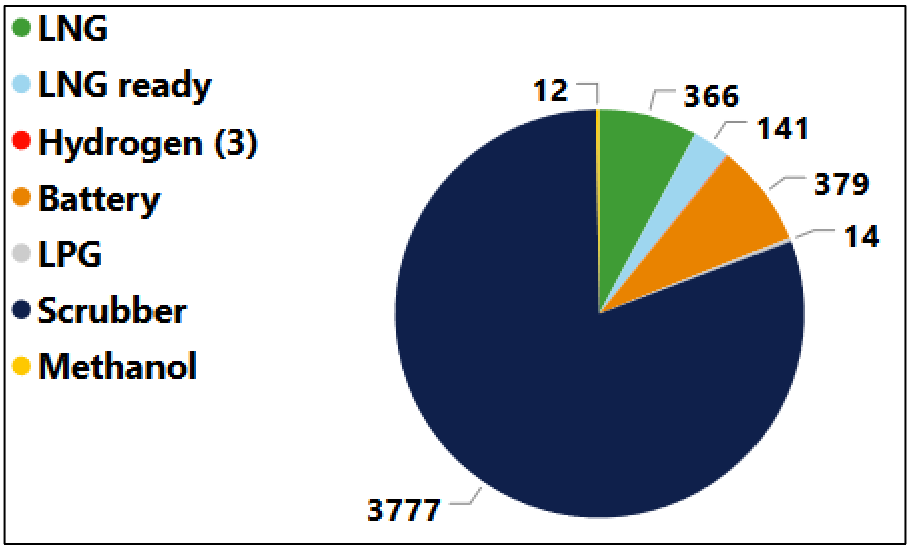


**Figure 6-4. Number of maritime vessels globally in operation or on order**
**Source: (DNV-GL, 2019) [reproduced with permission from DNV GL]**

Concerning air transport, the sector is still fully relying on fossil fuel based kerosene. Large aircraft powered by electricity or hydrogen have not been deployed for commercial operation yet.

In the following **Figure 6-5** and **Figure 6-6** the situation is shown in a slightly different way. The charts indicate the market status of alternative fuels in road transport (for four vehicle types), air transport, rail transport and waterborne transport (IWWs and maritime). Four levels of market status are reported: under development (prototype or test), low commercialisation, niche market, market domination. For rail transport, electricity via catenary is reported (battery electric trains are being tested but approaching low commercialisation; see **section 5.1, p. 119**.

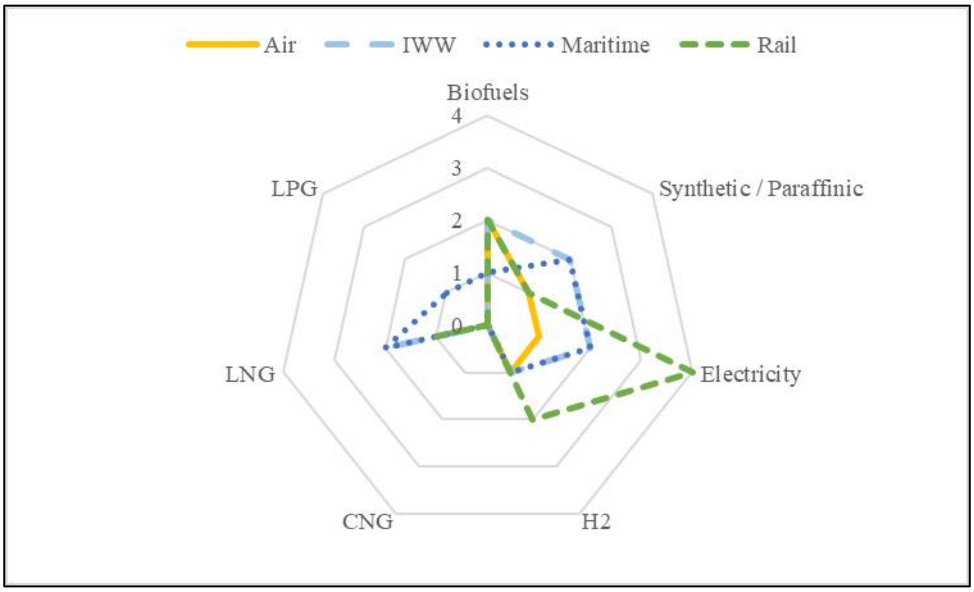


**Figure 6-5. Market status of alternative fuels in air, rail and water transport systems**
**Notes: 0 = not applicable/concept, 1 = under development/prototype/test,**
**2 = commercial in EU but <2% of market share, 3 = ≥2% of market share,**
**4 = fuel has dominant market position.**
**Source: own work based on the sources indicated in the Appendix**

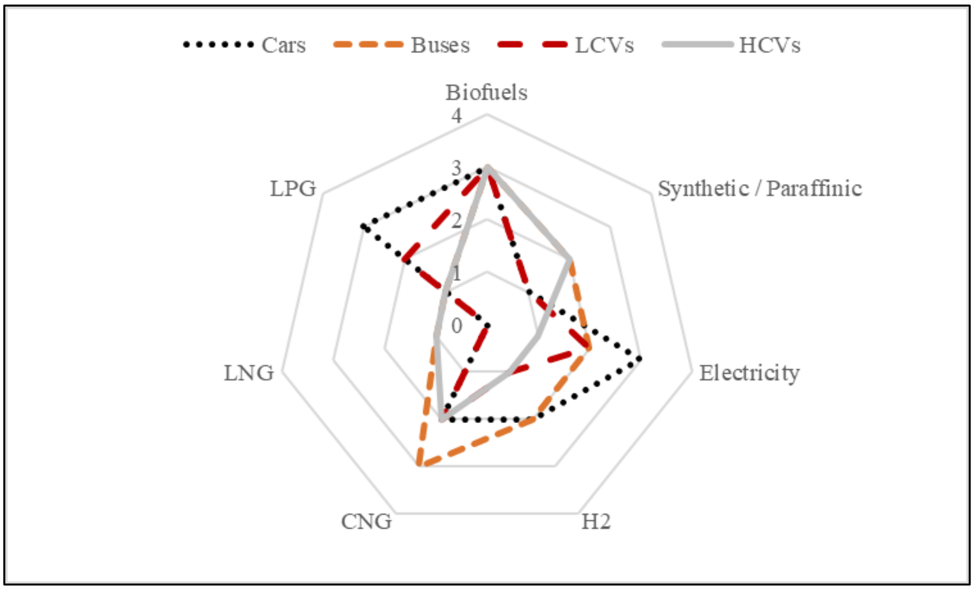


**Figure 6-6. Market status of alternative fuels in road transport systems**
**Same notes as in the previous chart**
**Source: own work based on the sources indicated in the Appendix**

### 6.2.1.2 MARKET PERSPECTIVES

With regards to market developments, the next five figures show the share that car, LCV, HCV, maritime and aviation stocks with different fuel/powertrain technologies might have in the EU in 2030 and 2050 according to few selected scenarios of the in-depth analysis accompanying the long-term climate strategy proposal (see also **Chapter 2, p. 3**).

**Figure 6-7** shows that the EU car stock continues to be dominated by gasoline and diesel ICE vehicles in 2030 but the situation changes dramatically by 2050. In the 1.5TECH scenario, 96% of the car stock in 2050 consists of zero emission cars (of which 80% are battery electric cars and 16% FCEVs).

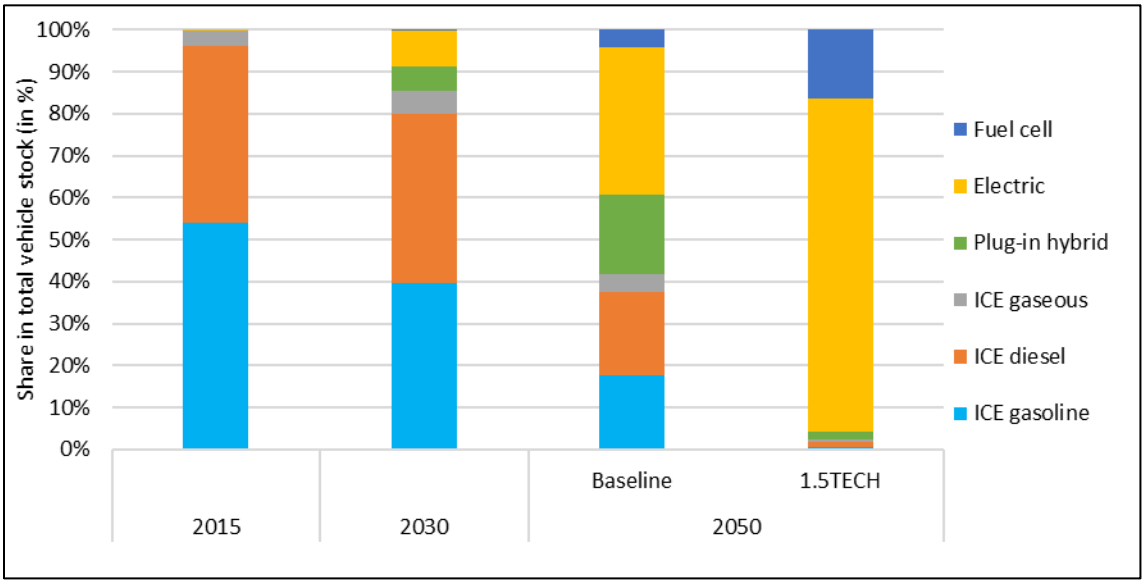


**Figure 6-7. Market development: EU car stock, by fuel type and scenario**
**Source: adapted from (EC, 2018c)**

**Figure 6-8** shows the projected stock of LCVs by powertrain technology. The general picture is similar to that of cars, albeit with a stronger presence of diesel LCVs. Almost half of the market would rely on diesel in 2050 in the Baseline scenario. However, the share of diesel LCVs is projected to decline to 5% in the 1.5TECH scenario, which is dominated by battery electric LCVs (78%). In this scenario, fuel cell LCVs represent 14% of the total stock.

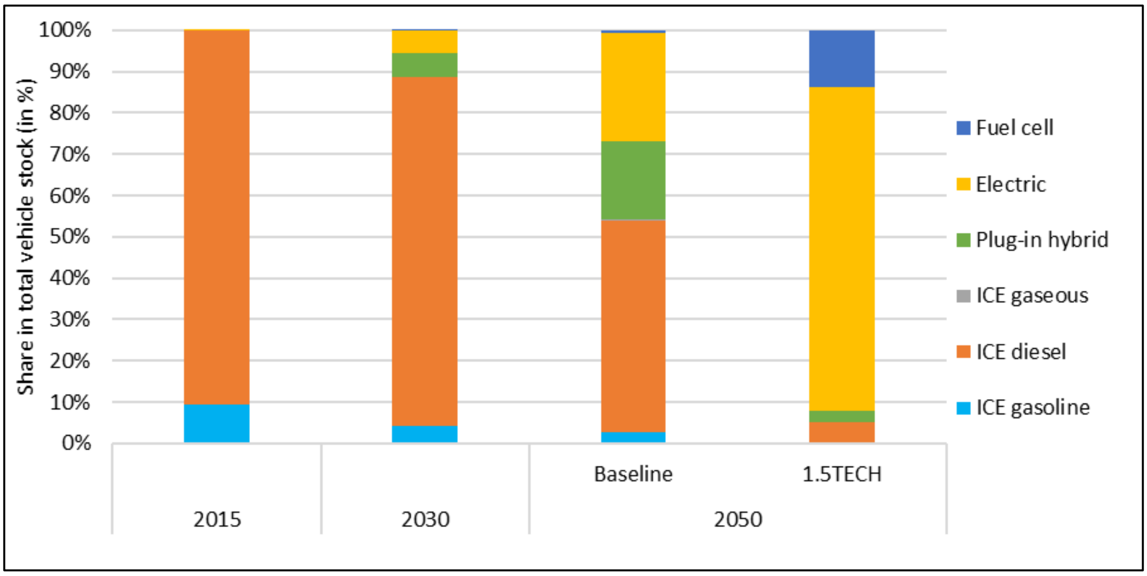


**Figure 6-8. Market development: EU LCV stock, by fuel type and scenario**
**Source: adapted from (EC, 2018c)**

The Baseline scenario projects that 21% of the buses and coaches in use in the EU in 2050 would be gas-fuelled. In this scenario, around 5% of the bus and coach stock would be electrified (battery and trolleys) by 2050. The share of electric buses, however, increases dramatically in the 1.5TECH scenario. In this scenario, biofuels (liquid and gaseous) and e-fuels (e-liquids and e-gas) play a stronger role. In the case of coaches, the market share held by fuel cells in the 1.5TECH scenario is significant.

**Figure 6-9** shows a more modest penetration of alternative fuels in the HCV market than in the previous two charts. In 2050, electric and fuel cell HCVs are projected to account for 14% of the total stock in the 1.5TECH scenario.

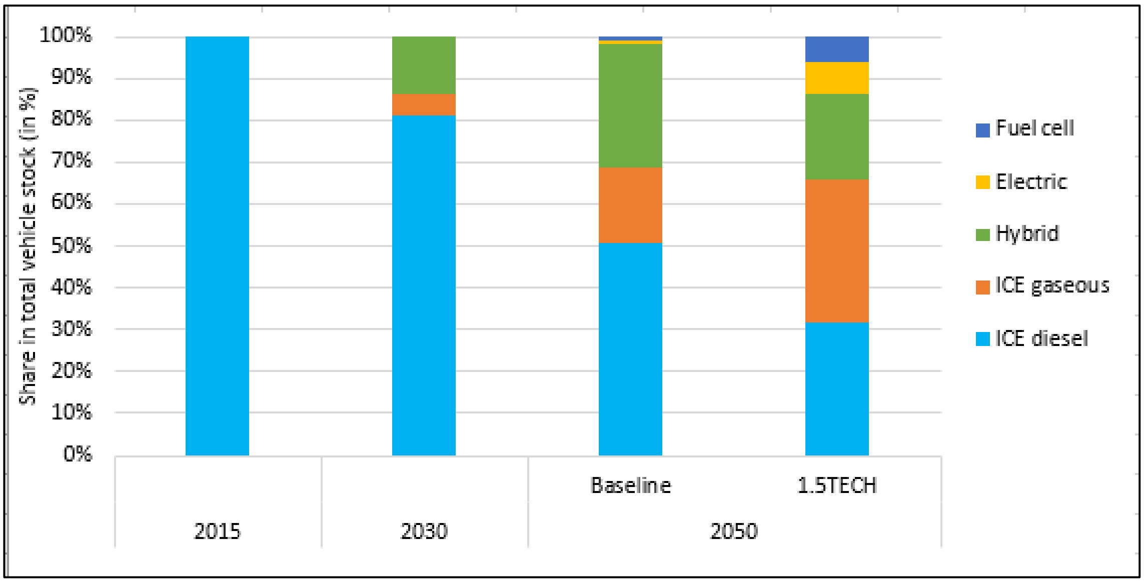


**Figure 6-9. Market development: EU HCV stock, by fuel type and scenario**
**Source: adapted from (EC, 2018c)**

Concerning rail transport, around 87% and 77% of the rolling stock, respectively for passenger and freight, is projected to be electric by 2050 in the Baseline scenario. Those shares respectively increase in the scenarios reaching net zero GHG emissions by 2050.

In the in-depth analysis accompanying the long-term climate strategy proposal, inland navigation includes IWWs and national maritime transport. In the Baseline scenario, around 13% of the inland navigation fleet would be powered by LNG by 2050.

For international maritime transport (see **Figure 6-10**), the projected importance of HFO and marine diesel oil declines significantly by 2050 in the decarbonisation scenarios, compared to the Baseline scenario. In these scenarios, liquid biofuels dominate. While in the H2Mar50 and H2Mar70 scenarios hydrogen becomes a relevant fuel (almost 8 Mtoe, a volume similar to that of natural gas), in 1.5LIFEMar the projected demand for e-fuels grows to reach 13.5 Mtoe by 2050.

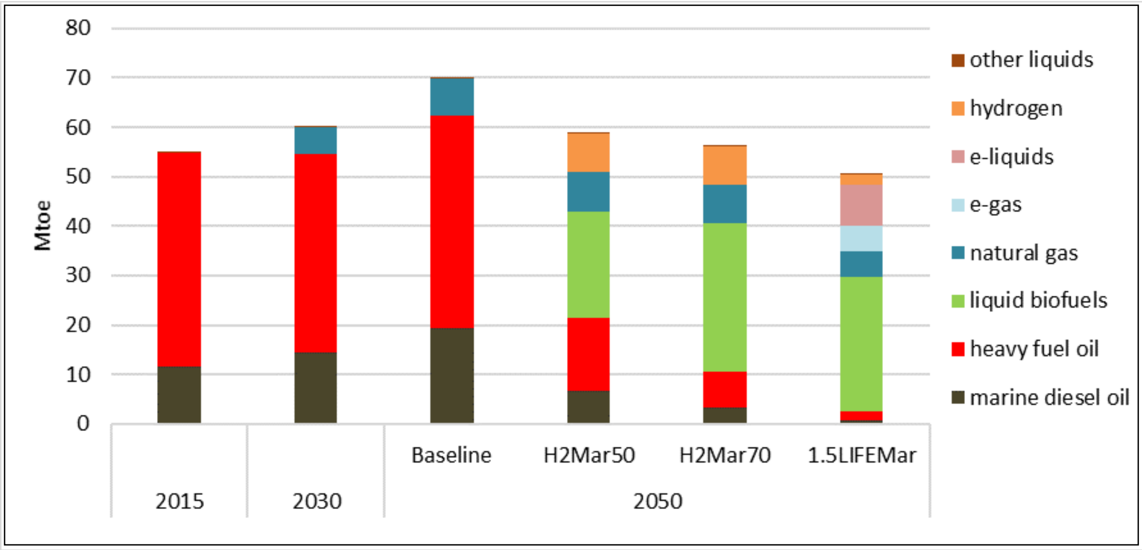


**Figure 6-10. Market development: EU international maritime, by fuel type and scenario[67]**
**Source: EC, 2018c**

Finally, the total energy needs from the air transport system are projected to decline by 2050 in the 1.5TECH scenario relative to the Baseline scenario (see **Figure 6-11**). In the 1.5TECH scenario, liquid biofuels and e-liquids have a substantial role to play (almost 23% and 34% of the energy mix by 2050, respectively).

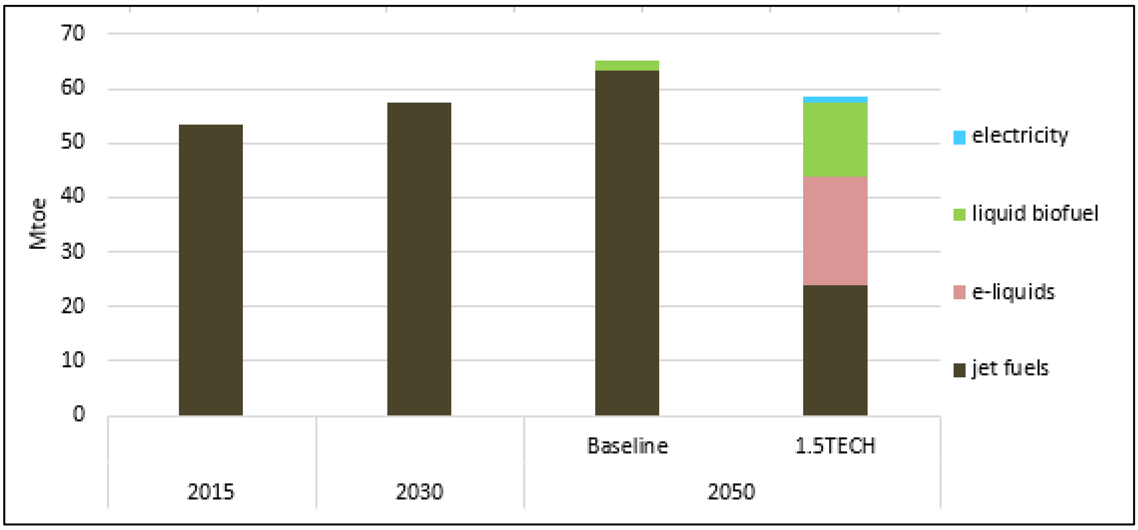


**Figure 6-11. Market development: EU aviation, by fuel type and scenario**
**Source: adapted from (EC, 2018c)**

### 6.2.1.3 VEHICLE COSTS

With regards to vehicle costs, the production costs of BEVs, PHEVs and FCEVs are currently higher than those of conventional powertrains, despite declining costs of key components such as LIBs for EVs (see **section 5.1.3, p. 143**). While the purchase price of different alternative fuels cars are relatively easy to gather from online

[67] (EC, 2018c) reports a modelling exercise for the EU international shipping. This includes three decarbonisation scenarios: H2Mar50 (a 50% reduction in the EU GHG emissions by 2050 compared to 2008, based on the H2 scenario), H2Mar70 (a 70% reduction in the EU GHG emissions by 2050 compared to 2008, based on the H2 scenario), and 1.5LIFEMar (with maritime transport supporting the net zero GHG emissions target by 2050 and reducing emissions by ca. 88% by 2050 compared to 2008, based on the 1.5LIFE scenario).

information provided by OEMs, this is not the case for HDVs and railway vehicles. For that, we relied on the sources of information indicated at the bottom of **Figure 6-12** and **Figure 6-13**. The cost estimates shown in these figures should be considered with caution, as vehicle heterogeneity in these markets is very large. Furthermore, it can be argued that operating costs play a much greater role in the purchase decision of the actors involved in these markets than it does for private car purchasers. This means that these figures provide only partial view of the issue and cover only a part of the TCO (a thorough evaluation of which is beyond the scope of this report, as stressed in **Chapter 3, p. 10**).

The left chart of **Figure 6-12** shows the cost for LDVs, for those powertrains for which relatively comparable data could be found at the time of writing. In the case of cars, the comparison was constrained by the availability of fuel cell cars in the large segment only, so the compared vehicles are all in this segment. The prices of electric crossovers tend to be lower than those reported in the chart. No data for similar E85 and LPG cars were found in the EU market and thus these technologies are not shown in the chart (while the cost of an E85 model was reported in **section 5.3.3, p. 177**, data on LPG for LCVs is visible in the chart).

The right chart of **Figure 6-12** shows the cost for HDVs, namely urban buses and HCVs for electricity, hydrogen and natural gas, in addition to the reference vehicle, which is diesel. As can be seen, the cost gap between fuel cell HDVs and the rest is currently quite significant. There is also a sizeable variability in cost for electric buses, as this reflects the choice operators face between opportunity and overnight charging buses, which have differing battery capacities and hence battery costs.

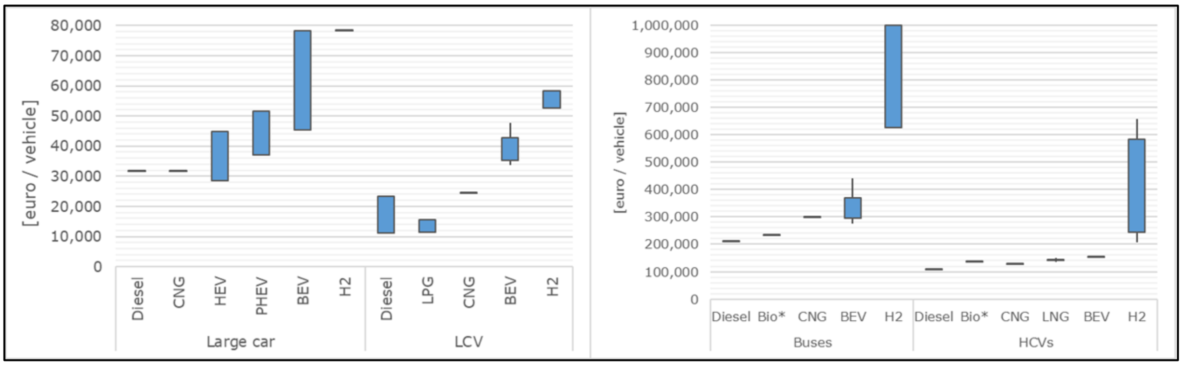


**Figure 6-12. Road vehicle cost by fuel type: LDVs (left) and HDVs (right)**
***Bio means bioethanol for buses and ED95 for trucks**
**Source: own work based on the sources indicated in the Appendix**

Cost information on railway vehicles available in the EU market is scarce. The cost of alternative fuel options is highly uncertain. Notwithstanding this, an example of the Coradia regional train series is shown in **Figure 6-13**. As with HDVs, the estimated cost of fuel cell trains is positioned at the upper end. However, there is a great degree of variability in cost estimates for this alternative fuels technology. The figure does not show the cost of battery-powered electric trains. As indicated in **section 5.1, p. 119**, this technology is being trialled and cost data was not found at the time of writing.

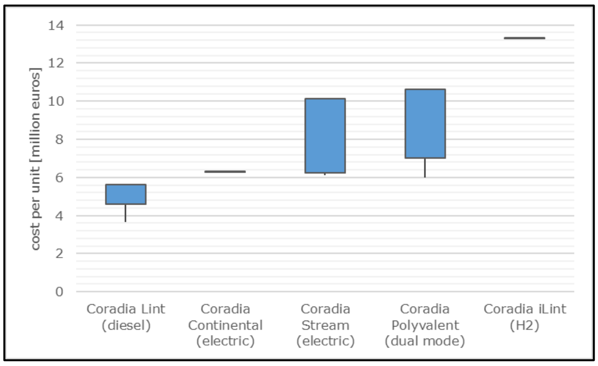


**Figure 6-13. An example of railway vehicle cost, by fuel type**
**Source: own work based on the sources indicated in the Appendix**

For water transport, information on comparative cost for all the potential alternative fuels cannot be provided in a meaningful manner in this chapter because of the heterogeneity and complexity of that market. Based on the example shown in **Figure 5-63** (see **Chapter 5, p. 193**), the left chart of **Figure 6-14** shows capital cost estimates for a hypothetical newbuild 14,000 TEU container vessel. The right chart of **Figure 6-14** distinguishes between newbuild and retrofitting investment costs for three types of vessels: chemical tanker, ro-ro ferry and cruise ship. In addition to HFO with scrubber, the cost values for the ethanol, methanol and LNG options are shown.

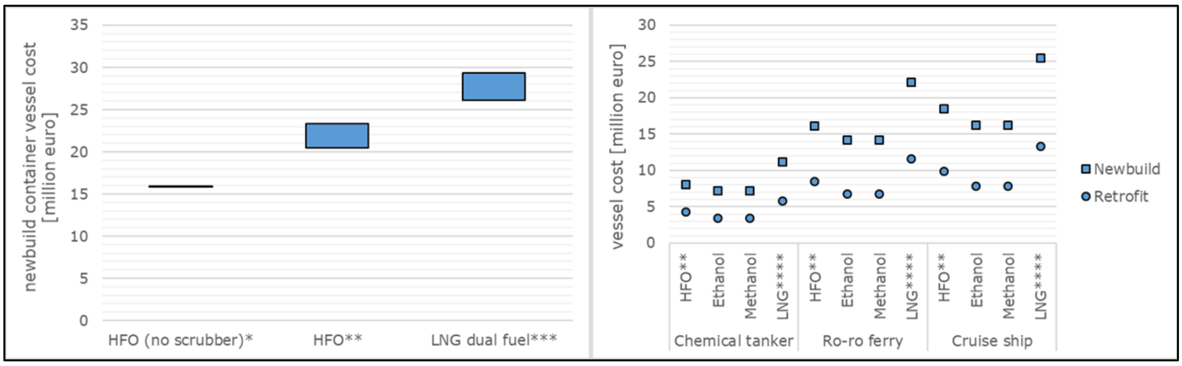


**Figure 6-14. Maritime vessel cost, by fuel type**
***But featuring selective catalytic reduction. **Fitted with both selective catalytic reduction and scrubber. ***2-stroke engine. ****4-stroke dual fuel engine.**
**Source: own work based on the sources indicated in the Appendix**

For aviation, fuel production costs (see **section 6.1, p. 244**) are more relevant than aircraft costs in the context of alternative fuel uptake in the sector.

The cost of powertrain technologies over the next few years could also be used as a leading indicator for market uptake. Unfortunately, the corresponding future cost of alternative fuel vehicles and vessels is highly uncertain, as it depends on industry investments and the policy framework. Due to this, a quantification of future costs is not reported here, as it would require a modelling exercise that is beyond the scope of this study. Qualitatively, it is expected that the future cost evolution of alternative fuel vehicles and vessels will be favourable, thanks to technological progress and economies of scale exploitation. In contrast, the costs of high-emission vehicles are expected to be higher in the future, in real terms, as internalisation of negative external effects proceeds.

### 6.2.2 INFRASTRUCTURE

#### 6.2.2.1 INFRASTRUCTURE AVAILABILITY

The road-dedicated AFI situation across EU in 2018 and the development trends during the period 2015-2018 are presented in **Figure 6-15**.

With regards to infrastructure at the end of 2018, around 140,000 publicly accessible recharging points were installed on the EU roads (EAFO, 2019). In the period 2015 - 2018, the increase of total recharging point's number was of 139% (with a 132% variation of the normal power points and a 214% variation of the high power points). The share of high power charging points increased from 8.3% in 2015 to 10.9% in 2018 of the total publicly accessible recharging infrastructure.

The number of road hydrogen refuelling stations in 2018 remained low in absolute terms (113), despite a significant percentage variation for 2016 – 2018 (169%).

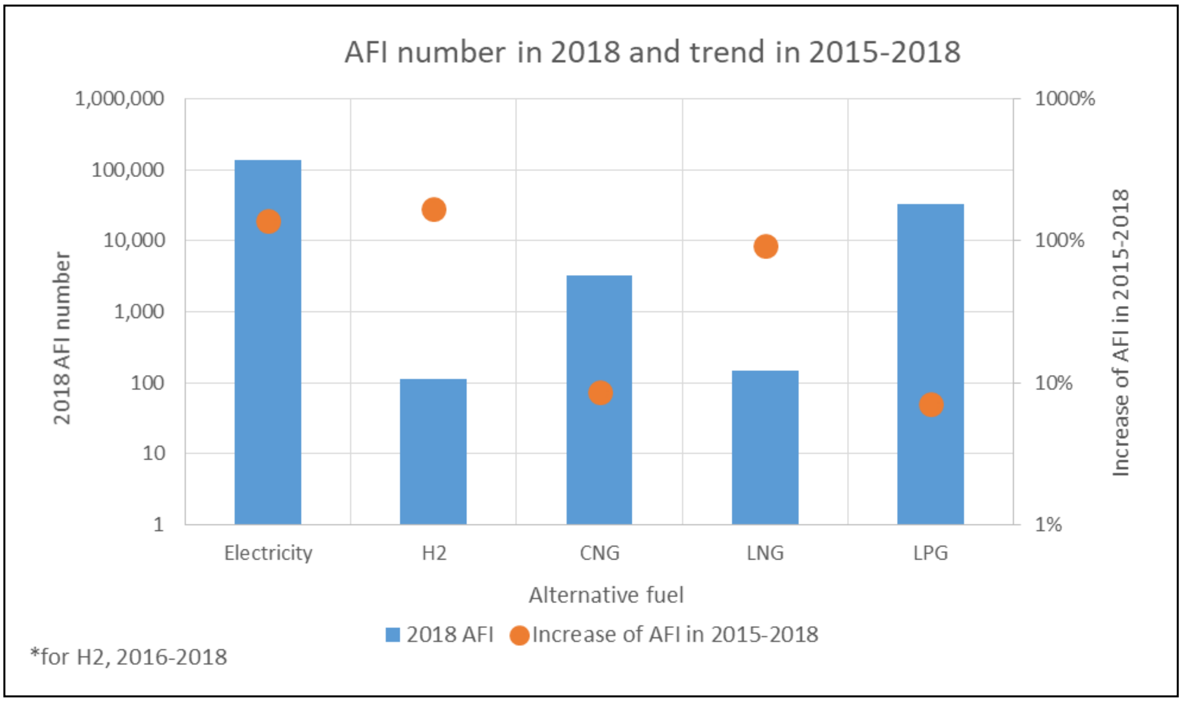


**Figure 6-15. Alternative fuel recharging / refuelling stations in the EU**
**Source: own work based on (EAFO, 2019)**

High bioethanol blends (E85, E100 and ED95) require dedicated infrastructure, whereas low blends (e.g. E5, E10) do not. In 2015, the leader in E85 refuelling infrastructure was Sweden that had more than 1,700 refuelling points. This was more than the following top 4 MSs together (France, Hungary, Germany and Czechia) (ePURE, 2019). During the period 2015-2018, the number of E85 refuelling points decreased by 6.7% in Sweden (SPBI, 2019), while it increased by 52.1% in France (SNPAA, 2019).

Concerning CNG road refuelling infrastructure at EU level, there were 3,218 points available in 2018 (of which around 65% situated in Italy and Germany) (EAFO, 2019). The period 2014 – 2018 presented a CNG infrastructure increase of 8.5%. Regarding LNG road infrastructure, only 146 refuelling stations existed in 2018, but the increase during the period 2015 – 2018 was quite significant and overpassed 92%, due especially to the developments in the top 5 MSs (Spain, Italy, Netherlands, France and UK).

In road transport, the LPG refuelling infrastructure is well developed in the EU and consisted of 33,346 points at the end of 2018 (EAFO, 2019), with the highest number being situated in Poland, Germany, Italy, Bulgaria and France. During the period 2015 – 2018, the increase of LPG refuelling point's number was of 7.1%.

Having very similar properties to their fossil fuels counterparts, the paraffinic fuels can be used neat or blended in existing refuelling infrastructure (e.g. the transport and distribution of DME could use the existing LPG infrastructure with some modifications, GTL is blended with diesel by the fuel suppliers and sold in the refuelling stations as diesel).

#### 6.2.2.2 INFRASTRUCTURE COSTS

The cost for an AFI depends on many parameters including site, power level or capacity, and AF access. Total costs found in the literature for different types of AF infrastructure have been described in **Chapter 5, p. 113**. Since in some cases, several cost sources were identified but not all the parameters were given, the costs show different levels of variation. It should also be considered that actual infrastructure costs can vary substantially depending on site-specific factors. An overview of the main costs estimates from literature referred to in **Chapter 5** is presented below; these estimates are not always directly comparable, since they do not all include the same cost components, and they are based on different assumptions (e.g. on number of refuelling/recharging points installed in a given site). However, they can provide a general indication of the likely cost ranges for different technologies.

**Table 6-1. Road recharging/refuelling infrastructure deployment costs**
**Source: own work based on several sources (see details in Chapter 5, p. 113)**

| Fuel | Estimated costs |
|---|---|
| Electricity – normal (up to 22kW) | Different estimated total costs (including administrative, installation, and siting costs) per normal power (Level 2) recharging point range between €3,000 and €14,000. |
| Electricity – fast (50 kW) | Estimated total costs per 50 kW DC high power recharging point range between €20,000 and €52,000, depending on the type of charging station (including its networking capabilities) and the setting (urban versus rural, mounted on walls or on posts). |
| Electricity – ultra-fast (150kW and more) | Estimated costs of around €75,000 - €150,000 for a 150 kW DC high power recharging point and €575,000 for a 350 kW recharging point have been reported; however, actual costs can vary significantly depending on several elements. |
| Hydrogen | Reported costs of a hydrogen refuelling station range between €600,000 and €2,700,000, depending on factors including scale/capacity and the hydrogen distribution and storage mechanisms. |
| CNG | Reported costs of a CNG filling station can vary between €100,000 and €500,000, depending on type and capacity. Substantial additional costs might derive from the need to connect to the gas network (€300,000-600,000 per km). |
| LNG | The LNG Blue Corridors project (LNG-BC, 2016) reported a total capital cost for LNG stations ranging between €500,000 and €1,150,000, depending on various factors including whether the station also provides CNG. |
| Biofuels | Reported cost of €100,000 for an E85 refuelling station, €200,000 for a bioDME refuelling station. ED95 costs comparable to an equivalent diesel refuelling station. |

In the case of the recharging infrastructure for the last years, the cost of the hardware part decreased substantially due to technological innovation and larger production scale while the costs related to installation, land procurement, administration, and maintenance tended to remain constant. In the case of hydrogen refuelling stations, the cost remains quite high but it is expected to decrease in the future (Hydrogen Europe, 2018).

## 6.3 GREENHOUSE GAS EMISSIONS AND ENERGY EFFICIENCY

The GHG emissions presented in the report are based on the Well-to-Wheel report (JEC, 2019); the main reason for this choice is that, when compared to other sources, it implements an up-to-date picture of the sector, in a comprehensive way. **Chapter 4 (p. 19)** deals with the production phase of the fuels: the Well-to-Tank (WTT) Greenhouse Gas emissions and the energy efficiency for different fuel and production pathways are presented thoroughly. A summary of the Well-to-Wheel (WTW) GHG and energy efficiency for the most representative production pathways is presented here; this allows for a better comparison among the different fuels. It may worth reminding that WTW values are obtained by summing WTT (production of the fuel) and Tank-to Wheel (TTW) (use of the fuel); the resulting WTW values are therefore dependent on the characteristics of the vehicle used.

In the present study, a generic C-segment vehicle has been chosen as the representative of EU market passenger car (PC) and its performance has been estimated through simulated Worldwide Harmonised Light duty Test Procedure (WLTP) cycle. For the sake of consistency, the powertrain performances have been selected from (JEC, 2019). The fuels considered for the comparison have been chosen according to the powertrain, namely DISI: Direct Injection Spark Ignition, DICI: Direct Injection Compression Ignition, PHEV: Plug-In Hybrid Electric Vehicle, BEV: Battery Electric Vehicle and FCEV: Fuel Cell Electric Vehicle. More fuel production pathways and more vehicle options are available in (JEC, 2019).

**Figure 6-16** and **Figure 6-17** present the range of the WTW GHG emissions for different fuels (blue lines) in 2015 and 2025+ scenario, respectively. For each fuel, a specific production pathway has been selected as representative of the current production and its WTW GHG emissions is represented with a pink marker. The pathways selected are in line with (JEC, 2019), where detailed explanation of the choice are reported. The code of the production pathway can be found in the graph, and an explanation of the pathway is available in the footnotes.

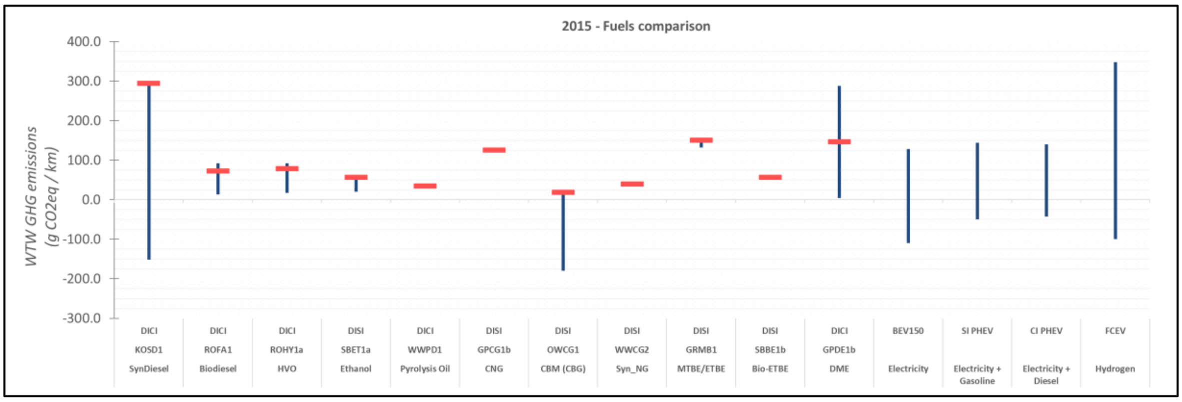


**Figure 6-16. 2015 WTW GHG emissions for different fuels[68]**
**Source: own work based on (JEC, 2019)**

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[68] **KOSD1:** EU-mix hard coal to Syndiesel.

**ROFA1:** Rapeseed to biodiesel (Rapeseed Methylester), Meal export (animal feed), Glycerine export to chemical.

**ROHY1a:** Rapeseed, meal export to animal feed, NexBTL process.

**SBET1a:** EU sugar beet to ethanol. Pulp to animal feed. Slops not used.

**WWPD1:** Waste wood to pyrolysis diesel.

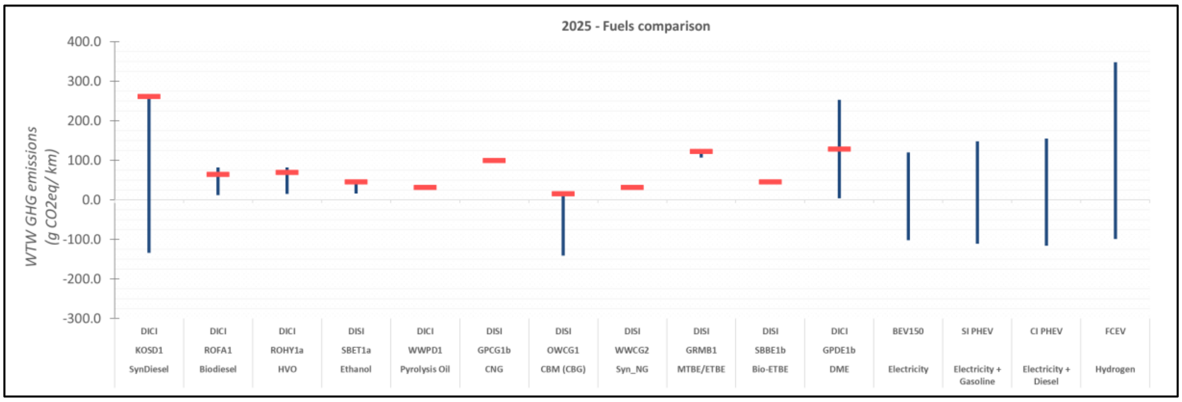


**Figure 6-17. 2025+ estimations of WTW GHG emissions for different fuels**
**Source: own work based on (JEC, 2019)**

It is worth noticing that electricity and hydrogen are not primary energy sources, but energy carriers. Environmental performances of fuel pathways based on electricity, either used as final fuel or as energy vector, are defined by the primary source for its production. More precisely, the use of electrical energy in the transport sector is, in terms of GHG emissions saving, mainly affected by the pathway considered for power production. This is properly shown in **Figure 6-18**: when power for car is taken from the grid, this can lead to an increase in emissions, if the system reaction to this increased demand is increasing production from fossil source (e.g. Natural Gas). This issue is country specific and time specific (as production is a non-steady process by definition), and it does not allow to define an average WTT, and consequently WTW values. On the other end, a relevant uptake of electrical energy for road sector may act as a driver for increasing the share of renewable energies in the EU mix. It is worth remarking that electricity should be considered as an energy carrier, and not a source, as well as hydrogen. Hydrogen production, as well as e-fuels, is based on electricity, therefore the above-mentioned net consideration can be extended to these cases. From a mere GHG reduction perspective, the use of hydrogen fuel cells may not lead to any advantages, if the electricity used is not from carbon neutral source. All this considered, for electricity, hydrogen and e-fuels, it is not possible to define a representative case - as done for the other alternative fuels - as today all the values represent possible cases. As an attempt to specify some possibilities, **Figure 6-18** presents the WTW emissions of some characteristic pathways for hydrogen and electricity.

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**GPCG1b:** Natural gas from Russia, transport to EU by pipeline from Middle East (4000 km), distribution through gas high-pressure trunk lines and low pressure grid, compression to CNG at retail point.

**OWCG1:** Upgraded biogas from municipal organic waste as CBG. Closed digestate storage.

**WWCG2:** Synthetic methane (as CNG) via gasification of waste wood and methanation.

**GRMB1:** Typical large-scale plant. MTBE is synthesised from isobutene and methanol.

**SBBE1b:** Bio-ETBE from sugar beet.

**GPDE1b:** Piped natural gas (4000 km) to DME, synthesis plant in EU.

**GPCH1b:** Natural gas from Russia, transport to EU by pipeline from Middle East (4000 km), distribution through high-pressure trunk lines, distribution in low pressure grid, small scale reformer at retail station, compression to 88 MPa.

Negative emissions are for SynDiesel from wood residue with CCS; CBM from manure (closed digestate storage); electricity from manure (closed digestate storage); hydrogen from biogas SMR.

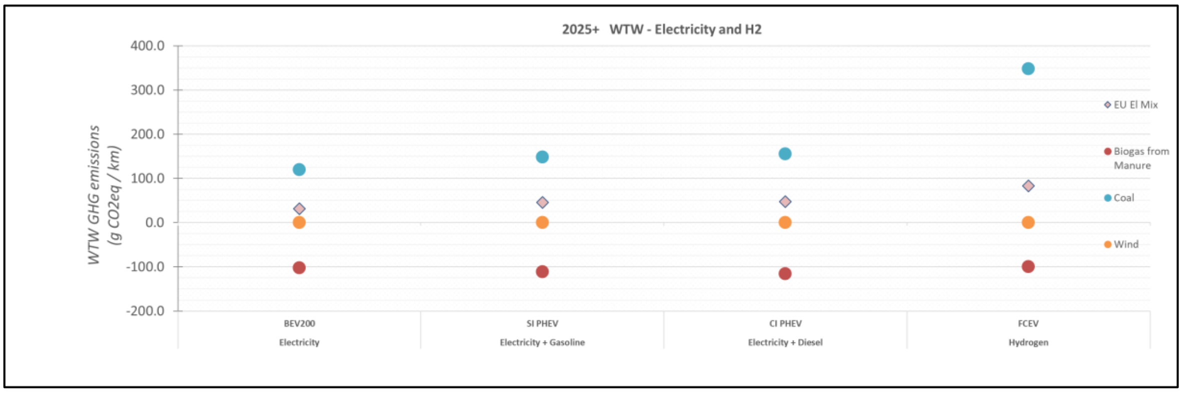


**Figure 6-18. 2025+ estimations of WTW GHG emissions for electricity and hydrogen**

**Figure 6-19** and **Figure 6-20** present the WTW energy efficiency for different fuels in 2015 and 2025, respectively. As described above, a representative production pathway has been identified for each fuel (shown with a blue marker) and the range of the energy expended is shown with a green bar. Electricity presents the highest WTW energy efficiency and this trend seems to be even more intense in the midterm future (2025+).

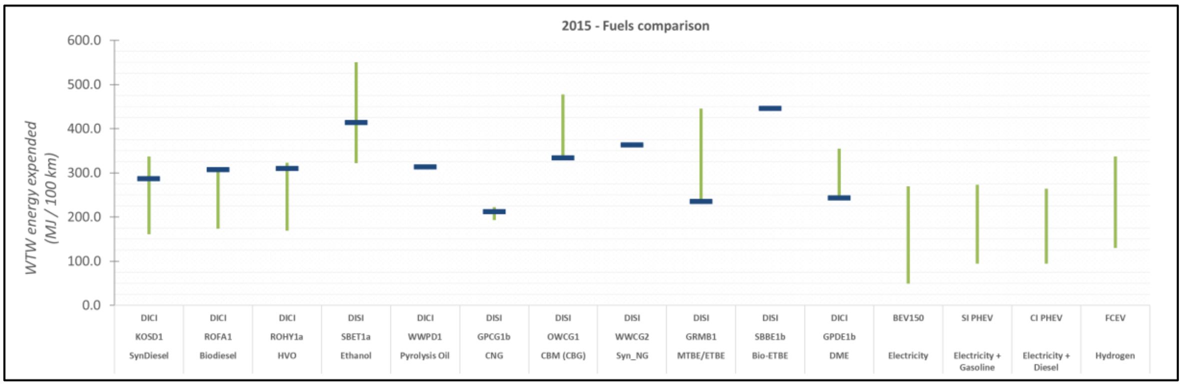


**Figure 6-19. 2015 estimations of the energy efficiency for different fuels**
**Source: own work based on (JEC, 2019)**

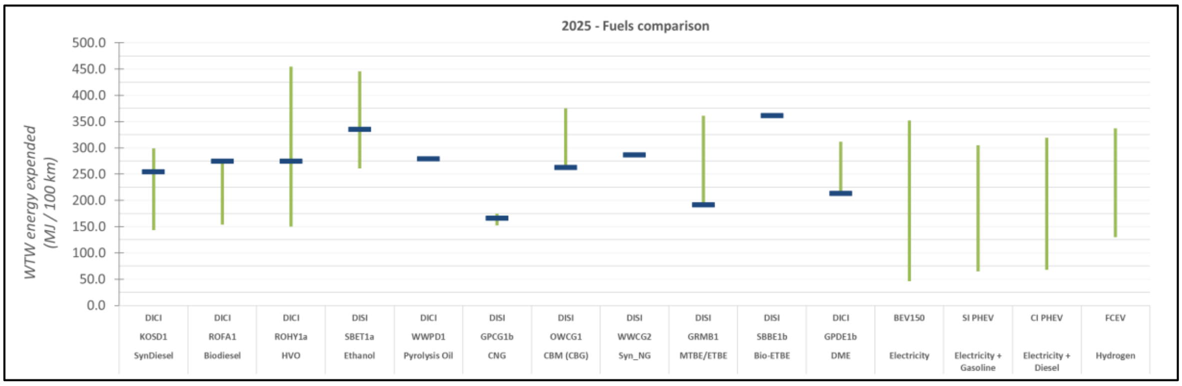


**Figure 6-20. 2025+ estimations of the energy efficiency for different fuels**
**Source: own work based on (JEC, 2019)**

### 6.4 THE STATUS IN 2019

Today, the low development of alternative fuel infrastructures for renewable and non-renewable alternative fuels in EU makes it impossible to travel across EU without oil-based fuels, to the exception of the railway mode. This fact not only does not allow reducing the EU oil dependence and GHG emissions but also threatens the EU competitiveness and the leadership position of the EU car industry in the world. The following facts and figures may help appreciate the impact of the current lack of a market for alternative fuels:

- In 2017, the EU transport depended on oil and oil products for about 94% of energy needs. Oil was imported in 2017 at a high rate, 86.7% with a growing trend, from few regions, giving rise to concerns on security of supply.
- The combustion of oil has also caused the increase of $CO_2$ emissions from transport, by more than 28% since 1990.
- The European economy is strongly affected by the high costs of the oil imports (in 2017 it was estimated at €180.8 billion).
- The European automotive industry is a key sector for the European economy, providing over 12 million jobs and a very positive contribution to the trade balance, which is essential for continued European prosperity. However, environmental and climate-related policies, together with the need to ensure security of energy supply, impose the production of more efficient and less pollutant vehicles, which could be achieved by alternatively fuelled powered vehicles. Therefore, the current prominent position of the EU industry in the automotive sector can only be kept if industry proves able to tackle this challenge successfully. Should the EU fail, the place of the European companies will be taken over by car manufactures from third countries.

On top of building up of a sufficient and interoperable infrastructure, the main barriers for the market uptake of alternative fuels transport systems are:

- **Electric transport systems** have the advantage of presenting higher energy efficiency than internal combustion engines. However, the low energy density and high cost of batteries are still a significant barrier for a broad market introduction of electric heavy-duty vehicles and vessels and to a lesser extent for passenger cars. Almost 1.2 million of electric vehicles (BEV and PHEV) are circulating in the EU; however, there are important differences in the evolution of the passenger cars markets across Member States. Some Western Member States, such as The Netherlands, Germany, France and Sweden, have seen a fast take up of this technology, while in several other Member States the number of electric vehicles registered are still in an early phase. On the other hand, major announcements by OEM suggest a significant increase in the electric vehicles that will be on the market over the next 3-4 years. As regards electric vessels for inland navigation, the market is at a very early stage. The existing infrastructure remains insufficient to ensure smooth mobility with electric vehicles and vessels across the EU. In relation to the overall economic performance of the technology, the relatively high cost of electricity in public fast and ultra-fast charging points can result in lower advantages compared to home-charging. Action should be taken to make sure that battery technology continue to improve and shorter charging times be achieved.
- **Hydrogen powered fuel cell transport systems** can provide longer ranges than battery electric vehicles. Refuelling times are short and comparable to those of the present internal combustion engines transport systems. The main drawbacks of hydrogen powered transport systems are their high cost, mainly due to expensive fuel cells, and the lower tank-to-wheel efficiency in

comparison to battery electric vehicles (approximately 53% vs 78%). The current availability of vehicles represents another significant important limiting factor. Hydrogen also requires the construction of refuelling infrastructure. The actual cost of building a station varies considerably across countries, mainly because of different safety and permitting requirements. The need to use hydrogen with a high degree of purity to avoid damaging to fuel cells makes this fuel expensive in comparison with other alternative fuels. Nonetheless, the cost is a variable that hugely depends on economies of scale[69] and market uptake. Therefore a greater use of hydrogen technologies throughout the entire value chain (energy production and storage, industry usage etc.), together with possible research-driven advances in technology, could in the future lower the cost for hydrogen technologies in transport. As regards the market of FCH vehicles and vessels, it is at a very early stage in all modes of transport and sectors. Only FCH buses have started today to entry the market in some European cities, while only four car models and one LCV model are currently available in the EU; no HFC trucks or coaches are yet available on the EU market.

- **Biofuels** could technically substitute oil in all transport modes, using the existing power train technologies and refuelling infrastructure up to certain limits in concentration (higher blends, to the exception of HVO blends, require some adaptations of engine design and existing infrastructure). However, the finite resources and sustainability considerations limit the potential production of biofuels. Besides their compatibility with existing vehicles and infrastructure, the main advantage of liquid biofuels is their high energy density. As regards aviation, low and high blends up to 50% are certified, and higher blends (up to 100%) have been successfully trialled. In addition to the limited feedstock availability, another main barrier is the cost of the production of advanced biofuels. The impacts of these barriers on the aviation sector could be mitigated over time, if feedstock such as waste and residues are better directed towards advanced jet biofuel production. Policy measures would also need to better drive the establishment of a market at EU scale including with competition between a diversity of players driving the costs down over time. A very limited market for ED95 and E85 vehicles currently exists in Sweden and Finland with some minor development in other Member States such as France.

- **Methane** can be sourced from fossil natural gas or from biomass and wastes as biomethane, and can be injected into the general gas grid. Methane in liquefied form as LNG is an attractive option for trucks and ships due to its high energy density and low sulphur emissions. The technology is mature for vehicles and to a lesser extent for vessels. Nevertheless, the contribution of fossil natural gas vehicles to the decarbonisation of transport is limited, as they only offer limited emission reductions compared to petrol and diesel. A high use of biomethane could lead to further reductions, but it is not clear how much biomethane would be available for the transport sector in the long term, given limited available feedstock and strong expected competing demands from other sectors such as heating and industry. The number of CNG vehicles in the EU is approximately 1.2 million of vehicles; however, the new CNG registered passenger cars in EU is declining. On the other hand, the number of LNG is expected to reach the figure of 10,000 trucks in 2019.

[69] In the case of Hydrogen refuelling stations, increasing the capacity from 50 to 500 $kgH_2$/day would be likely to reduce the specific cost (i.e. the capital cost per kg of hydrogen dispensed) by 75% (IEA, 2019). Larger capacity stations of up to a few 1000 $kgH_2$/day are being planned, especially for heavy-duty applications, and these offer potential for further economies of scale. There is also potential for costs to be reduced through a shift to more advanced supply options (such as very high-pressure or liquid hydrogen) and through scale-up in the manufacturing of refuelling station products (via mass production of components, such as the compressors).

- **E-fuels (e-liquids and e-gas)** are not currently available on the market; they would have the potential to deliver important benefits in terms of GHG emission reductions (but not in terms of pollution) compared to fossil fuels, but only if they are produced from renewable electricity; when non-renewable electricity is used, this leads to substantially higher emissions compared to petrol and diesel. No dedicated infrastructure is necessary for fully fungible synthetic fuels, i.e. those whose characteristics are the same as conventional fuels. The main barrier is the very low efficiency of the production process, leading to high production cost and high intensity of energy to be used. The technology for the production of e-fuels is not yet commercially mature.

  Synthetic and paraffinic fuels substituting diesel and jet fuel, can be produced from different feedstocks, principally converting biomass, but also fossil sources such as natural gas and plastic wastes into paraffinic liquid fuel. Synthetic paraffinic diesel fuels are fungible and can be blended into fossil diesel fuel at very high blends and they can be used in all existing or future diesel vehicles. These fuels can also be distributed, stored and used with the existing infrastructure. The $CO_2$ emission reduction potential of such fuels depends on the GHGi of the primary feedstock.

  Synthetic fuels such as methanol and ammonia can be used as fuels for ships although their usage remains negligible, especially for ammonia. The use of methanol in ships can reduce emissions of sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM). Ammonia can also be seen as having favourable properties for use as a transport fuel, namely good storage properties and its mature production and distribution infrastructure. The use of ammonia as fuel can also reduce $CO_2$, SOx, NOx, and PM from ships. However, the sustainability of ammonia is questionable due to its environmental impact from conventional production technology, and the need for a secondary hydrocarbon fuel to promote combustion when used in internal combustion engines. Also, safety concerns exist with the use of ammonia fuels.

- **LPG** (Liquefied Petroleum Gas) is a by-product of the hydrocarbon fuel chain, currently resulting from crude oil and natural gas. Bio-LPG is already in production and being sold in the EU albeit in low volumes. LPG is currently the most widely used alternative fuel, with the most mature market; infrastructure is well developed with a significant number of filling stations already present in the EU. However, this infrastructure is unevenly available in some Member States. The contribution of LPG transport systems to the decarbonisation of transport is limited and could only be increased through a high use of bio-LPG; the potential production of bio-LPG is however extremely limited. Approximately 8 million of LPG vehicles are registered in the EU and the number of refuelling stations is approximately 33,000.

### 6.5 OVERVIEW OF THE ALTERNATIVE FUELS TRANSPORT SYSTEM IN THE EU

A synthetic overview of the market uptake of the alternative fuels transport systems and the relevant infrastructure for road, water and air transport is presented in **Table 6-2**,

Table 6-3 and **Table 6-4**, respectively. As the situation is in continuous evolution and new data are being published at the time of writing, there are a few differences for the vehicle stock between these tables (which are including information up to the first semester of 2019) and **Chapter 5 (p. 113)** (which is mostly based on the situation at the end of 2018).

**Table 6-2. Road transport overview**

| **Road** | **Electricity (full BEV)** | **Hydrogen** | **Liquid biofuels** | **Natural gas & bio-methane (LNG, CNG)** | **E-fuels & e-gas** | **LPG & bio-LPG** |
|---|---|---|---|---|---|---|
| **Market readiness: vehicles on the road (EU)** | Approx. 600,000 cars (plus 600,000 plug-in hybrids),<br><br>90,000 vans,<br><br>1,800 buses;<br><br>trucks and coaches at pilot phase | Approx. 800 cars,<br><br>300 vans,<br><br>100 buses;<br><br>trucks and coaches at pilot phase | Low blends used in most vehicles with no or limited modification.<br><br>Up to 10,000 buses using high-blends. | Approx. 1.2 million cars, 130,000 vans, 20,000 buses/coaches and 24,000 trucks (19,000 CNG and 5,000 LNG) | Not currently on the market, but use is possible in most existing vehicles with limited or no modification | Approx. 8 million LPG vehicles on the EU market. Less than 500 LPG buses |
| **Market readiness: fuel and refuelling / charging infrastructure** | Infrastructure adequate for now, but not sufficient to cover expected expansion (at the end of 2018, approx. 140,000 recharging points, incl. 15,000 fast recharging points) | Infrastructure limited but sufficient for existing fleet (at the end of 2018, there were 113 refuelling stations available in EU Member States, of which 59 in Germany). | Currently low production volume; could however be scaled up in the next decade<br><br>Can use existing infrastructure for diesel/petrol. | Infrastructure broadly available: "(at the end of 2018, approx. 3200 CNG refuelling points - especially in IT, DE, SE, CZ, NL - and approx. 150 LNG refuelling points - especially in ES, IT, NL,FR, UK). | Hardly any production volume currently.<br><br>Scaling up would require significant technology development and investment.<br><br>Can use existing infrastructure. | Infrastructure broadly available. (at the end of 2018, approx. 33,000 LPG refuelling points - especially in PL, DE, IT, BG, FR). |

| | | | | | | |
|---|---|---|---|---|---|---|
| **GHG emissions reductions (tailpipe)** | Zero emission | Zero emission | Comparable to diesel/petrol | CNG: almost 22% compared to petrol and almost 8% in relation to diesel[70]. | Comparable to diesel/petrol | Approximately 9% lower than petrol; 8% higher than diesel |
| **GHG emissions (well-to-wheel)**<br><br>**$gCO_{2eq}$/km[71],[72]** | BEV<br><br>50 for current EU-mix[73], 0 if only additional renewable (wind) electricity is used | FCEV<br><br>122 for electrolysis with current EU-mix, 79 for methane reforming, and 7 if only additional renewable (wind) electricity is used for electrolysis | Range: from 14 (FAME from waste feedstock) to 92 (HVO from palm oil without methane capture) | Range: from -179 (CBG from manure feedstock with methane capture) to 126 (CNG from imported natural gas) | Substantially higher emissions than diesel/petrol with current energy mix(more than 300); potentially lower (2-4) with future technological improvements and using only additional renewable electricity | Fossil LPG: 147; for bio-LPG: general trend of GHG emissions will follow the GHGi of the vegetable oil used (waste or new oil) |
| **Energy efficiency (WTW energy expended**<br><br>**(MJ / 100 km from JEC, 2019)** | BEV<br><br>135 for current EU-mix, 49 if only additional renewable (wind) electricity is used | FCEV<br><br>328 for electrolysis with current EU-mix, 141 for methane reforming, and 130 if only | Range: from 169 (HVO from waste feedstock) to 550 (second gen ethanol using waste wood) | Range: from 193 (CNG from EU shale gas) to 477 (CBG from manure with methane capture) | Very low overall efficiencies (over 300), although it can in theory use energy which may otherwise be wasted | Fossil LPG: 197; for bio-LPG: NA |

[70] The figures provided are referring to passenger cars; for trucks, values may differ. For example for HPDI trucks using NG the reduction might reach up to 20% according to the LNG Blue Corridors project. It should also be considered that potential leakages from the vehicle operation may lead to higher GHG emissions due to the significant GHG potential of $CH_4$.

[71] Figures from JEC 2019 except for e-fuels and e-gas, where figures from (Moro & Lonza, 2017), calculated using (Cerulogy, 2017) guide, have been used for production using the current energy mix. This is because JEC only provides two estimates of energy efficiency for e-fuels, and both assume the use of renewable electricity only.

[72] Please note that the GHGi reported in Council Directive (EU) 2015/652 expressed per kilometre are 162 g CO2 eq/km for gasoline and 138 g CO2 eq/km for diesel.

[73] Please see **Chapter 4 (p. 19)** as GHG intensity for electricity varies significantly by MS.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | additional renewable (wind) electricity is used for electrolysis | | | | |
| **Scalability, limitations and opportunities** | A high share of road transport electrification is possible with marginal increases in electricity generation, provided smart charging solutions are deployed. | High share of hydrogen in road transport would require expansion of electricity generation due to its relatively low efficiency of production.<br><br>Rollout of infrastructure needed. | Depends on availability of sustainable feedstock and potential indirect land use change (ILUC) impact. Competition for limited resources with other modes (aviation). | Natural gas: scalable, but would bring limited emission reductions. Biomethane: potential production limited, and facing competing uses (heating, industry) and competing demand from other modes. | High share of e-fuels or e-gas in road transport would require a substantial expansion of electricity generation due to their low efficiency of production. | LPG production is scalable, but would not bring significant emission reductions. Very limited production of bio-LPG in the EU. |

**Table 6-3. Waterborne transport overview**

| **Waterborne** | **Electricity** | **Hydrogen** | **Liquid biofuels** | **Natural gas & biomethane (LNG, CNG)** | **E-fuels & e-gas** | **LPG & bio-LPG** |
|---|---|---|---|---|---|---|
| **Market readiness: number of vessels in use (EU 2019)** | Growing number of electric and hybrid ferries for inland local transport on relatively short journeys;<br><br>on-going pilots of few battery swapping electric inland ship. In maritime, electricity is only used for auxiliary power or in hybrid operation. | Technology under development (pilot/demonstration projects) but not currently in commercial operation. Few pilot projects on FCH inland vessels | Very limited use in low blends has been reported.<br><br>Engine technology similar to current standards. | Less than 20 LNG vessels in use in EU inland waterways; approximately 250 confirmed LNG fuelled ships, and 110 additional maritime LNG vessels in the world, mostly operating in the EU and / or Norway. | Very limited use reported.<br><br>Engine technology similar to current standards. | LPG is presently not considered a sufficiently attractive option for this mode of transport. |
| **Market readiness: fuel and infrastructure** | Pilot projects underway in inland navigation.<br><br>Scarce charging infrastructure; OPS in ports is mainly used as an alternative to generators and not necessarily to charge batteries. | No refuelling infrastructure currently available. For the moment, pilot projects focussed on inland waterways and short sea shipping.<br><br>Size of fuel cells not yet delivering power requirements required for maritime | Infrastructure in practice the same as the existing one for conventional fuels. | There are 85 large-scale operational LNG tanks installed in 35 EU ports | Infrastructure in practice the same as the existing one for conventional fuels. | N/A; LPG is presently not considered a sufficiently attractive option for this mode of transport. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | transport. | | | | |
| **GHG emissions reductions (tailpipe)** | Zero emission | Zero emission | Emissions comparable to current fuels | 20% (compared to MDO) in a zero methane slip scenario, and -10% with CH slip (data from EMSA LNG bunkering guidelines) | Emissions comparable to current fuels | N/A; LPG is presently not considered a sufficiently attractive option for this mode of transport |
| **GHG emissions reductions (well-to-wake)** | Significant reductions with current energy mix, up to 100% reduction with renewable electricity | Significant reductions with current energy mix, up to 100% reduction with renewable electricity | Reductions will depend on production pathway | Natural gas: minimal to no reduction; bio-methane: up to WTW100% reduction (depending on production pathway) | Reductions will depend on production pathway | N/A; LPG is presently not considered a sufficiently attractive option for this mode of transport |
| **Scalability, limitations and opportunities** | Attractive solution for inland waterways. Potential limited to short-distance operations and short-sea shipping in general, due to the energy density required in maritime transport. | High share of hydrogen to meet the energy needs on both maritime and inland waterways require substantial expansion of electricity generation. | Depends on availability of sustainable feedstock and potential indirect land use change (ILUC) impact. Competition for limited resources with other modes (aviation). | Natural gas: scalable, but would bring limited emission reductions. Biomethane: potential production limited, and facing competing uses (heating, industry) and competing demand from other modes. | High share of e-fuels or e-gas in waterborne transport would require a substantial expansion of electricity generation due to their low efficiency of production. | No significant growth foreseen in LPG waterborne vessels. |

**Table 6-4. Air transport overview**

| Aviation | Electricity | Hydrogen | Liquid biofuels | Natural gas & biomethane (LNG, CNG) | E-fuels & e-gas | LPG & bio-LPG |
|---|---|---|---|---|---|---|
| **Market readiness: airplanes** | No commercial aircraft in operation; not expected to play a significant role in the near future. Prototype/pilot small non-commercial aircraft under development | No commercial aircraft in operation; not expected to play a significant role in the near future. Prototype/pilot small non-commercial aircraft under development | More than 200,000 commercial flights operated on biofuels have been made as of June 2019, including on 100% biofuels. Growing interest of airlines for Sustainable Aviation Fuels. | N/A | Limited commercial production, but growing interest in the development electrofuels, which would be compatible with current airplane engines. | N/A |
| **Market readiness: fuel and infrastructure** | N/A | N/A | 6 pathways certified. Biofuels are compatible with current aircraft engines. But current production volumes are limited; existing infrastructure can be used with limited/no modification. | N/A | 1 pathway certified, compatible with current airplane engines. Production capacity currently only is lab scale, and such fuels are not expected to become available in larger scale prior to 2025. | N/A |
| **GHG emission savings (well-to-wake)** | N/A | N/A | Emission savings up to 80% in the case of waste-based advanced biofuels. | N/A | Expected emission reductions of up to 80% depending on technology development and use of renewable energy. | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Scalability, limitations and opportunities** | N/A | N/A | Current estimates suggest that future expanded biofuels production could amount to up to 5-10% of aviation fuel (this would require prioritisation of resources to this transport mode). Price is currently a limitation (can be 2 to 3 times more expensive than conventional jet fuel). | N/A | Price is currently a limitation (3 to 5 times more expensive than conventional jet fuel). A high share of e-fuels or e-gas in waterborne transport would require a substantial expansion of electricity generation due to their low efficiency of production. | |

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## 6.7 APPENDIX TO CHAPTER 6

### 6.7.1 SOURCES OF INFORMATION

Information used to derive **Figure 6-5** and **Figure 6-6** is shown in **Table 6-5**.

**Table 6-5. Sources of information to derive market status**
***S&P means synthetic and paraffinic**
**Source: own work**

| | Air | Maritime | IWWs | Rail | Cars | Buses | LCVs | HCVs |
|---|---|---|---|---|---|---|---|---|
| Biofuels | (IATA, 2019) | (EC, 2018c) | (EC, 2018c)/ Survey | (EC, 2018c) | (EEA, 2018a) | (ZeEUS, 2016) | (EEA, 2018b) | (Scania, 2019) |
| S&P | (EASA, 2019) | Survey | Survey | Survey | (T&E, 2017) | (Jääskeläinen, 2017) | (T&E, 2017) | (IEA, 2017a) |
| Electric | (EC, 2018c) | (DNV-GL, 2018) | Survey | (Eurostat, 2019) | (EAFO, 2019) | (EAFO, 2019) | (EAFO, 2019) | (EAFO, 2019) |
| $H_2$ | Survey | Survey | Survey | (Alstom, 2018) | (EAFO, 2019) | (EAFO, 2019) | (H2M, 2018) | (H2energy, 2017) |
| CNG | | | | | (EEA, 2018a) | (EAFO, 2019) | (EEA, 2018b) | (EAFO, 2019) |
| LNG | | (DNV-GL, 2018) | Survey | (Renfe, 2018) | | (EAFO, 2019) | | (EAFO, 2019) |
| LPG | | (DNV-GL, 2018) | | Survey | (EEA, 2018a) | (EAFO, 2019) | (EAFO, 2019) | (EAFO, 2019) |

For the creation of the left chart of **Figure 6-12**, which reflects the German market, the reported data for large cars is sourced as follows:

- the diesel and CNG cars correspond to respectively the Volkswagen Passat and the Volkswagen Golf Variant TGI (VW, 2019a);
- the range for HEV is based on the Toyota Prius HEV and Volkswagen Passat GTE (Toyota, 2019) (VW, 2019a);
- the range for PHEV reflects the values of the Toyota Prius PHEV and BMW 330e (Toyota, 2019) (BMW, 2019);
- the range for BEV is the result of the Tesla Model 3 and Model S (Tesla, 2019a) (Tesla, 2019b);
- the fuel cell value is taken from the Toyota Mirai (H2M, 2018).

With regards to LCVs, the reported data is sourced as follows:

- the range for diesel corresponds to the Volkswagen Caddy Conceptline TDI, the Renault Kangoo Rapid and the Dacia Dokker (Dacia, 2019) (Renault, 2019) (VW, 2019b);
- the LPG value is based on the Dacia Dokker (Dacia, 2019);
- the CNG LCV reflects the Volkswagen Caddy Conceptline TGI (VW, 2019b);
- the range for the electric LCV corresponds to the Renault Kangoo Z.E. and the StreetScooter E-Transporter WORK (Renault, 2019) (StreetScooter, 2019);
- the fuel cell LCV reflects the range of the Renault Kangoo Z.E. $H_2$ (H2M, 2018).

The right chart of **Figure 6-12** also draws from various sources. For buses:

- the cost of the diesel powertrain is sourced from (T&E, 2018) (which is based on (IEA, 2018));
- the cost of the electric bus is also sourced from (T&E, 2018) (based not only on (IEA, 2018) but also on (BNEF, 2018) for the battery price), with the upper values reflecting higher battery capacities;
- the cost a bus powered by bioethanol comes from (BEST, 2009);
- CNG cost data was calculated from (EMT, 2018);
- the range for the fuel cell bus is based on (FCH-JU, 2019) and (HE, 2018).

For trucks (note that the costs reported for electric and $H_2$ HCVs refer to products for which commercialisation is currently very low):

- the sources for the cost of diesel and CNG trucks are (EC, 2018a) and (IEA, 2017a);
- the cost value of a truck powered by ED95 is taken from (Stockholm, 2015);
- the range of LNG truck costs is based on (Vos, n.d.) and (UBA, 2015);
- the reported electric truck cost relates to the Tesla Semi truck (Tesla, 2019c);
- the range of costs for the hydrogen truck was estimated based on (ICCT, 2017) (Hyundai, 2018) and (Nikola, n.d.).

Press releases by Alstom were used to compute the cost of a Coradia train unit, for five variants, as shown in **Figure 6-13**. No cost data was found for the following battery electric trains: Alstom’s retrofitted Coradia Lint, Bombardier’s Talent 3, Siemens’ Desiro ML and Stadler’s FLIRT Akku.

For the creation of the left chart of **Figure 6-14**, information from (Reuters, 2018) and (SEA\LNG, 2019) was used. The HFO options reflects a conventional diesel cycle low-speed engine fitted with selective catalytic reduction. The range in values for LNG, translated into euro, reflects the two options considered by (SEA\LNG, 2019): WinGD 9X-92DF Winterthur Gas & Diesel engines and a MAN ME-GI main engine. The same authors assumed that a scrubber costs almost €7.5 million, including yard work. Based on information from (Reuters, 2018), we also calculated and reported the cost that results from assuming a lower cost for the scrubber: €4 million. To create the right chart of **Figure 6-14**, the data reported by (EMSA, 2015) was used.

# 7 PROMOTING ALTERNATIVE FUELS IN THE EU: ASSESSMENT OF RESULTS

The European Green Deal[74] sets the overall ambition of transforming the EU into a fair and prosperous society, with a modern, competitive economy, where there are no net-emissions of greenhouse gases in 2050, a decoupling of economic growth from resource use and a preservation of natural capital. Against this backdrop, the Green Deal notes that the transport sector has to decrease its emissions by 90% by 2050. Road, rail, aviation, and waterborne transport, all have to make a significant effort to decarbonise in order contribute to this transition.

In addition to significantly increasing the overall efficiency of the transport system, the production and deployment of sustainable alternative transport fuels, vehicles and infrastructure need to be ramped-up in the EU. Transport fuels themselves need to be almost completely decarbonised by 2050. The deployment of related vehicles, vessels and aircraft as well as infrastructure and services needs to happen everywhere in the EU, in an interoperable manner. Use of sustainable alternative fuels (incl. electricity) needs to accelerate quickly in all transport modes. This would help to deliver the necessary significant reduction in greenhouse gas emissions and in most cases of air pollutant emissions and even noise pollution.

We need all sustainable alternative fuels, each to be used according to its potential environmental benefits and to the specific needs of the different transport modes. Some modes, like aviation and deep-sea shipping, have limited alternatives to decarbonise. They critically depend on advanced biofuels and e-fuels (aviation) or high blends of biogas/e-gas (deep-sea shipping). The issue of prioritisation of certain fuels for those transport modes that need them most could therefore demand further consideration.

Given the various modes' needs, we also need a systemic overview of fuel availability (currently and in the future), taking into account existing and future limitations of production of some fuels (biofuels and biogas, due to feedstock limits) and the demand from other sectors, e.g. from heating and industry. It is already clear that there has to be a drastic increase in the production of advanced sustainable biofuels, biogas and hydrogen from renewable resources, in addition to continuing the transition towards electricity from renewable resources.

**Chapter 6 (p. 244)** of this report provides a comprehensive overview of the current degree of market readiness of the different alternative fuels, the opportunities for scaling up, the technical and market uncertainties as well as the costs of the relevant transport systems and infrastructure. It shows that an accelerated push for the development of sustainable alternative fuels, low and zero emission powertrain technologies and infrastructure in all modes of transport is needed in order to contribute to the required emission reductions.

**Chapter 6** builds on the scenarios in the long-term climate strategy (LTS) of the Commission[75]. These scenarios project the following developments of alternative fuels use in the different transport modes, with a view to reaching a climate-neutral economy by 2050:

- *Road (light-duty vehicles):* strong push for zero and low emission vehicles; in the LTS scenarios, battery electric and fuel cell powertrains reach 96% of market share in passenger cars and 92% in light commercial vehicles; this transition must be accompanied and accelerated. Further electrification of the

[74] COM/2019/640 final

[75] COM/2018/773 final

transport sector should go hand in hand with the progressive decarbonisation of the power generation system and the development of a clear pathway to low-carbon hydrogen.

- *Road (heavy-duty vehicles)*: for trucks, buses and coaches, a variety of alternative fuel technologies, including electrification (battery electric, fuel cell electric, hybrids), (bio) methane fuelled vehicles and liquid biofuels will remain relevant in the short term; while sustainable advanced biofuels are also used in road transport, they should be deployed primarily in aviation, however; similarly biomethane should be deployed primarily in waterborne. There is a need to push for full electrification (battery electric, fuel cells). For buses, a strong push towards electrification is already underway and should be supported (in the LTS scenarios, 79-80% of market share being battery electric, 14% fuel cells);

- *Rail:* further electrification should be considered as the main option, depending on its economic viability, for the future. Other fuels such as hydrogen for passenger and freight rail could be considered an interesting alternative for areas where electrification of the line is not viable or possible.

- *Waterborne:* measures are needed to significantly accelerate the shift towards liquefied natural gas, and to ensure that this is increasingly decarbonised by higher blends of biomethane - giving priority to waterborne for the access to this limited resource - and e-gas. For inland navigation and short-sea shipping, electrification will need to play a role and should be supported, also in view of further cost reduction. In the longer term, hydrogen can also support the decarbonisation of the inland waterways sector and short sea shipping, but also the deep sea shipping. Applications for smaller inland navigation vessels are already tested, and there is potential for larger ships (>1 MW power);

- *Aviation:* the sector needs to blend jet fuels with sustainable aviation fuels to increasing extent, including both advanced biofuels (bio-kerosene) and e-fuels. Given the lack of fuel alternatives, deployment of these fuels in the aviation sector needs to be prioritised. The environmental benefits of e-fuels (and e-gas) depend on the source of electricity or carbon capture. Hence they should either be produced from carbon-free electricity or linked to carbon capture. In the longer term, low-carbon hydrogen could also play a role as a base fuel for aviation depending on technological progress; support to R&I for the development of zero emission options is required.

## 7.1 POLICY ISSUES IN EACH MODE OF TRANSPORT

### 7.1.1 ROAD TRANSPORT

Low and zero emission cars, vans and buses are gaining market shares, but they still represent a small part of the EU fleet; those powertrains are now also entering the market of trucks for local and regional logistics. In order to ensure a timely decarbonisation of road transport, it is necessary to accelerate their deployment, with a clear pathway towards zero emission vehicles by 2050

For long-haul freight and coaches, zero emission solutions (hydrogen fuel cells and battery electric) are less advanced. For these use cases, natural gas blended with biomethane at a certain percentage and biofuels will play a role in the short term; it is however important to take into account competing demand for these fuels from other modes.

The necessary recharging and refuelling infrastructure needs to be in place to meet the growing demand from low and zero emission vehicles, both in the short and the long term. Adequate coverage and seamless customer services (including ad hoc payment and roaming options) will be necessary.

A number of actions/measures could be further explored to promote the use of low and zero emission vehicles in road transport:

- Purchase of zero emission vehicles can be accelerated by different enablers, such as reduced taxation for the registration of new vehicles or the lower circulation fees for zero emission vehicles, in line with the application of the 'polluter pays' and 'user pays' principles. Many Member States also support the purchase directly.

- The deployment of the relevant recharging/refuelling infrastructure should be considered as a priority. Requirements need to be strengthened to ensure full network coverage in the EU, but also easy use.

- Specific recharging/refuelling needs of heavy-duty vehicles should be taken into account; the needs for effective grid integration of fast charging for long-haul trucks and coaches should be analysed and addressed. Action to support safe and secure parking for trucks can provide synergies for roll out of recharging and refuelling infrastructure.

- Public authorities already experiment with new schemes of distribution of urban freight, particularly in urban agglomerations, where zero emission vans and trucks play an important role for the last mile coverage.

- As part of approaches to regulate access of urban vehicles to (parts of) cities, authorities are working with differentiating requirements for low emission zones, prioritising circulation of electric/hydrogen vehicles.

- The implementation of schemes for the transition period, such as purchase incentives, favourable taxation, and free parking (or reduced fee) for alternatively fuelled vehicles. These support schemes would reassure industry and customers in fragile start-up markets.

### 7.1.2 RAIL

Further electrification of railways could be explored taking into account its economic viability. Hydrogen could be considered an interesting alternative for passenger and freight rail in isolated areas and islands or other parts of the network that are difficult to electrify. In this respect, the possible technological developments emerging from EU joint activities on research and synergies between them (e.g. Shift2Rail and FCH JUs) should be taken into account.

### 7.1.3 WATERBORNE TRANSPORT (INLAND WATERWAYS AND MARITIME)

The deployment of low and zero emissions pathways in inland waterways has just started. Electric and hydrogen ships are being demonstrated but are limited by the higher cost of these technologies.

Given the power required in the maritime sector, the need for high-energy density fuels and the varying degree of maturity of alternative solutions, further research and innovation is necessary to establish clear pathways towards sustainable alternative low- and zero-carbon fuels (such as bio- or synthetic fuels, biomethane, e-gas, hydrogen, ammonia, etc.) possibly in combination with electrification of ships (hybridisation).

In the past years, a certain number of EU countries have already invested in developing LNG infrastructure in ports and inland waterways[76]. LNG delivers a satisfactory solution in terms of sulphur emissions and to a lesser extent as regards air pollution, but its GHG savings are limited. This infrastructure could also be used in the future for the deployment of bio-LNG or synthetic LNG from power-to-gas technologies facilitating the transition from fossil natural gas to bio and e-gas. This can represent a viable option in the short and medium terms.

Possible actions/measures which could be explored to promote the use of low and zero emissions vessels in waterborne transport could include:

- Developing a realistic roadmap for developing and deploying zero emission vessels by 2050, in both maritime and inland waterways.

- Accelerating the deployment of battery electric and hydrogen fuel cells vessels in inland waterway transport, and to a lesser extent LNG vessels.

- Accelerating the deployment of sustainable bio-LNG and e-LNG in inland waterways and maritime transport. Because of the current lack of alternatives, further reflection on prioritisation of access to these fuels for the maritime sector compared to other transport modes like the road sector, for which electrification is going to play a major role in the near future, could be explored.

- In the short term, on-shore power supply (OPS, also referred to as 'cold-ironing') represents a zero emission solution for ships at berth. The deployment of OPS infrastructure and the use of OPS by ships should therefore be an important priority enabling emission reductions, also in the short term, in both inland waterways and maritime transport. OPS can also contribute to immediate air pollution improvements in port areas.

### 7.1.4 AVIATION

For decades, the aviation sector has been reliant on the use of crude oil based kerosene to fuel aircraft. Faced with intense pressure to reduce its carbon footprint, the only alternative to crude oil for aviation in the period up to 2050 is the use of advanced biofuels and electrofuels. Technologies based on hydrogen and electrical propulsion are currently at an early stage of research and are not likely to play a meaningful role in decarbonising mid and long haul aviation in the transition pathway to 2050, also taking into account the use lifecycles of aircraft.

There are currently six production pathways that are already approved for use in aviation. Fuels from all these pathways have already been successfully used in commercial airline service or on a trial basis. However, the use of SAFs remains at this stage marginal in comparison with the total fuel demand for the sector. This is due to the current lack of effective incentives to direct sustainable fuels to air transport, compared to other sectors like road transport, which acquire the vast majority of biofuels in Europe today. The questions of availability of feedstock and green energy (wastes, renewable electricity, etc.) as well as the current high prices of sustainable aviation fuels also constitute barriers that need to be addressed in order to increase significantly the share of SAF in aviation.

[76] Directive 2014/94/EU establishes that Member States shall ensure, by means of their national policy frameworks, that an appropriate number of refuelling points for LNG are put in place in the maritime and inland ports of the TEN-T Core Network, respectively by 31 December 2025 and 31 December 2030.

Measures aimed at kick-starting the SAF market, notably with production in the EU, that could be further explored, include:

- Sustainability requirements should be aligned with the sustainability and greenhouse gas saving criteria set out in recast Renewable Energy Directive (Directive (EU) 2018/2001). Given that the objective of increasing the share of SAF is to allow aviation to continue to operate while achieving a meaningful reduction of its emissions, the sustainability criteria framing the use of SAF are of utmost importance. It is important to ensure that fuels resulting either directly or indirectly in higher overall emissions are not incentivised.

- Given the fewer alternatives at hand to decarbonise aviation compared to other modes of transport, an important reflection is necessary on the prioritisation of advanced biofuels and e-fuels in Europe.

- The establishment of requirements for SAF, e.g. through a blending obligation.

- Competition issues, and more generally the competitiveness of the aviation industry, is another important aspect to keep in mind when designing any measure aiming to increase substantially the share of SAF available in the EU market. At the same time, it would not be appropriate to bar the Member States via any measure to set a higher level of ambition than agreed at Union level. Financial support and incentives could help address this issue. Currently, the upper limit for approved SAF blending amounts to 50% of bio-kerosene content. It is necessary to increase the number of pathways that can be used, and to facilitate the certification processes for these pathways. This is relevant for liquid sustainable aviation fuels but also for other energy sources.

## 7.2 RESEARCH AND INNOVATION

As discussed in **Chapter 5 (p. 113)** and **Chapter 6 (p. 244)**, zero emission solutions are relatively developed for light-duty road transport and buses, while they are still in earlier development phases for heavy-duty trucks and very early on for use in aviation and maritime sectors. These two modes need the deployment of clean fuels in the short term, and a strong R&I effort to foster the development of zero emission solutions in the longer term.

There are clear interdependencies between the decarbonisation of the transport and energy sectors. This also applies to R&I on alternative fuel transport systems and R&I in technologies for the production of low carbon transport fuels aiming to achieve an increase in their availability as well as a reduction in costs compared to the existing ones and their effective integration into energy and transport systems.

In this respect, R&I and the building of large demonstration plants for the production of sustainable advanced biofuels to be used particularly in aviation, biomethane, e-fuels/synthetic fuels and hydrogen from carbon-neutral sources are of particular relevance as well carbon capture and storage technologies.

Road transport R&I in the short-term could include:

- development of the next generation batteries; need to improve range and decrease weight, reduce costs and improve sustainability (use of rare earth materials, recycling)

- improve fast charging capability

- reduction of the cost of the fuel cell stack and hydrogen tank for road vehicles

- improve CNG and LNG engine efficiency, develop appropriate and cost-effective after treatment systems to reduce NOx and PN and PM emissions, mitigation of methane slip/leakage from the fuelling system (short-term)

Rail R&I in the short and mid-term could include:

- development of dedicated fuel cell stacks and reduction of the cost of the fuel cell stack and hydrogen tank

- development of dedicated batteries, cost–savings

Waterborne R&I could include:

- short-term:

    - mitigation of methane slip/leakage from LNG tank and refuelling system, further reduction of LNG pollutant emissions and increase in the LNG engine efficiency
    - development of more fuel flexible engines able to switch between fuels in different sailing regions
    - cost reductions of battery electric IWW vessels through the optimisation of engine and battery sizes

- short and mid-term:

    - development of a new generation of batteries to be used in maritime and inland waterways vessels
    - development of dedicated fuel cell stacks and reduction of the cost of the fuel cell stack and hydrogen tank
    - production of biomethanol and development of dedicated engines

- in the mid and long-term, production of ammonia and development of dedicated engines.

More particularly, aviation R&I could include:

- short term - identification of possible pathways versus availability of relevant feedstock, of technology gaps, of barriers and catalyse the technology breakthroughs for sustainable aviation fuels

- long term - development of zero emission solutions through:

    - dedicated fuel cell stacks and hydrogen tanks
    - development of batteries to be used in aircraft
    - development of dedicated electric engines

## 7.3 STANDARDISATION NEEDS AND POSSIBLE ACTIONS FOR CONSIDERATION

### 7.3.1 FUEL QUALITY STANDARDS

The European Standardisation Organizations have adopted the relevant (voluntary) fuel quality standards as regards natural gas and biomethane to be used in transport, liquefied petroleum gas and paraffinic fuels. These standards are:

- Natural gas and biomethane for use in road transport as established in the standard EN 16723-2. This standard defines the fuel quality of the natural gas, biomethane or blends of natural gas and biomethane, dispensed for automotive fuel.

- Liquefied Petroleum Gas (LPG) as established in the standard EN589. The standard introduces LPG quality specifications for automotive use, ensuring a minimum quality level throughout Europe. The standard underlines that LPG (and its possible biomass-based variant) is a feasible alternative fuel

- Paraffinic fuels as established in the standard EN15940. This standard describes the requirements and test methods for paraffinic diesel fuel marketed and delivered as such, and containing a level of up to 7,0% (V/V) fatty acid methyl ester (FAME)". It is applicable to fuel for use in diesel engines and vehicles compatible with paraffinic diesel fuel.

The possibility of making these standards binding through their inclusion in legislation could be explored.

The following sections of the report outline additional standards that could be developed.

### 7.3.2 STANDARDS TO ENSURE THE INTEROPERABILITY OF THE ELECTRIC RECHARGING INFRASTRUCTURE

- identification and authentication of electric vehicle users

- e-roaming protocols

- interface to energy networks and markets (V2G)

- pricing information to users of electric vehicles

Important principles to be considered in the development of any new standards could include:

- open and royalty-free standards – no proprietary protocols or licence (fee) requirements, focused on creating a level playing field between all market actors and allowing for fair competition between them, by inhibiting any risk of favouring one or more market actors;

- all standards should take into account and, insofar as possible and useful, build upon standards developed at international level (ISO/ICE), taking account of market support (use and acceptance by market parties) and maturity (can be implemented quickly while requiring only limited changes to existing systems);

- all standards should be safe and (cyber) secure.

### 7.3.3 STANDARDS FOR COMPLETING THE STANDARDISATION OF THE OVERALL RECHARGING/REFUELLING INFRASTRUCTURE

- Electric recharging points for maritime vessels

- Electric recharging points for inland waterways vessels

- Battery swapping for inland waterways vessels

- Hydrogen refuelling points for maritime FCH vessels

- Hydrogen refuelling points for inland waterways FCH vessels

- Methanol bunkering

- Ammonia bunkering

### 7.3.4 STANDARDS TO COMPLETE THE STANDARDISATION OF FUEL QUALITY

- Methanol as fuel for maritime and inland waterways transport
- Ammonia as fuel for maritime and inland waterways transport
- The certification processes (ASTM International, formerly known as American Society for Testing and Materials) for all pathways producing sustainable aviation fuels (SAFs) should be a priority

The annex of the Commission' communication "The European Green Deal"[77] proposes the review of a set of legislation which, to different extents, will boost the development of the most environmentally performant fuels and the relevant alternative fuels transport systems in the EU.

[77] COM/2019/640 final

# 8 FINANCING MECHANISMS

## 8.1 GRANT SUPPORT UNDER THE CONNECTING EUROPE FACILITY

The Connecting Europe Facility (CEF) has been supporting the deployment of alternative fuels infrastructure since 2014. The financial support has been provided through different priorities namely Innovation, Motorways of the Sea and Ports. CEF has financed, through several calls, different types of alternative fuels infrastructure. Support addressed mainly recharging/refuelling stations, but also storage, terminal adaptations for bunkering operations, NG supply networks and small-scale production units.

All fuel types have received financial support, i.e. electricity (light duty vehicles, buses, and ferries), LNG/CNG (trucks, utility vehicles, maritime and inland navigation vessels), LPG and $H_2$ (buses, utility vehicles and cars). In total, 131 projects have been awarded a grant, representing more than €983 million of EU funding for €3.26 billion of total investments. The expected results amount to support for the rollout of around 12,000 recharging points for electric vehicles, 275 LNG refuelling stations, 424 CNG refuelling stations and 51 $H_2$ refuelling stations. The infrastructure will be deployed along the TEN-T Core Network, in all 9 Core Network Corridors, though the network is not equally developed in all Member States. Beneficiaries of the EU support are mainly private operators.

## 8.2 GRANT SUPPORT UNDER HORIZON 2020 PROGRAMME

The different elements covered in **Chapter 4 (p. 19)** for each of the fuels are:

<u>Alternative fuels for combustion engines</u>

In the area of alternative fuels (CNG, LNG, biofuels including methanol) in all transport modes, eight projects in total have been funded in the following transport modes (road transport, maritime and aviation), with an overall EU contribution of €87 million.

More specifically, two projects dealing with alternative fuels in road transport received an EU contribution of approximately €36 million, one in aviation with an EU contribution of €7.5 million and two in maritime transport with an EU contribution of approximately €24 million.

<u>Electrification, batteries, hydrogen and fuel cells</u>

Within Horizon 2020 programme, 15 projects on batteries were funded until 2018 with a total EU contribution of €95 million. As a result of the Battery Action Plan, additional €100 million were allocated for research and innovation on electric batteries within Horizon 2020 to be implemented in 2019 and 2020.

The budget for the 2019 call on batteries was €114 million covering 7 topics. A 2020 call is already published. The budget of €132 million will cover work on next generation batteries for stationary energy storage and towards the hybridisation of stationary energy storage.

With a total budget of €750 million from the Horizon 2020 programme, and an expected adequate amount from private investments, the European Green Vehicles Initiative (EGVI) contractual Public Private Partnership covers topics which contribute to reaching the goal of energy efficiency of vehicles using alternative powertrains, in particular the electrification and hybridisation of powertrains and their adaptation to renewable fuels. The "electrification" pillar of the European Green Cars Initiative has been extended from passenger cars to all types of vehicles (2 wheelers, passenger cars, trucks & buses and new vehicles concept) focusing on the improvement of energy efficiency of vehicles using alternative powertrain.

In the area of vehicle electrification, 35 projects were funded with the total EU contribution of €225.8 million. Out of these, 30 projects are related to development of drivetrains, vehicle concepts and design, energy management, development of electric architectures, components and systems, vehicle testing and product development. A further five projects were funded in the area of integration of electric vehicles into the transport system and grid.

In addition, four projects with the total EU contribution of €47.8 million were funded in the area of vehicle hybridisation.

In waterborne transport, one project with the total EU contribution of €15.1 million was funded that deals with a full-scale demonstration of the next generation 100% electrically powered ferry for passengers and vehicles.

Three projects with the total EU contribution of €17 million were selected for funding in the aviation domain. They are dealing with electrification and hybridisation of aircraft powertrains.

Regarding the support provided through the FCH 2 JU for demonstration and research projects on the use of hydrogen in fuel cells for transport applications, 25 projects on road transport applications (cars, buses, and trucks) received a EU total contribution of €213 million, two project in commercial aviation received an EU contribution of €9 million and in the area of waterborne applications, three further projects were funded with a total EU contribution of approximately €12 million.

## 8.3 FINANCIAL INSTRUMENTS UNDER THE CLEANER TRANSPORT FACILITY

The Cleaner Transport Facility (CTF) was launched by the EC and the European Investment Bank (EIB) in 2016 and targets the deployment of new cleaner technology in transport by making use of the tools the EIB and the EC can offer. The objective of CTF is to support the accelerated deployment of cleaner transport vehicles and their associated infrastructure needs, such as for charging and refuelling, which are expected to foster socio-economic benefits including reduced health costs due to cleaner air and lower noise.

The facility is demand driven and is an umbrella gathering a set of financing tools addressing the various financing needs of alternative fuels projects, depending on their financial and risk profiles. The initiative will seek to focus on life cycle cost models involving risk-sharing financial instruments leveraging also private sector funds, rather than on more traditional models entailing higher capital investment with a debt burden on the public sector. This will be done through the full range of EIB and EC financial products, and advisory services available to eligible public and private entities. Financing can be provided by the European Fund for Strategic Investment (EFSI), the CEF and InnovFIN programme under Horizon 2020.

Projects that deploy alternative fuels, according to the Directive on the deployment of alternative fuels infrastructure (2014/94/EU), will fall under the CTF. According to the Directive, alternative fuels include inter alia: electricity, hydrogen, biofuels and natural gas (including biogas) as compressed natural gas (CNG) or liquefied natural gas (LNG). Cleaner transport vehicles are defined as having lower greenhouse gas emissions or enhanced environmental performance compared to conventionally-fuelled transport vehicles.

### 8.3.1 FINANCING UNDER THE CONNECTING EUROPE FACILITY: BLENDING AND DEBT INSTRUMENT

The Connecting Europe Facility is a building component of the CTF in the form of the CEF Blending and of the CEF Debt Instrument (CEF-DI). In both cases, the projects should comply with the TEN-T Regulation Article 33 on New Technologies and Innovation.

The blending approach addresses projects requiring a grant component to reach financial viability and attract market-based financing. The scope notably includes AF infrastructure on TEN-T Core Network and nodes; public transport AF buses; and AF trucks and vessels. The blending call was carried out in 2017 leading to supporting 31 projects through €0.3 billion of funding and entailing the deployment of ultra-fast recharging points for electric vehicles, the development of hydrogen, (bio)LNG, (bio)CNG refuelling station networks, the rollout of LNG terminals for inland and at sea navigation, or the acquisition of LNG/electric vessels.

In addition, a blending facility is to be launched by end 2019 with a budget of €200 million. The facility will allow projects to apply on a rolling basis as opposed to fixed deadline as done under the CEF Transport calls for proposals. This approach aligns the grant decision and management process in a way better attuned to the life cycle of projects, and favours the application of mature projects. Several implementing partners such as the EIB and National Promotional Banks will participate to the blending facility. The scope will address alternative fuels in the form of mobile assets (incl. deployment of electric, hydrogen, LNG powered assets) and recharging and refuelling infrastructure for vehicles (incl. electricity, hydrogen and compressed or liquefied natural gas supply). Under this facility, only the difference between the costs of a conventional solution and the costs of a new technology solution are eligible.

The CEF-DI addresses projects with expected financial viability but risk profiles too high to reach financial close. The CEF-DI consists in facilitating access to EIB loans by guaranteeing a part of the loan amount. The EIB loan can then attract market-based financing and in turn can allow the project to be fully financed. The CEF-DI Delegation Agreement between the EC and EIB was revised in 2019 to strengthen the focus on green innovative investments and thereby address projects of various risk profiles in the AF market.

High-risk projects characterised by untested business cases, lack of collaterals, and/or deploying highly innovative technologies can be supported under the Future Mobility product. This also includes proven technologies but with very low market penetration rates and associated uncertainties on customer base and demand forecasts. Projects supported under the Future Mobility product may for instance include the large-scale deployment of electricity recharging points, the deployment of hydrogen refuelling stations and vehicles, or the development of car-sharing services using free-floating electric vehicles.

Medium to low risk projects may also be supported by the CEF-DI when it is shown that financial close in market conditions is not achievable and access to EIB financing still requires an EU guarantee. These projects include for instance the development of natural gas distribution stations, the large-scale deployment of electric and hybrid vehicles for leasing services, or the purchase of electric public buses and set-up of the associated recharging points.

Lastly, the CEF-DI also comprises the Green Shipping Guarantee Programme, set-up in 2016 as a close to market instrument, with the aim for the EIB to provide risk-bearing capacity to financial intermediaries (commercial banks) for investments in new vessels and environmentally focussed retrofitting. The focus of the Programme is on the reduction of SOx, NOx, particulates and $CO_2$ as well as ballast water handling. The operations include the construction of a dual-fuelled (LNG and normal marine fuel oils) passenger & vehicle ferry for operation between France and Great Britain and the construction of 3 new eco-cement carriers serving Northern European ports.

In addition, the CEF Regulation allows CEF Grants (including coming from blending mentioned above) to be combined with CEF Debt Instrument financing.

#### 8.3.2 FINANCING UNDER INNOVFIN, EFSI OR EIB OWN RISK

The CTF umbrella covers all existing instruments that the European Investment Bank can provide. In addition to CEF, this includes for instance for financing the InnovFin Energy Demonstration Project and the European Growth Finance Facility under EFSI.

#### 8.3.3 ADVISORY SERVICES COMPONENT

The European Investment Advisory Hub (EIAH), a joint initiative of the EIB and the EC in the context of the Investment Plan for Europe, provides technical and financial advisory services to project promoters to enhance their institutional capacity, strengthen project preparation and implementation and, where applicable, optimise the use of EU funds. It helps promoters in the transport sector to transition to cleaner options, including electro-mobility. EIAH assignments include for instance: the development of options for fleet greening strategies for regions and public transport operators; the analysis of options for combined mobility and energy transition at local authority level; or the initial screening and assessment of projects seeking access to the InnovFin Energy Demo Projects (EDP) funding. Project promoters can also be supported in the development of project proposals for the CEF Blending Call / Facility.

In addition, the European Local ENergy Assistance (ELENA), an initiative managed by the EIB under the Horizon 2020 programme, supports project promoters with grant funding for technical assistance for the preparation of innovative sustainable urban mobility projects, including the deployment of alternative fuels.

### 8.4 EIB SUPPORT TO R&D AND INNOVATIVE PRODUCTION INVESTMENTS

The EIB continues to support a wide range of companies' R&D and innovative production investments at a time of profound technology- and regulation-driven transformation of the involved industries. The EIB is ready to support the increased pace of investments by all industry participants, including smaller companies, across the entire value chain. This support covers the development of relevant electrification technologies, the investments for the development and deployment of an innovative, sustainable and competitive battery manufacturing supply chain and the investments in the field of fuel cell and hydrogen technologies across the full value chain.

### 8.5 PROGRAMMING PERIOD 2021-2027

#### 8.5.1 CONNECTING EUROPE FACILITY II

CEF II will tackle the challenge of decarbonisation and digitalisation of the transport sector as 60% of the CEF expenditures will have to be climate-oriented, with 40% of the General envelope and 15% of the Cohesion envelope dedicated to actions supporting the modernisation of the existing network and therefore the transition to smart, sustainable, safe and secure mobility. Future specific support to Alternative Fuels will be defined in detail in future work programmes and call texts.

#### 8.5.2 INVESTEU

The InvestEU Programme will bring together under one roof the multitude of EU financial instruments currently available and expand the successful model of the Investment Plan for Europe. It will notably gather the above mentioned EFSI, CEF-DI and InnovFin.

Transport will be part of the Sustainable Infrastructure Window of InvestEU under which 55% of the investments will have to be climate-oriented. Support to alternative fuels, including electric charging infrastructure, is a priority of the transport sector where financial products will take the form of either loan, equity or guarantee.

The profile of final recipients may cover public transport authorities, mobile asset renting and leasing companies, railway operators, ship operators, or operators of alternative fuels infrastructure. InvestEU will also cover the high-risk deployment of alternative fuels infrastructure and electric and $H_2$ vehicles/vessels/rolling stock where business cases are at pre-commercial level or early commercialisation stage, or have not yet reached a commercial scale at a sustained pace.

### 8.5.3 COHESION POLICY (COHESION FUND AND EUROPEAN REGIONAL DEVELOPMENT FUND)

Cohesion Fund and European Regional Development Fund are important sources of financial support from the EU budget for investment into sustainable transport and mobility. This includes alternative fuels and clean vehicles. The funds can co-finance relevant research, technical development and innovation, support SMEs active in the field, and co-finance the deployment of alternative fuels infrastructure and the procurement of clean vehicles.

### 8.5.4 FUTURE GRANT SUPPORT UNDER HORIZON EUROPE

The "Horizon Europe" proposal is fully in line with the Commission's proposal on the next long-term Union budget for 2021 to 2027 as well as with the Commission's priorities as set out in its Agenda for Jobs, Growth, Fairness and Democratic Change and global policy priorities (the Sustainable Development Goals). It supports the EU post-2020 agenda as agreed in the Rome Declaration of 25 March 2017.

The proposal is framed by the premise that research and innovation delivers on citizens' priorities, boosts the EU's productivity and competitiveness, and is crucial for sustaining our socio-economic model and values, and for enabling solutions that address challenges in a more systemic way.

Horizon Europe is designed for maximum impact in the context of the evolving nature of research and innovation, with an architecture designed for enhanced coherence and performance. It is proposed to use a three-pillar structure, with each pillar interconnected with the others and complemented by underpinning activities, to strengthen the European Research Area.

Synergies between different EU programmes will be highly encouraged and enhanced through the strategic planning process, which will act as a reference framework for R&I support across the EU's budget. Effective and operational synergies will thus be ensured with other EU programmes, notably to develop a more effective science-policy interface and address policy needs, as well as to promote faster dissemination and uptake of research and innovation results and to enable the pursuit of common objectives and common areas for activities (such as partnership areas or mission areas).

# 9 ABBREVIATIONS

Alternative Current

AEL: Alkaline Electrolysis

AFI: Alternative Fuel Infrastructure

APU: Auxiliary Power Unit

ATR: Autothermal Reforming

BEV: Battery Electric Vehicle

BTL: Biomass To Liquid

CCS: Carbon Capture and Storage

CEF: Connecting Europe Facility / CORSIA Eligible Fuel

CEF-DI: Connecting Europe Facility Debt Instrument

CEP: Clean Energy Partnership

CHP: Combined Heat and Power

CNG: Compressed Natural Gas

CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation

CPT: Clean Power for Transport Directive

CRL: Commercial Readiness Level

CSC: Chemical Scrubbing

CSP: Concentrated Solar Power

CTF: Cleaner Transport Facility

CTL: Coal To Liquid

DC: Direct Current

DDGS: Distiller's Dried Grains

DICI: Direct Injection Compression Ignition

DISI: Direct Injection Spark Ignition

DME: Dimethyl Ether

DNI: Direct Normal Irradiance

E85: Ethanol 85

EAFO: European Alternative Fuels Observatory

EBA: European Biogas Association

ECA: Emission Control Areas

EFTA: European Free Trade Association

EIAH: European Investment Advisory Hub

EIB: European Investment Bank

ENTSO-E: European Network of Transmission System Operators for Electricity

ERS: Electric Road Systems

ESO: European Standardisation Organization

ETS: Emission Trading System

EU: European Union

EV: Electric Vehicle

FAME: Fatty Acid Methyl Ester

FEGP: Fixed Electrical Ground Power

FC: Fuel Cell

FCEB: Fuel Cell Electric Buses

FCEV: Fuel Cell Electric Vehicles

FCH: Fuel Cell and Hydrogen

FCH JU: Fuel Cells and Hydrogen Joint Undertaking

FCH 2 JU: Fuel Cells and Hydrogen 2 Joint Undertaking

FFA: Free Fatty Acid

FQD: Fuel Quality Directive

FT: Fisher-Tropsch

GHG: Green House Gas

GHGi: Green House Gas intensity

GTL: Gas to Liquid

HCV: Heavy Commercial Vehicles

HDV: Heavy Duty Vehicles

HEFA: Hydrogenated Ether and Fatty Acids

HESI: High Efficiency Spark Ignited

HEV: Hybrid Electric Vehicle

HFO: Heavy Fuel Oil

HHV: Higher Heating Value

HPDI: High-Pressure Direct Injection

HRS: Hydrogen Refuelling Stations

HVO: Hydrotreated Vegetable Oils

IATA: International Air Transportation Association

ICE: Internal Combustion Engine

IEA: International Energy Agency

IGCC: Gasification in a Combined Cycle

ILUC: Indirect Land-Use Changes

IMO: International Maritime Organisation

INEA: Innovation and Networks Executive Agency

IRENA: International Renewable Energy Agency

IWW: Inland Waterways

JRC: Joint Research Centre

JU: Joint Undertaking

LCO: Lithium Cobalt Oxide

LCOE: Levelised Cost Of Electricity

LCV: Light Commercial Vehicles

LDV: Light Duty Vehicles

LFL: Low Flashpoint Fuels

LFP: Lithium Iron Phosphate

LHV: Lower Heating Value

LIB: Lithium-Ion Battery

LMO: Lithium Manganese Oxide

LNG: Liquefied Natural Gas

LPG: Liquefied Petroleum Gas

LTS: Long-Term Strategy

MENA: Middle East North Africa

MESP: Minimum Ethanol Selling Price

MDO: Marine Diesel Oil

MHV: Material Handling Vehicles

MGO: Marine Gas Oil

MJ: Mega Joule

MMT: Million Metric Tonne

MS: Member State

MSW: Municipal Solid Waste

NCA: Nickel Cobalt Aluminium

NG: Natural Gas

NGVA: Natural Gas vehicle Association

NPF: National Policy Framework

NMC: Nickel Manganese Cobalt

OECD: Organization for Economic Cooperation and Development

OEM: Original Equipment Manufacturer

OPEX: Operating Expense

OPS: On-shore Power Supply

PC: Passenger Car

PEMEL: Proton Exchange Membrane Electrolyser

PFAD: Palm Fatty Acid Distillate

PHEV: Plug-in Hybrid Electric Vehicle

PM: Particulate Matter

PN: Particle Number

PPA: Power Purchase Agreement

PSA: Pressure Swing Adsorption

PTL: Power To Liquid

PTF: Power To Fuels

R&I: Research and Innovation

RATP: Régie Autonome des Transports Parisiens

RED: Renewable Energy Directive

REEV: Range Extended Electric Vehicles

REFUNOBIO: Renewable fuels of non-biological origin

RES: Renewable Energy Sources

RP: Recharging Points

RoPax: Roll-on/roll-off Passenger

SAF: Sustainable Aviation Fuel

SECA: Sulphur Emission Control Areas

SMR: Steam Methane Reforming

SNG: Synthetic Natural Gas

SPF: Synthetic and Paraffinic Fuel

SPK: Synthesised Paraffinic Kerosene

SR: Steam Reforming

SSE: Shore-Side Electricity

STRIA: Strategic Transport Research and Innovation Agenda

TEU: Twenty-foot Equivalent Units

TCO: Total Cost of Ownership

TOE: Ton of Oil Equivalents

TRIMIS: Transport and Research and Innovation Monitoring and Information System

TRL: Technology Readiness Level

TTW: Tank To Wheel

UCO: Used Cooking Oil

ULSFO: Ultra-Low Sulphur Fuel Oil

WECV: Wireless Electric Charging Vehicle

WLTP: Worldwide Harmonised Light duty Test Procedure

WSC: Water Scrubbing

WTT: Well To Tank

WTW: Well To Wheel

ZEB: Full battery electric bus

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