European Commission

STRIA Roadmap
on Low-emission Alternative Energy for Transport (ALT)

Mobility and Transport

STRIA Roadmap

Low-emission Alternative Energy for Transport

2020 update based on original 2016 version

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(* Contributed to 2016 version)
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1 Introduction

1.1 Context for the STRIAs and the current update

Transport plays a crucial and dual role for society. On the one hand, it enables economic activity as it favours trade, generate jobs and is a factor of permanent innovation with spill over effects on other activities. On the other hand, it improves the quality of life allowing citizens to be better connected and goods to be more widely available across EU's entire territory.

Nonetheless, the EU's transport sector faces several challenges in relation to addressing climate change, air pollution, energy security (oil dependency) and competitiveness, which are all key EU policy drivers. The present document focuses on its impact on climate change and how to act to reduce it.

Within the Paris Agreement, the EU has committed to limiting greenhouse gases (GHG) emissions to levels as low as needed to stay below a 2°C rise in average global temperature compared to pre-industrial levels, and to make efforts to limit the temperature increase to 1.5°C. Global emissions must be reduced radically to achieve this goal. Within a world effort-sharing allocation, it is likely that OECD countries will need to limit energy-related emissions at a level close to zero shortly after 2050. The EU acting with this target in mind, in 2015 adopted an "**Energy Union**" package[1] with ambitious targets for GHG emission reductions, renewables and energy efficiency in 2030 (at least 40% domestic reduction of greenhouse gas emissions, 32% share of renewable energy consumed in the EU and a 32.5% improvement in energy efficiency). In 2016 it set out a "**Clean energy for all Europeans**" package[2] , which set more ambitious targets for renewables and energy efficiency following the Paris Agreement (at least a 32% share of renewable energy consumed in the EU and a 32.5% improvement in energy efficiency), which were to be set into legislation by 2019, and in 2018 it published a long-term vision for a climate neutral economy[3] reaching (and if possible exceeding) the intermediary objectives is essential, in order the EU to pursue climate neutrality by 2050.

In the recast of the Renewable Energy Directive (RED) adopted by EU[4], the RES target in 2030 has been set at 32%. As part of this, Member States (MS) must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 from renewable energy. The exact trajectory to achieve these targets will be defined for each Member State in its Integrated National Energy and Climate Plan. These plans will be designed by each Member State following the guidelines set out in the **Energy Union Governance Regulation**[5]. Within the 14% transport target, there is a sub-target for advanced biofuels produced from feedstocks in Part A of Annex IX. These fuels are mandated 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. Biofuels produced from feedstocks in Part B of Annex IX will be capped at 1.7% in 2030 and will be double-counted towards the 14% target. The promotion of several alternative fuels options for transport offers

[1] COM(2015) 80 final, Energy Union package - A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy
[2] European Commission (2019), Clean energy for all Europeans
[3] COM(2018) 773 final, A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy
[4] EC, Clean Energy for All Europeans," DG Energy, European Commission, <accessed March 7th, 2018>.) https://tinyurl.com/yd9dm6bd
[5] EC , DG Energy, 'Governance of the Energy Union'. Accessed on 23/04/2019 https://tinyurl.com/y5ta9jan

promising solutions to meet the above-mentioned objectives. This should complement the vehicle CO_2 standards part of the **Clean Mobility Package**[6].

The Energy Union Communication included a "***Research, Innovation and Competitiveness***" dimension comprising of three initiatives: *the integrated Strategic Energy Technology Plan (SET Plan), the Strategic Transport Research and Innovation Agenda (STRIA) and Global Technology and Innovation Leadership Initiative*. The STRIA contributes to the realisation of the Energy Union vision by identifying the contribution of the transport sector to the achievement of the climate and energy goals and providing input for research and innovation policy to maximise the impact of low-carbon technology solutions. The STRIA Roadmap on alternative fuels was carried out jointly by DG RTD and DG MOVE, and was fed into the Communication on the R&I and competitiveness component of the Energy Union in November 2016. STRIAs were developed for seven key transport innovation areas: Electromobility, Alternative fuels, Vehicle design and manufacturing, Connectivity and automation of transport, Transport infrastructure, Network and traffic management systems, Smart transport and mobility services (incl. urban). The STRIAs identify R&I that will speed up technological changes in transport and better target both public and private investments in the transport sector to tackle technical and non-technical challenges to meeting energy and climate objectives of the Energy Union and beyond 2050.

The European Communication of 20 July 2016 on "***A European Strategy for Low-Emission Mobility***"[7] also stressed the need to develop and deploy alternative low carbon energy options in transport, including gaseous and liquid fuels, and the need for research and innovation that brings together three interconnected strands: energy technologies, transport and industry, through an Integrated Research, Innovation and Competitiveness Strategy for the Energy Union.

Three years after the original publication of the STRIA on Alternative Fuels, this update aims to provide an updated set of **R&I priorities for alternative fuel powertrains to meet the EU's transport decarbonisation goals**. The roadmap covers all transport modes and addresses all types of emissions (CO_2, SOx, NOx, particulates), and focuses on the powertrain developments needed to efficiently use a wide range of fuel options, with a **focus on low carbon sustainable fuels**. The focus of the update is to report on progress and trends on the use of alternative fuels and associated R&I in different transport modes since the original STRIA, and to include hydrogen, which was not part of the scope of the previous version.

1.2 Transport energy consumption in the EU

In 2016, the EU 28 transport sector, excluding international shipping, consumed 367.3 Mtoe, which accounted for 33.3 % of total energy consumption (**Figure 1**). This figure does not include the fuel stored in maritime bunkers in Europe, which would bring the total energy consumed to 398 Mtoe. Out of this amount, the largest consumer is road traffic (82%), followed by domestic and international aviation (14%), then rail (2%) and navigation (11%) (**Figures 2 & 3**). The dependency on oil in 2016 was still very high (94% of the energy demand from transport) as compared to 1990 (98%)[8]. In 2016, the transport sector was by far the main consumer of petroleum products, with road transport

[6] COM(2017) 675 final, Delivering on low-emission mobility - A European Union that protects the planet, empowers its consumers and defends its industry and workers
[7] COM(2016) 501 final, A European Strategy for Low-Emission Mobility
[8] Eurostat: https://ec.europa.eu/eurostat <accessed on April 17th 2019>

responsible for 47.8 %[9]. Increasing battery electrification of road transport is expected to reduce its oil dependency.

The alternatives to oil-based liquid fuels for transport in an internal combustion engine include biofuels (FAME biodiesel, HVO biodiesel, Fischer-Tropsch biodiesel and biokerosene, upgraded pyrolysis oils, bioethanol, and methanol), hydrogen, ammonia, power-to-gas and liquids (synthesised methanol, methane, diesel and kerosene), as well as fossil based fuels such as CNG, LNG, LPG, GTL, methanol and steam reformed hydrogen, only some of which have some moderate decarbonisation potential (unless hydrogen from fossil sources is produced with carbon capture and storage). The fuel alternatives for fully electric powertrains are electricity in batteries and hydrogen in fuel cells, or fuels like LNG and ammonia for use in fuel cells.

When looking at the dependence on oil, rail remains the transport mode that is proportionally least dependent on fossil fuels due to electrification, with petroleum-based products accounting for 33% of energy consumption in 2016 (whereas road transport had a dependency of 94%).

Petroleum-based products satisfied also almost all the energy demand in waterborne and air transport in 2016. Air transport is most dependent on oil, with the main alternative energy source being biofuels. Alternatives in waterborne transport are very similar to those for long-range heavy-duty road transport.

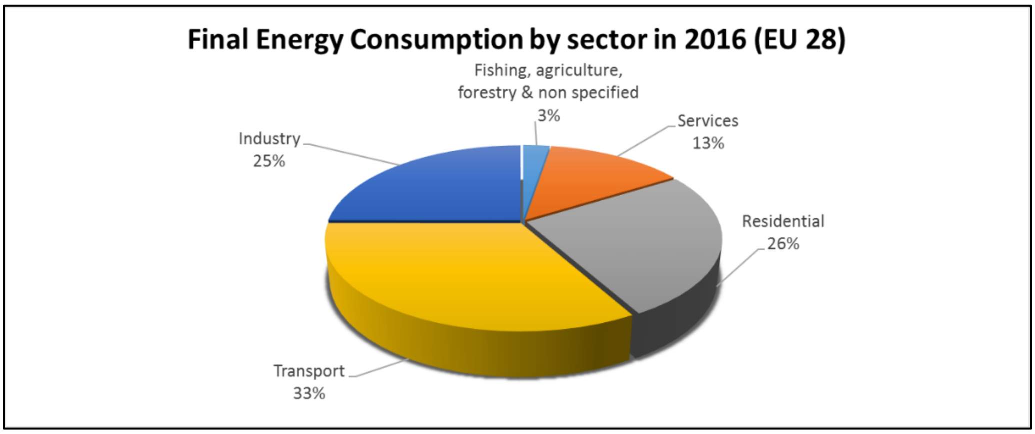
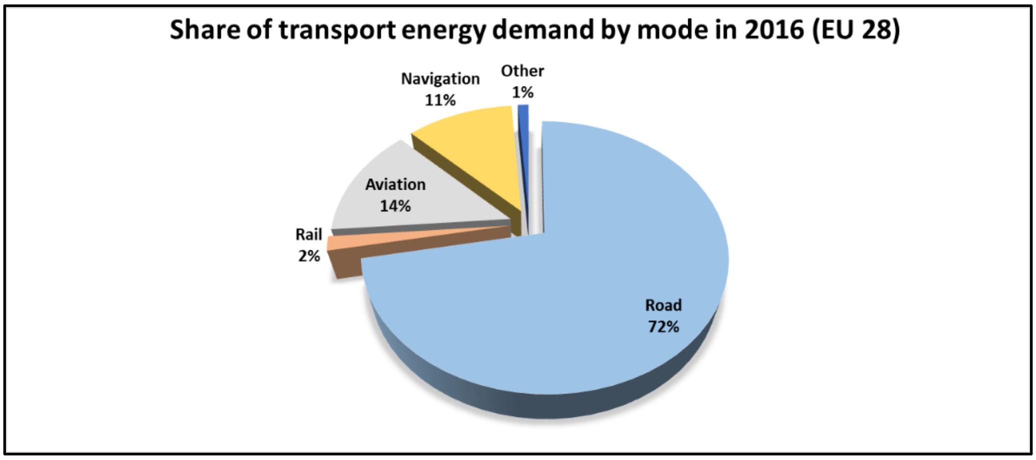


Figure 1 - Share of final Energy Consumption by sector (EU 28)[3]



[9] Eurostat: https://ec.europa.eu/eurostat <accessed on April 17th 2019>

Figure 2 - Share of transport energy demand by mode, including international shipping, in 2016 (EU 28) [10].

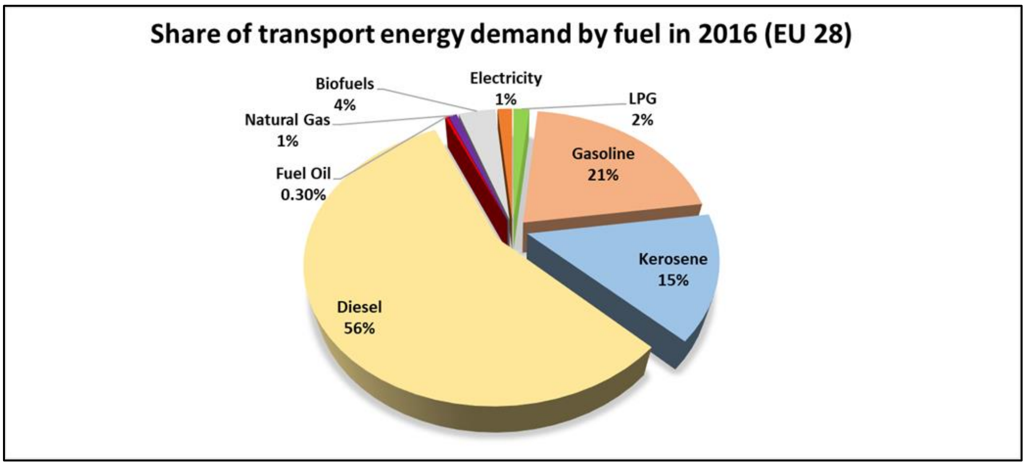


Figure 3 - Share of transport energy demand by source, excluding international shipping, in 2016 (EU 28)[4]

1.3 Greenhouse gas emissions from the EU transport sector

Since 1990, total greenhouse gas (GHG) emissions in Europe show a downward trend, from 5,720 Mt (CO_2 eq.) in 1990 to 4,441 Mt (CO_2 eq.) in 2016, corresponding to a 22,3% decrease. However, the share of transportation in total emissions increased significantly during the last two decades from 20.2% in 1990 to 31.6% in 2016, of which road transportation accounted for the largest share (72%) (**Figures 4 & 5**).

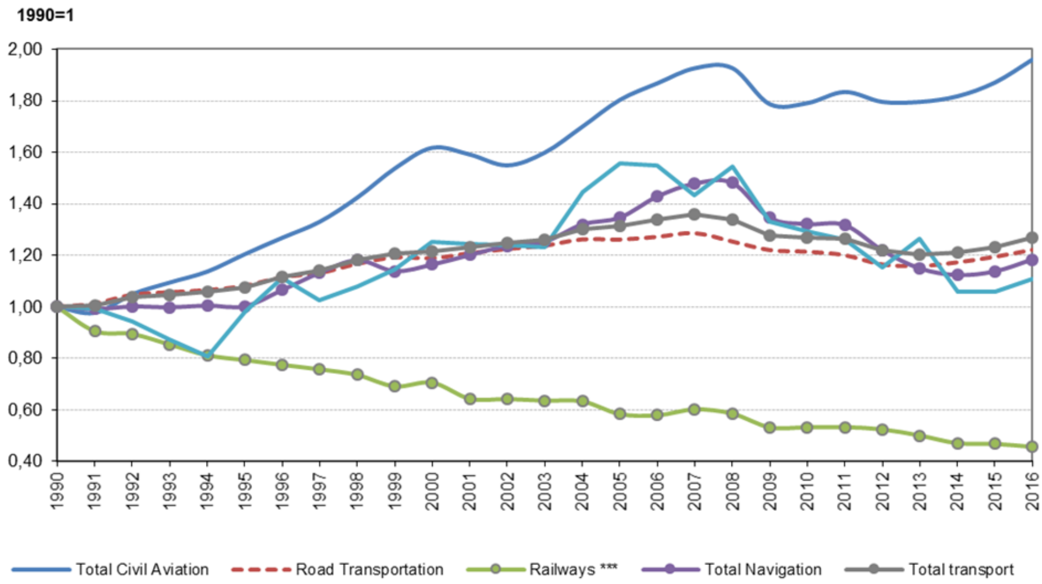


Figure 4 – Greenhouse Gas Emissions from Transport by Mode compared to 1990 base line (EU 28) [11]
*** Excluding indirect emissions from electricity consumption.

[10] European Commission (2018), EU Transport in figures – Statistical pocketbook 2018, Directorate-General for Mobility and Transport, available at: https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2018_en

[11] Eurostat, Greenhouse gas emission statistics- Emission inventories : https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics <accessed on March 28th 2019>

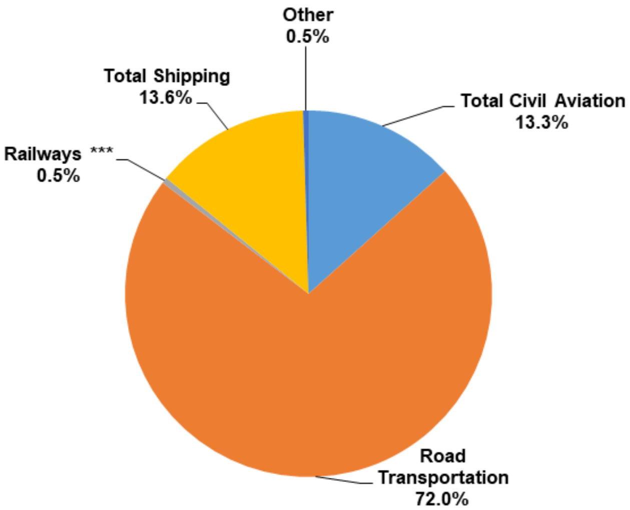


Figure 5 - Share by mode in Transport GHG (including Maritime International Bunkers "Navigation") in 2016 (EU 28)[11]

Transport GHG emissions, including international aviation and maritime transport, increased in volume by around 34% between 1990 and 2008. Over the same period, energy industries reduced their emissions by about 9%. Then there was a transport emissions decline between 2008 and 2013, but up to 19,4% compared to 1990 levels[12]. The transport sector has clearly been inherently difficult to decarbonise, and improvements in energy efficiency have been offset by increasing transport volumes and distances, while the take up of alternative fuels has so far been limited.

Unless decisive action is taken, this trend is likely to continue and by 2030 transport is expected to become the main source of GHG emissions in the EU, surpassing the power sector[13]. This is largely due to the continued important reliance of all transport modes on oil (94% of energy used in transport consists of oil products, 90% of which are imported) . Based on current trends[14], oil products are expected to cover 88% of the EU transport energy needs in 2030 and 84% in 2050.

Policies such as the **renewable energy directive (RED)**, the **fuel quality directive (FQD)**, as well as related national support schemes aiming to promote a wide range of renewable and low carbon energy sources in the transportation sector, have led to a rise in renewable energy in transport, standing for 7.1% of the energy used in transport in 2016[15]. The RED mandates the use of 10% renewable energy in transport by 2020; whereas the FQD requires a 6% carbon intensity reduction in fuel supplied by 2020. In this framework, the **Alternative Fuels Infrastructure Directive** (AFID)[16] establishes a common framework of measures for the deployment of alternative fuels infrastructure in the European Union, in order to minimize dependence on oil and to mitigate the environmental impact of transport. It sets out minimum requirements for the build-up of alternative fuels infrastructure, including refuelling points for

[12] European Environmental Agency -EEA, Greenhouse gas emissions from transport. Available at: https://tinyurl.com/y2wsqxnq <accessed on 28th March 2019>

[13] EC (2015).EU energy, transport and GHG emissions. Trends to 2050,COWI, July 2015, : https://tinyurl.com/y6pecbfm

[14] EC (2015). State of the Art on Alternative Fuels Transport Systems in the European Union: https://tinyurl.com/y4ywhxjx

[15] Eurostat (2018) : https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20180312-1 <accessed on April 17th 2019>

[16] https://ec.europa.eu/transport/themes/urban/cpt_en

hydrogen, while until today hydrogen is not a mandatory fuel for deployment in the AFID. In the case a Member State decides to deploy it, it must nevertheless then follow unified rules as set by the directive.

Air quality also remains an issue for all transport modes (emissions from road vehicles, diesel locomotives, planes in airports and ships in coastal regions and ports). As an illustration, it is estimated that one third of the EU citizens live in urban areas with pollution levels above legal thresholds and that around 500,000 premature deaths every year can be attributed to pollution, where road transport is one the main contributors[17] (40%).

The **2011 EC White Paper on Transport**[18] is the main reference document in Europe when it comes to tackling emissions in transport. It sets a target of 60% reduction in transport GHG emissions by 2050 (compared to 2005 levels), with specific targets for different transport modes, while at the same time drastically reducing other negative impacts (accidents, emissions/noise, congestion) and achieving sustainable mobility services for citizens and transport services for businesses. The COP21 agreement is likely to require even greater reductions, up to 100% decarbonisation by 2050 for the 1.5°C scenario. This is reflected in the EU long term decarbonisation strategy "**A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy** "[19].

Achieving deep GHG emissions savings and other energy and environment improvements in the transport sector will therefore require both bold moves and a holistic approach that tackles demand for transport services, more efficient technologies, electrification, low carbon alternative fuels and their production.

1.4 The case for alternative fuels in transport

a) The IEA emissions reduction scenarios

The International Energy Agency's scenarios in its World Energy Outlook[20] and Energy Technologies Perspectives[21] publications illustrate the significance of zero emissions energy systems. The **IEA's ETP 2017** presents three scenarios for energy sector development to 2060:

- The **Reference Technology Scenario (RTS)** takes into account today's commitments by countries to limit emissions and improve energy efficiency, including the Nationally Determined Contributions (NDCs) pledged under the Paris Agreement. The RTS requires significant changes in policy and technologies in the period to 2060 as well as substantial additional cuts in emissions thereafter. These efforts would result in an average temperature increase of 2.7°C by 2100, at which point temperatures are unlikely to have stabilized and would continue to rise.
- The **2°C Scenario (2DS)** lays out an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. Annual energy sector CO_2 emissions are reduced by 70% from today's levels by 2060, with cumulative emissions of around 1,170 gigatons of CO_2 ($GtCO_2$) between 2015 and 2100 (including industrial process emissions). In transport, this reflects clear policy choices favoring less

[17] European Environmental Agency – EEA (2018): Air quality in Europe — 2018 report
[18] EC White Paper (2011): Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Available at: https://tinyurl.com/y4ktdszp
[19] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-long-term-strategy
[20] IEA (2018), World Energy Outlook, International Energy Agency, Paris
[21] IEA (2017), Energy Technologies Perspectives, International Energy Agency, Paris

energy intensive modes, the rapid uptake of all cost-effective energy efficiency opportunities and the transition towards a much higher reliance on low-carbon energy carriers by 2060.

- The **Beyond 2°C Scenario (B2DS**) falls within the Paris Agreement range of ambition, and corresponds to a 50% probability of limiting the increase of the global average temperature to 1.75°C. In transport, this requires even greater reliance on the most efficient modes, a very rapid deployment of zero-carbon vehicle technologies and energy carriers to shift away from fossil fuels, and needs to be accompanied by effective near-term accelerated and ambitious policy changes.

Figure 6 illustrates the **importance of low carbon alternative fuels in achieving GHG emissions savings in transport**, in conjunction with demand and efficiency measures. In the **Reference Technology Scenario (RTS)**, total final energy consumption in the transportation sector grows from 113 exajoules (EJ) in 2015 to 165 EJ in 2060. In 2060, most of the demand (36%) comes from road freight vehicles (light commercial vehicles [LCVs] and trucks), followed (28%) by passenger light-duty vehicles (PLDVs). Energy use increases most in long-distance transport modes (rail, air, shipping and road freight) between 2015 and 2060. Well-to-wheel (WTW) GHG emissions from transport increase from 9.5 gigatons of CO_2-equivalent ($GtCO_2$-eq) in 2015 to 14.4 $GtCO_2$-eq in 2060 (**Figure 6**). In the **B2DS** well-to-wheel (WTW) GHG emissions from transport are 89% lower in 2060 compared to 2015, while in the **2DS** they decline by 54% over the same period. All modes contribute to decarbonisation. Measures to shift and to avoid passenger transport result in a 25-27% reduction in passenger activity (passenger kilometres -pkm) for cars by 2060 in both low-carbon scenarios relative to the RTS. Systemic improvements in road freight can reduce the vehicle kilometres (vkm) driven by trucks by 16-26% relative to the RTS by 2060. This leads to a stabilisation of transport energy demand in both scenarios, therefore the **reductions in emissions rely almost entirely on the use of low carbon fuels**[22].

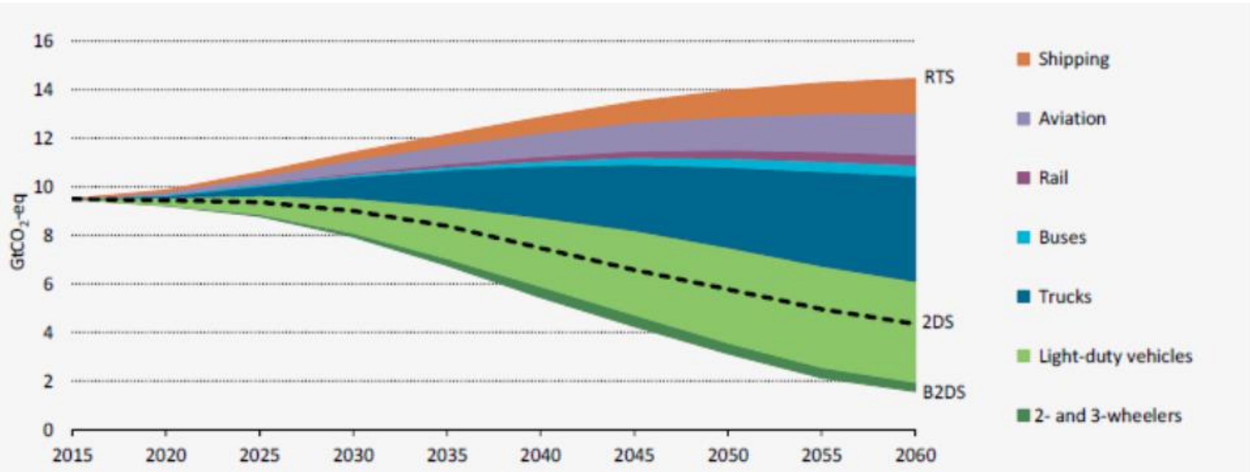


Figure 6 - WTW emissions reductions from transport by mode (2015-2060)[20]

Figure 7 shows the transport energy demand in **2DS scenario**, and an illustration of how GHG emissions reductions could be met through alternative fuels. The deployment of alternative energy in transport

[22] https://ec.europa.eu/transport/themes/urban/cpt_en and electricity

expected to grow, representing roughly half of energy demand in 2060 (in a 2DS scenario). Reliance on liquid fuels however persists, leading to a high demand for alternative liquid fuels.

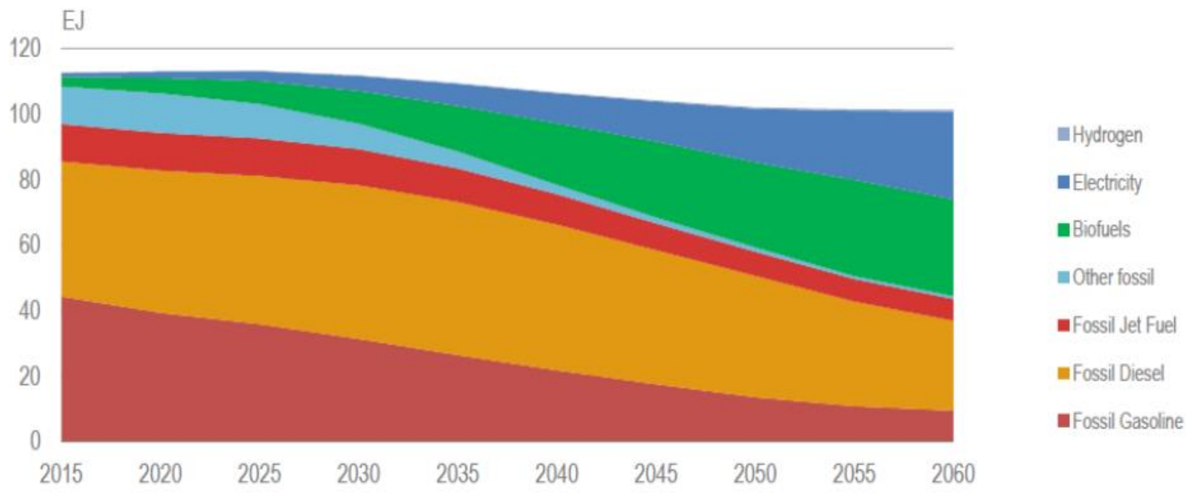


Figure 7- Global transport energy demand in 2DS scenario[21]

Dependency on oil in the transport sector is high due to: high energy density; easy handling and existing infrastructure; and cost competitiveness compared to alternatives. Globally, in a business as usual scenario oil is expected to remain the dominant fuel in transport accounting for 85% of transport energy demand in 2040[17] **(Sustainable Development Scenario)**, emphasising the need for additional action to reduce emissions in transport. Road transport would continue to account for around three quarters of transport oil demand. While aviation would be the fastest growing transport energy demand (expected to grow by 50% until 2050), road transport would still account for two thirds of transport oil demand growth. However, in OECD countries transport oil demand would decrease in all sub-sectors except aviation. As freight transport demand is expected to grow faster than passenger transport demand, diesel would surpass gasoline demand in the 2030s. Nevertheless, such a scenario is not compatible with meeting future ambitions of mitigating climate change. Based on the abovementioned, it is obvious that high oil dependency means that further action is required, in order to move to a zero carbon energy future.

Alternative fuel penetration in energy scenarios is largely driven by the need to reduce GHG emissions, but other forces may be at play too. For example, more stringent SOx, NOx and PM limits concerning waterborne transport, are likely to lead to fuel switching.

b) The EU emissions reduction scenarios[23]

Description of the scenarios

The scenarios cover the potential range of reductions needed in the EU to contribute to the Paris Agreement's temperature objectives of between the well below 2°C, and to pursue efforts to achieve a 1.5°C temperature change. This is translated into a reduction for the EU in 2050 (compared to 1990) of between 80% (excluding Land Use, Land-Use Change and Forestry - LULUCF) and 100% (i.e. achieving net zero GHG emissions). Various sectoral options are explored as possible pathways to reduce GHG emissions: demand reduction, technological options to decarbonise energy supply (mainly

[23] EC (2018). In depth analysis in support of the Commission Communication COM (2018) 773. Available at: https://tinyurl.com/y52ttpkr

by fuel-switching to alternative zero carbon/carbon neutral carriers such as electricity from RES, hydrogen, e-fuels), as well as the use of negative emissions.

Three categories of scenarios are investigated. The first category addresses the well below 2°C ambition, aiming for GHG emissions reduction levels in 2050 of around 80% compared to 1990. It is noted, that GHG reductions of 80% are reached excluding the LULUCF sector. Including the LULUCF carbon sink in the analysis, results in overall reductions (increasing on average by 4 percentage points). Five different scenarios are assessed in this category, considering differentiated portfolios of decarbonisation options. All scenarios integrate strong improvement in energy efficiency and developments of renewable energy, as well as improvements in transport system efficiency, which goes well beyond the assumptions of the Baseline scenario. On top of this, three of these scenarios are driven by decarbonised energy carriers and examine the impacts of switching from the direct use of fossil fuels to zero/ carbon-neutral carbon carriers, namely **electricity (ELEC)**, **hydrogen (H2)** and **e-fuels (P2X)**, in order to meet the prescribed level of ambition. The other two scenarios examine how stronger energy **efficiency measures (EE)** or the transition to a more **circular economy (CIRC)** can deliver the desired emissions reduction.

The second category consists of one scenario, which serves as a bridge between the other two main scenario categories. It combines the actions and technologies of the five scenarios of the first category into a sixth scenario **(COMBO)**, without reaching though the level of deployment of each technology as in the first category. All pathways are assumed to be available and a GHG reductions can be achieved through all of them. This results in net GHG emissions reduction (including LULUCF) in 2050 close to 90% compared to 1990. The scenario aims at identifying how much emissions can be reduced combining technological solutions and options assessed in the scenarios achieving 80% GHG emissions reduction, with small reliance on negative emissions technologies and without changes to consumer preferences. All scenarios of the first and this second category continue to undertake efforts to reduce emissions after 2050, resulting in a decreasing trend in GHG emissions towards net zero GHG emissions.

The third category of scenarios achieves even stronger emissions reduction, reaching net zero GHG emissions by 2050 and thus pursuing efforts to achieve a 1.5°C temperature change. In this scenario category, remaining emissions that cannot be abated by 2050 need to be balanced out with negative emissions, including from the LULUCF sink. One scenario **(1.5TECH)** aims to further increase the contribution of all the technology options, and relies more heavily on the deployment of **bioenergy with carbon capture and storage (BECCS),** in order to reach net zero emissions in 2050. The second scenario **(1.5LIFE)** relies less on the technology options of 1.5TECH, but assumes a drive by EU business and consumption patterns towards a more circular economy. Similarly, the increase in climate awareness of EU citizens is translated to lifestyle changes and consumer choices more beneficial for the climate. These include a continuation of the trend by EU consumers towards less carbon intensive diets, the sharing economy in transport, limiting growth in air transport demand and more rational use of energy demand for heating and cooling. Both scenarios have additional incentives to enhance the LULUCF sink, but this incentive is much stronger in the 1.5LIFE scenario.

Table 1 summarizes the key aspects of each scenario.

Table 1 – European transport scenarios[21]

	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation • Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.							
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

<u>Fuels for transport in each of the scenarios</u>

<u>Electricity</u>: the strongest contributor to fuel consumption reduction in the transport sector is projected to be the electrification of the road transport sector. In the scenario where emissions are reduced by 80% by 2050, the share of electricity in final energy demand would range between 15% (in P2X and H_2 scenarios) and 26% (in EE and ELEC scenarios) by 2050, compared to 11% in the Baseline scenario. The share of electricity is only incrementally higher in more ambitious scenarios (foreseeing net zero emissions by 2050); despite the fact that in these scenarios the electrification of passenger car transport is faster. This is due to the fact that in more ambitious scenarios, the role of e-gas and e-liquids is of great significance to the transport energy mix (especially to road freight, and aviation).

<u>Biofuels:</u> the total amount of liquid biofuels used in transport is not very different across the scenarios, although the allocation between transport modes is very different.

<u>E-fuels</u> :(e-liquids and e-gas) are projected to represent about 28% of the energy demand in 2050 in the P2X scenario (around 71 Mtoe). It is highlighted that the P2X scenario achieves less than the baseline in terms of reduction of primary energy demand [24].

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

Hydrogen: Carbon neutral hydrogen is projected to have the highest share in transport energy demand in the H2 scenario (21% in 2050) but it is part of the transport fuel mix in all scenarios, including the Baseline (around 2%). In the scenarios reducing by -80% by 2050, except for the H2 scenario, hydrogen would provide around 4-5% of the energy demand in 2050 while more ambitious scenarios project larger shares (9% in COMBO and 15-16% in the scenarios reaching net zero by 2050).

Diesel and gasoline: in a baseline scenario transport energy demand decreases slightly to 2050 with gasoline demand decreasing substantially as a result of efficiency improvements and electrification of LDVs, diesel demand staying roughly constant with efficiency gains offset by increased freight travel demand, and aviation demand increasing gradually. Ambitious GHG emissions reduction targets require significant further improvements in reducing demand and in using alternative fuels, with alternative fuels contributing over half of transport energy demand in such scenarios. However, it is not possible to expect that all sectors can equally benefit from biofuels due to restrictions in available biomass. A later section in this report provides a brief review of the potential for biofuels and other alternative renewable fuels.

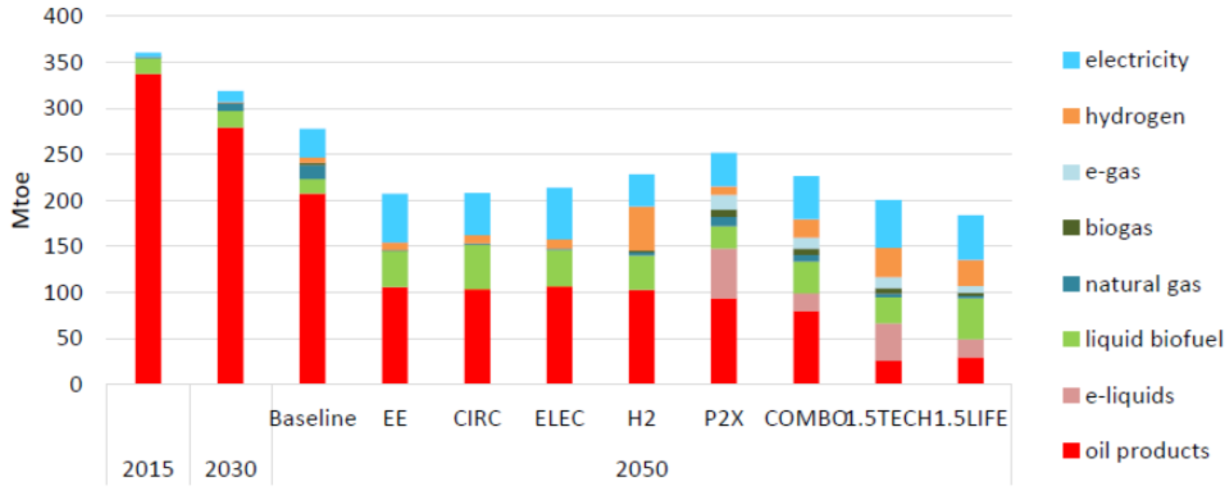

Figure 8 – Total final consumption on the transport sector by 2050, EU 28[27]

As a summary, **these scenarios illustrate the importance of low carbon alternative fuels in achieving future decarbonisation scenarios** (**Figure 8**). **Electricity and biofuels play a major role across all scenarios, but their potential to decarbonise all transport modes has a limit. Hydrogen and synthetic liquid fuels derived from it are needed to reduce the dependency on oil and to achieve deep GHG emissions reductions, in particular in the heavy duty and aviation segments.**

Given the **likely continued demand for liquid and gaseous fuel in all transport modes in the long term (albeit to different extents)**, prioritising use in different modes over time could be based on the range of benefits that alternative fuels can bring to a particular mode. From a GHG perspective displacing petroleum based fuels in any sector is likely to bring similar benefits, so additional benefits in terms of air quality improvements, infrastructure costs, fungibility with current assets (drop-in fuels) and affordability become important distinguishing considerations. In terms of R&I an additional consideration in relation to prioritisation is to foster those areas of public and private sector R&I where the EU is most competitive and the potential impacts across different objectives are greatest. Also, consideration should be given to the potential export markets of innovative technologies in other regions of the world affected by pollution and decarbonisation.

1.5 GHG emissions savings from alternative fuels in the EU 28

Foreseen evolution of emissions in transport

According to the EU's long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, in the Baseline scenario, CO2 emissions from transport, including domestic and international aviation but excluding international shipping, are projected to decrease by 19% by 2030 relative to 2005 and by 38% by 2050 (**Figure 9**). 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 transport emissions during the 1990s. The baseline scenario for shipping is that without action CO2 emissions are expected to grow by between[25] 50 and 250% globally.

Foreseen evolution of passenger car emissions

CO_2 emissions from passenger cars would be 65% lower by 2050 compared to 2005, and 10% lower for heavy goods vehicles. By 2030-2035, emissions from heavy goods vehicles and air transport together are projected to overtake those of passenger cars.

The main drivers for the emissions reductions in the **Baseline scenario** are the CO_2 standards for new cars, vans and heavy goods vehicles, consistent with the Commission's proposal for 2030, supported by the deployment of recharging infrastructure for electric vehicles and refuelling stations for hydrogen. Other policies recently proposed by the Commission would also contribute to the emissions reductions (e.g. the revision of the **Eurovignette Directive, Clean Vehicles Directive, Combined Transport Directive** and the assumed implementation of electronic documentation for freight transport), in particular in the freight transport sector.

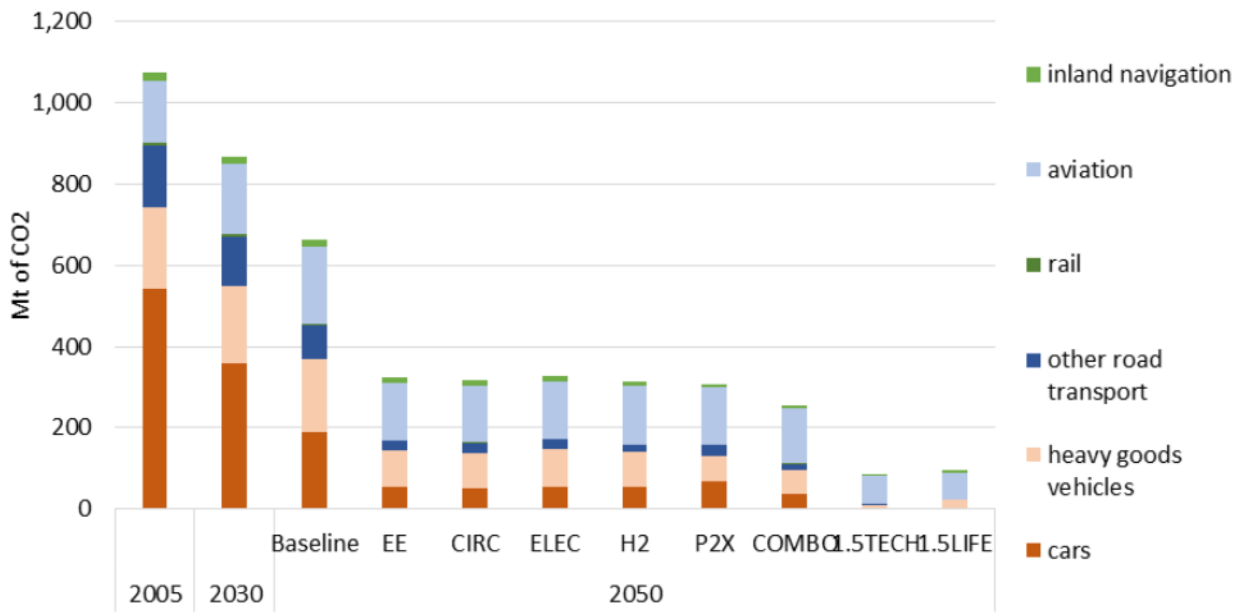

Figure 9 – CO_2 emissions (in $MtCO_2$) from transport in 2050 (Including aviation but excluding international maritime)

[25] 3rd International Maritime Organisation Green House Gas study (2014): https://tinyurl.com/ybe5flzf

Figure 9 shows that in the scenarios reducing emissions by -80% by 2050, emissions from transport excluding international shipping would decrease by 70-71% by 2050 compared to 2005 (61-63% relative to 1990). Thanks to more CO_2 efficient new cars post-2030 and the roll out of recharging and refuelling infrastructure, which both support electro-mobility, emissions from passenger cars are projected to decline substantially by 2050 relative to 2005 (by 87% in the P2X scenario and 90% in all other scenarios). For heavy goods vehicles, emissions reductions would range between 52% (in the ELEC scenario) and 69% (in the P2X scenario). By 2040, passenger cars would only represent around 24-25% of emissions in most scenarios reducing emissions by -80% by 2050 (except for the P2X scenario), having been overtaken in importance by heavy goods vehicles (28-29% of emissions) and aviation (31-32% of emissions).

In the COMBO scenario emissions from transport are projected to be 76% lower in 2050 relative to 2005 (69% lower relative to 1990), while in the scenarios reaching net zero by 2050 deeper emissions reductions are needed (91-92% relative to 2005, equivalent to 89-90% relative to 1990). In the scenarios reaching net zero by 2050, almost the entire passenger car stock would be zero-emitting by 2050. In addition, the rapid penetration of low- and zero-emission vehicles and of alternative and net-zero carbon fuels, and the significant improvements in the transport system efficiency, as described in the previous sections, results in a rapid decrease in emissions from heavy goods vehicles and aviation. In the 1.5LIFE scenario, this is complemented by significant changes in consumer preferences.

2 Objective, scope and approach of the STRIA on Alternative Fuels

The aim of the STRIA on Alternative Fuels is to: identify R&I priorities to improve, accelerate and maximise the impact of the use of alternative fuels in transport to substantially reduce greenhouse gas emissions, while reducing emissions affecting air quality; focus public and private funding in this area; and support the alignment of the EU & MS research agendas.

While this document discusses the wide range of alternative fuels and the R&I needs associated with their use, further analysis beyond the scope of this study is needed to determine the scale of the challenges, effort needed to address them, prioritisation of efforts, and fit with other STRIAs (e.g. electromobility) and SET plans.

A technical glossary is provided in ***Appendix 7.2***.

2.1 Scope

The STRIA on Alternative Fuels wishes to be comprehensive in its coverage of transport modes, possible alternative fuels and the powertrains they can be used in. Hydrogen has been added to the STRIA on Alternative Fuels as part of the 2019 update. Direct electricity use in vehicles is not within the scope of this STRIA but is the subject of a separate STRIA on electromobility.

The alternative fuel categories considered for the different transport modes are provided in **Table 2**, bearing in mind that electricity is the subject of a separate STRIA on electromobility. The **fuels considered could be of renewable or fossil origin, but while some alternative fuels of fossil origin could have benefits in relation to air quality and energy security, the carbon emissions reductions they can lead to are very limited and they should therefore only be seen as potential short term interim solutions where they help with the transition to sustainable renewable alternatives**. An exception to this could be

hydrogen derived from fossil sources with carbon capture and storage, as long as it can be demonstrated that the life cycle carbon emissions of such chains are low.

Table 2 - Alternative fuel categories and transport modes considered by the STRIA

Fuel categories	Road		Rail	Waterborne	Aviation
	LDV	HDV			
Methane-based (liquid)	✓	✓	✓	✓	
Methane-based (gas)	✓	✓			
LPG, bioLPG	✓	✓			
Alcohols, ethers & esters	✓	✓	✓	✓	
Synthetic paraffinic fuels	✓	✓	✓	✓	✓
Hydrogen	✓	✓	✓	✓	✓
Ammonia		✓	✓	✓	

Examples of fuels included in the different categories are provided in **Table 3**.

Table 3 – Fuel categories considered and examples considered by the STRIA

FUEL CATEGORIES	Examples
Methane-based fuels	CNG, LNG, bio-methane, E-gas
LPG (Propane- and Butane-based fuels)	LPG, BioLPG
Alcohols, Ethers & Esters	Ethanol, Butanol, Methanol, MTBE, ETBE, DME, BioDME, FAE
Synthetic paraffinic and aromatic fuel	GTL, HVO, BTL, SIP, ATJ, CH, SAK
Hydrogen	CH2, LH2, NH3

A schematic representation of the production pathways for some of the alternative fuels under consideration (i.e. advanced biofuels and hydrogen) are provided in **Figures 10 & 11**.

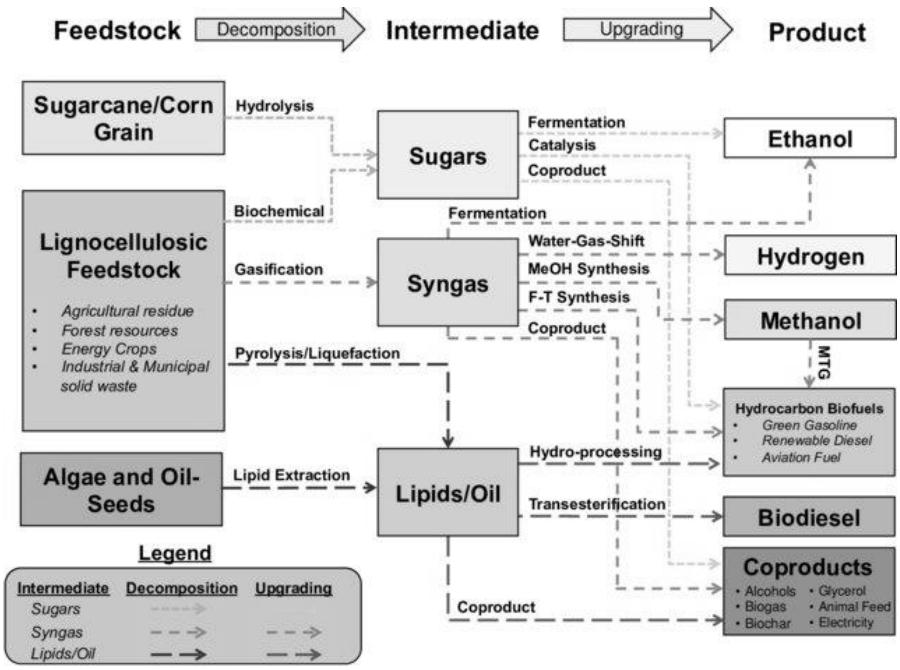

Figure 10- Feedstocks and conversion pathways for biofuel production. MTG: Methanol to Gasoline. F-T Synthesis: Fischer-Tropsch Synthesis[26] Note: Ammonia could also be produced via syngas.

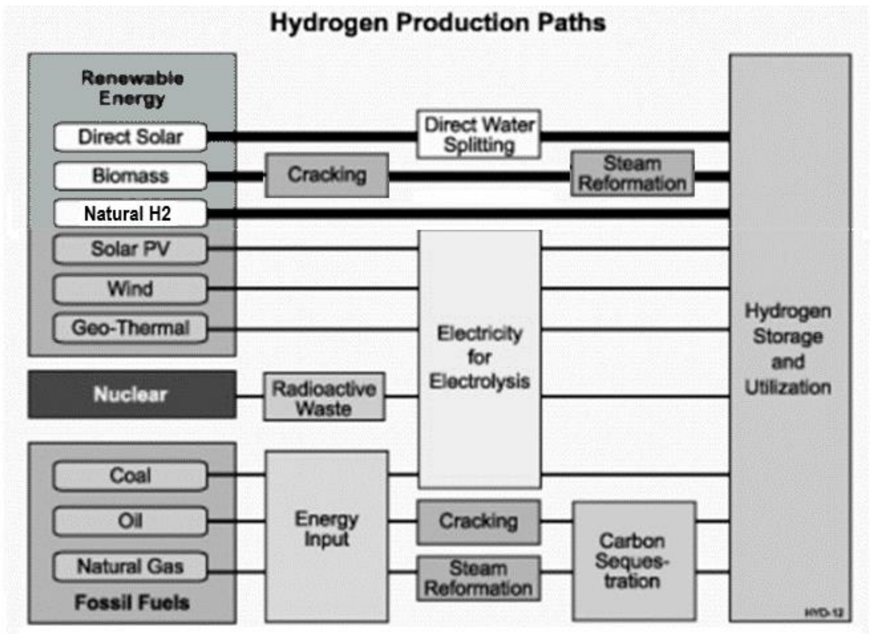

Figure 11- Hydrogen production pathways[27]. Note: The hydrogen produced from renewable electricity could also be used in combination with CO2 to produce gaseous and liquid fuels.

The powertrain technologies considered in scope for the STRIA are provided in **Table 4.**

[26] Adapted from: Zaimes, George & Vora, Nemi & Chopra, Shauhrat & Landis, Amy & Khanna, Vikas. (2015). Design of Sustainable Biofuel Processes and Supply Chains: Challenges and Opportunities. Processes. 2015. 634-663.

[27] Adapted from: http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/production.htm

Table 4 – Powertrain technologies considered by the STRIA

TECHNOLOGY Powertrain category	Powertrain technology	Acronym	Specific examples
Spark Ignition	Spark Ignition / assisted combustion	SI	CAI
Spark Ignition	Spark Ignition - lean combustion	SI - lean	Both homogeneous lean and stratified lean
Compression Ignition	Compression Ignition	CI	HCCI, PPC (also includes PPCI, GCI, LTGC and other low temperature combustion systems that are not spark assisted
Compression Ignition	Compression Ignition - Dual Fuel	CI - DF	Such as NG dual fuel (including HPDI) or methanol or ammonia dual fuel where the pilot fuel is a diesel type fuel for ignition purposes
Fuel cell	Fuel Cells	FC	Hydrogen FC, Ethanol Fuel Cell, LNG FC, Ammonia FC
Turbine	Turbine	Turbine	Turbofan aircraft engines, some marine

Table 5 below provides a definition of the transport modes considered.

Table 5 – Transport modes definition

TRANSPORT MODES Category	Definition
Light Duty Vehicles	Road vehicles <3.5T for people and goods transportation
Heavy Duty Vehicles	Road vehicles =>3.5T for people and goods transportation
Rail	Rail locomotives for people and goods transport*
Waterborne	From inland waterways to ocean going**
Aviation	Jet aviation***

* Only non-electrified locomotives are considered here
** Smaller boats for recreational use are not considered here
*** Only passenger and freight turbofan aircrafts are included. General aviation and particularly vehicles using AVGAS are not considered in this document due to their small size as energy consumers. Also, many are using standard automotive fuels and would therefore decarbonize in parallel to these

2.2 Approach

The following approach was taken to identify the strategic research and innovation priorities in relation to alternative fuel use in different transport modes:

- Identify **options** for using alternative fuels (i.e. alternative fuel and powertrain combinations)

- Assess the **potential impact** of different uses of alternative fuels based on criteria that reflect policy objectives (**GHG savings (TTW via engine efficiency); air quality pollutants reduction; energy diversification; EU competitiveness, resource potential**)
- Identify **challenges and opportunities** for improved or novel use of alternative fuels
- Identify **research needs** to accelerate development of alternative fuel use, with focus on high impact options (i.e. options that are likely to have greatest impact on across the criteria considered)

Identify **requirements to address R&I needs** In developing the STRIA, the following aspects need to be considered:

- Trade-offs between the different criteria of interest in relation to policy objectives
- Level of impact vs ease of implementation of alternative fuel options
- The timeframe over which the R&I can have an impact on the market

Extensive stakeholder consultation was conducted in preparing the original STRIA on Alternative Fuels in 2016, through a survey, interviews and a stakeholder workshop. The list of stakeholders consulted is provided in ***Annex 7.4***.

3 Status and trends in alternative fuel end-use

The following sections describe the status, trends and barriers of alternative fuels in transport. **Table 6** below shows current and future applicability of fuel and powertrain combinations to different transport modes, based on the following indicators:

- **Commercial in use**, meaning that the technology is mature and that it is currently sold into the market commercially (TRL 8-9)
- **Under development**, meaning that industry is actively developing products that are likely going to be launched into the market within 10 years (TRL 5-7)
- **Research stage**, meaning fundamental research is undertaken, and products using this technology are not expected to be market ready within 10 years (TRL 1-4)

In terms of technological maturity, four technology development phases related to the following technology readiness levels (TRL) are discerned[28] :

a. phase 1 -Fundamental research (TRL 1-3)
b. phase 2 –Validation (TRL 4-5)
c. phase 3 –Demonstration (TRL 6-7)
d. phase 4 –Implementation (TRL 8-9)

[28] Joint Research Center (2019), Assessing new and emerging transport technologies: Identifying opportunities for innovation - https://tinyurl.com/y28qfl8l

Table 6 – Maturity of fuel and powertrain combinations

Fuel Type	Power train	LDV	HDV	Waterborne	Rail	Aviation
Methane based liquid & gas	**SI**	Commercial	Commercial			
	CI		Commercial e.g. Volvo H2020 project HDGAS[29] on catalytic after-treatment	Commercial as dual fuel and dedicated gas engine applications.	Under development / Early commercial. Pilot dual-fuel retrofit projects in Latvia[30] and Spain[31]. GE dual-fuel retrofit kit – NextFuel™ [32]	
	Turbine	Under development (e.g. micro-turbines for CNG/LNG range extenders)	Under development (e.g. demo in refuse collection trucks in US)	Commercial. (Deployed on LNG carriers. Gas turbines have also been deployed on naval and high speed ferries.	Under development	
	Fuel Cell			Research Stage		
LPG	**SI**	Commercial - retro-fit technology. CEN standard in place	Commercial	Commercial as dual fuel engines	Research stage	
Alcohols, ethers, esters	**SI**	Commercial - Ethanol and M&ETBE are widely blended into gasoline.	Under development. MIT research on spark ignition dual-fuel (gasoline, alcohol) engines for HDV[33,34]	Under development. Swedish SUMMETH[35] project testing of direct injection SI combustion of methanol in small marine vessels.		

29 Heavy Duty Gas Engines integrated into Vehicles (HDGAS) - https://tinyurl.com/y6gqtlt6
30 https://tinyurl.com/y2dbx7lf
31 https://tinyurl.com/yxsjbpg2
32 https://tinyurl.com/y58j4fxz
33 https://www.sae.org/publications/technical-papers/content/2018-01-0888/
34 https://www.eurekalert.org/pub_releases/2019-04/miot-edc040819.php
35 SUMMETH: Sustainable Marine Methanol - https://tinyurl.com/yy4xstjk

Fuel Type	Power train	LDV	HDV	Waterborne	Rail	Aviation
	CI	Commercial - FAME widely adopted as blend with diesel.	Commercial - DME & ED95 in dedicated fleets. FAME widely adopted as blend with diesel	Commercial as dual fuel application with methanol.	Commercial use of B20 in the US (Amtrak, Virgin) and Netherlands (Arriva).	
	FC	Early commercial	Research stage	Research stage	Research stage	
SPF	**SI**					
	CI	Commercial – HVO used in vehicles. Under development – FT-diesel properties being investigated; pyrolysis and HTL routes being developed	Commercial – HVO used in vehicles. Under development – FT-diesel properties being investigated; pyrolysis and HTL routes being developed			
	Turbine/ Turbofan		Research stage			Commercial – HEFA in use. Under development - various SPK fuels
Other	**SI**	Research stage- Gasoline / Naphtha				
	Composite piston-turbo cycle	Research stage				
Hydrogen	**FC**	Early commercial	Early commercial	Under development, scaling up	Early commercial	Research stage for propulsion. Under development for small planes
Ammonia			Under development	Under development		

3.1 Light Duty Vehicles

Light Duty Vehicle technology and the fuels it uses are driven by tail pipe emission limits as well as fleet average CO_2 tail pipe targets. Both these emissions were measured across the **New European Drive Cycle**

(NEDC), following a particular testing procedure to determine road load and other factors. Nonetheless, due to evolutions in technology and driving conditions, it became outdated. The EU has therefore developed a new test, called the **Worldwide Harmonised Light Vehicle Test Procedure (WLTP)**. While the old NEDC test determined, values based on a theoretical driving profile, the WLTP cycle was developed using real-driving data, gathered from around the world. WLTP therefore represents better every day driving profiles. The WLTP driving cycle is divided into four parts with different average speeds: low, medium, high and extra high. Each part contains a variety of driving phases, stops, acceleration and braking phases. For a certain car type, each powertrain configuration is tested with WLTP for the car's lightest (most economical) and heaviest (least economical) version.

The **Real-Driving Emissions (RDE)** legislation is important to reduce the gap between type-approval vehicle emissions results and those in the real-world. The RDE legislation, introduced within the Euro 6 regulation, has been developed in four (4) packages. The first RDE package, adopted in May 2015, defines the RDE test procedure. The second RDE package, adopted in October 2015, defines the ***NOx Conformity Factors*** and the introduction dates. The third package, adopted in December 2016, adds a Particle Number (PN) Conformity Factor and inclusion of RDE cold-start emissions (i.e. at engine start). The fourth package adopted in May 2018 deals with In-Service Conformity RDE testing and market surveillance and lowers the error margin of the 2020 ***NOx Conformity Factor*** from 0.5 to 0.43. All four RDE acts have been published in the Official Journal and requirements entered into force from 1 September 2017 for new car and light duty vehicle types.

With respect to the 2025 and 2030 CO_2 standards, the transition to WLTP introduces an element of uncertainty regarding the de facto outcome achieved by the regulation. While the percentage reduction targets in the CO_2 regulation are fixed, the absolute CO_2 emission level to be met in 2025 and 2030 depends on the fleet average WLTP starting point of all manufacturers in 2021. This starting point, in turn, depends on the NEDC-WLTP adjustment factor, which is not yet fixed but will be determined for the 2020 new vehicle fleet for each manufacturer individually (**Figure 12**). To prevent manufacturers from inflating their 2021 WLTP-NEDC ratio by declaring unjustifiably high WLTP CO_2 emission values, the EC determined that the 2021 CO_2 baseline would not rely on the emission values declared by the manufacturers but directly on the measured values instead. Furthermore, the EC introduced an amendment to the WLTP-NEDC correlation procedure, which defines test parameters and conditions more precisely to prevent manipulation of the CO_2 test results[36].The regulation also contains provisions that improve transparency by requiring vehicle manufacturers to report both measured and declared CO_2 values to the European Commission.

[36] EC (2017). Draft Commission Implementing Regulation amending Implementing Regulation (EU) 2017/1153 to clarify the WLTP test conditions and provide for the monitoring of type approval data with regard to passenger car (European Commission: Brussels, 2018). https://tinyurl.com/ycayfenm

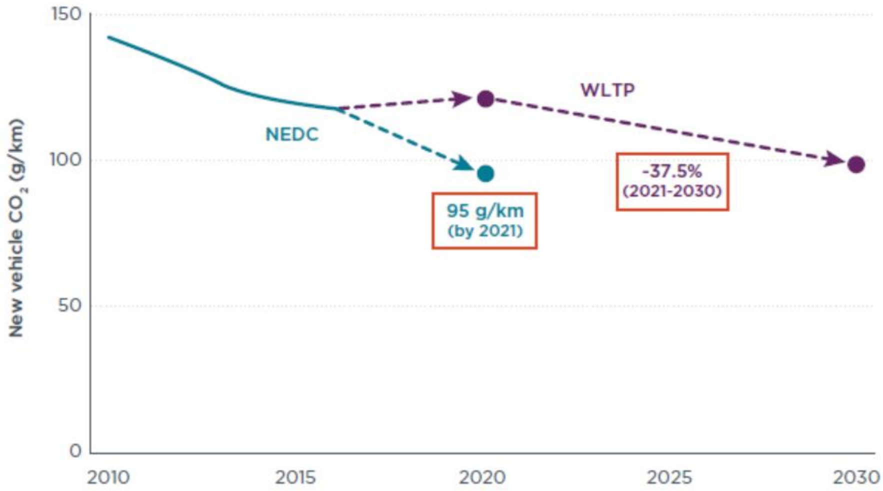

Figure 12 – CO_2 targets for LDVs until 2030[37].

Until now, these targets have driven large-scale uptake of diesel especially for the larger and heavier vehicles that do significant mileage such as larger passenger vehicles and vans due to the higher efficiency of the diesel cycle. This and fuel taxation favouring diesel has created a diesel / gasoline ratio that is significantly biased towards diesel [38] (2.6 in 2015). Consequently, the EU is still today an importer of diesel and an exporter of gasoline, potentially making the displacement of diesel by alternative fuels more attractive for refiners and in balance of payments terms. This situation will however change as recent developments (scandals around cars' emissions and a focus by politicians on the fine particles emitted by diesel cars) have led certain politicians to go for a ban in the near future of diesel based vehicles in cities.

The set CO_2 targets drive the uptake of electric powertrains in the LDV sector (with BEVs representing for instance half of the sales in Norway) as well as increased levels of electrification (hybrids) of Internal Combustion Engine (ICE) based vehicles. Next to BEVs refuelling with electricity from the network, FCEVs that are refuelling with hydrogen are gradually becoming available to purchase in Europe. While batteries based electric mobility is included in the STRIA on electromobility, hydrogen based electric mobility is included in the present document.

Further electrification through hybridisation of the current internal combustion base powertrains will have an impact on engine size and consequently on the type of engine and its fuel compatibility. A systems approach is required for the development of such powertrains. Increased electric propulsion power means that engines can be further optimised to operate more efficiently and more cleanly within a smaller speed / load operating window as well as have lower transient requirements. Early development into micro gas turbine hybrid vehicles illustrates the diversity of fuel and combustion options when considering hybrid vehicles.

EU emission standards apply to all motor vehicles and limits the permissible tailpipe emissions of CO, HC, NOx, PM and PN. Current **Euro6** standards came into force in 2013. Very effective after-treatment devices such as the **Three Way Catalysts (TWC)** for most gasoline vehicles and oxidation catalysts combined with a **Lean NOx Trap (LNT)** and / or **Selective Catalytic Reduction (SCR)** as well as a **Diesel Particulate Filter**

[37] The International Council on Clean Transportation (ICCT) : www.theicct.org <accessed on 22 April 2019>
[38] DG TAXUD (2015) "Excise duty tables". Available at: https://ec.europa.eu/taxation_customs/index_en

(DPF) for diesel vehicles have become a necessary additional expense to auto makers to meet emissions standards. These systems, especially the diesel aftertreatment systems, can be costly (about 15% of the car cost[39]), which could become another driver to push the development of alternatively fuelled powertrains. For example, fuels without carbon to carbon bonds inherently demonstrate very low levels of particulates, which would allow the engine to be optimised for lower GHG and NOx emissions leading to lower aftertreatment system costs, which in turn would offset possible engine adaptation costs for alternative fuels. The introduction of limits beyond Euro 6c to Euro 6d-TEMP introducing the RDE measurement methods and Euro 6d, which reduces the 2.1 conformity factor to 1.5 would require additional aftertreatment control systems making gasoline and diesel engine technology more expensive to produce and potentially more expensive to operate. With electrification however, comes a new challenge of low temperature exhaust systems for reducing NOx and oxidising PM/HC/CO, CH_4 for hybrid vehicles running at a lower speed and load.

CEN standards exist for Gasoline (EN228), Diesel (EN590), LPG (EN589), paraffinic fuels (EN15940), B10 (EN14214), natural gas and biomethane EN 16723-2, and are under development for E85. Gasoline and diesel are widely available throughout the EU. Various MSs have a separate pump for E10. Sweden has a significant E85 forecourt infrastructure. LPG is relatively widely available throughout the EU. A relatively dense natural gas (CNG) infrastructure exists in MSs, such as Austria, Belgium, Bulgaria, Czech Republic, Germany, Italy, the Netherlands, Sweden and Switzerland[40]. The LNG infrastructure is developing partly through the LNG Blue corridor projects, but is far from dense enough. While private infrastructure is already sufficient for many applications, public infrastructure for electric vehicles is expanding rapidly, but is not dense enough in some areas to provide an integrated network, in particular as far as fast charging is concerned. Fragmentation of the connectors and of the payment methods further contributes to this lack of coherency in the eyes of the end user. Hydrogen infrastructure is developing especially in Germany, the UK and Scandinavia, and now reaching new countries (France, Belgium, and the Netherlands) but is still in its early days. It should be noted that in the framework of the Alternative Fuels Infrastructure directive, several Members States committed EUR 707 million for the deployment of 820/842 hydrogen refuelling stations by 2025. Commonly accepted standards largely allow for the use of these vehicles across the various countries where such early infrastructure exists. While hydrogen is treated in the present document, batteries-based mobility is covered in STRIA on Electromobility[41].

Current research and innovation activities for the LDV sector focus strongly on smart, green and integrated transport aiming at:

a) Resource efficient transport that respects the environment. The aim is to minimise transport's systems' impact on climate and the environment by improving its efficiency in the use of natural resources, and by reducing its dependence on fossil fuels and energy imports.

b) Better mobility, less congestion, more safety and security. The aim is to reconcile the growing mobility needs with improved transport fluidity, through innovative solutions for seamless, inclusive, affordable, safe, secure and robust transport systems that make full use of modern information and communication technologies (ICT) capabilities.

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[39] https://www.theicct.org/sites/default/files/publications/ICCT_costs-emission-reduction-tech-HDV_20160229.pdf
[40] European Alternative Fuel Observatory (EAFO): https://www.eafo.eu/countries/european-union/23640/summary/compare
[41] https://trimis.ec.europa.eu/sites/default/files/roadmaps/STRIA%20Roadmap%20-%20Transport%20electrification.pdf

c) Global leadership for the European transport industry. The aim is to reinforce the competitiveness and performance of European transport manufacturing industries and related services on global markets including logistic processes and retain areas of European leadership.

d) Socio-economic and behavioural research and forward looking activities for policy making. The aim is to support improved policy making which is necessary to promote innovation and meet the challenges raised by transport, including the internalisation of external costs, and the societal needs related to it.

Consequently, research focuses on new high efficiency, low polluting combustions systems that work well in combination with increased levels of vehicle electrification. These include **Homogeneous Charge Compression Ignition (HCCI)**, **Cold Air Intake (CAI)**, **Partially Premixed Combustion (PPC)** and others, but essentially they share the aim of efficient combustion at lower temperatures to reduce engine out NOx emissions and are therefore captured in this report under the broad category of **Low Temperature Combustion (LTC) systems.** Improving combustion systems, taking into account the potential of alternative fuels should be a priority, together with the development of hydrogen fuel cell electric powertrains. This will enable deep decarbonisation and low pollutant emission across all transport modes.

In addition, research into control systems, new materials and manufacturing processes, improved modelling, simulation and testing, life cycle analysis will enable to even greater benefits from the use of alternative fuels.

Table 7 provides a summary on the state of the art of alternative fuel use in LDVs.

Table 7 – State of the art on alternative fuel use in LDVs

LDVs	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO, GTL)	Liquid petroleum gas and bio-LPG
How much is used and why?	Hydrogen is considered as a new green fuel for mobility provided the challenge of substantially increasing production without CO_2 emissions can be addressed. Its use would result in zero emissions (no CO_2, particles, NOx and SOx - latter two in fuel cells). Presently over 95 % of hydrogen is produced from steam reformed natural gas. Several car manufacturers have commercial vehicles on sale on the market: Honda, Toyota, Hyundai and Daimler. Still in the early days of adoption. By the end of 2018 there were about 120 Hydrogen filling stations and over 1200 vehicles on the roads in Europe.	For the LDV sector interest is partly driven by the lower carbon content of the fuel per unit of energy resulting in lower tailpipe CO_2 emissions helping OEMs to meet the 95 gCO_2/km target. Improving air quality is also an important driver. For HDVs lower noise levels may also be a consideration. Lower fuel cost as a result of lower fuel duty per unit of energy compared to gasoline and diesel has helped the uptake of this technology.	The use of ethanol and FAME is widespread and has steadily been increasing to satisfy RED requirements.	Not used Europe-wide on a large scale yet. HVO used in large quantities in Finland.	LPG consumption in LDVs is driven by lower fuel costs compared to Diesel, and is common in certain fleets e.g. taxis.

LDVs	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO, GTL)	Liquid petroleum gas and bio-LPG
Trends	Hydrogen for mobility is becoming a popular topic with several regions in Europe starting to work on zero emissions mobility plans that include the use of both battery electric vehicles and also fuel cell electric vehicles. Challenge for FCEVs will be the extent to which BEV can offer a practical and cost effective solution for all LDVs. In some countries, the production of hydrogen via electrolysis with green power is even competitive with diesel prices [42] e.g. Nordic countries and Switzerland.	CEN/TC 408 standard for natural gas and biomethane for use in transport and CEN/TC 326 standard for natural gas vehicles - fuelling and operation are being developed and will help increase the uptake of gas and promotion of the CNG infrastructure development, as the existence of standards helps various parties across the supply chain. Depending on the variation in gas specification allowed in the standard, engine efficiency improvements are to be expected due to the high octane of methane gas which is strongly synergetic with downsizing. The share of natural gas/ biomethane mixtures is expected to increase to 8.3 – 12.5 Mtoe by 2020 (5% market share in the transport sector) and 20.8 – 25Mtoe by 2030 (10% market share) [43]. It is thought that this is due to a combination of consumers willing to buy a CNG vehicle due to the lower operating costs and OEMs willing to produce due to the lower CO_2 emissions.	E10 and B7 limits constrain uptake. Sustainability concerns over use of raw vegetable oils for FAME will constrain supply. ILUC Directive cap of 7% by energy contribution from food-crop based biofuels may constrain growth[44].	The technology is at an early commercial stage. Production capacity is already at 5.7 million tonnes GTL per year and close to 3 million tonnes HVO per year. However, this production mainly takes place outside Europe.	LPG is widely established and has slowly been growing.

[42] http://powerswarm.co.uk/wp-content/uploads/2019/02/21.02.2019-E4Tech-The-cost-of-bulk-electrolytic-hydrogen.pdf

[43] COWI for DG MOVE (2015) "State of the Art on Alternative Fuels Transport Systems in the European Union". Available at: https://tinyurl.com/y39d42es

[44] IEA (2014) "Ethanol and biodiesel consumption in road transport by region in the New Policies Scenario": https://www.iea.org/tcep/transport/biofuels/

LDVs	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO, GTL)	Liquid petroleum gas and bio-LPG
Other technical and infrastructural barriers	Chicken and egg problem associated with the development of refuelling infrastructure and deployment of vehicles.	Lack of forecourt infrastructure in certain MSs remains the main barrier to uptake of CNG. Currently MSs such as Austria, Belgium, Bulgaria, Czech Republic, Germany, Italy, the Netherlands, Sweden and Switzerland have well developed CNG infrastructure. Methane slip throughout the WTT pathway presents a challenge, which needs to be further analysed and mitigated with new technologies. Transportation competes with power generation and heating for sustainable gas. The overall availability of sustainable gas and the exact nature of the regulatory framework will likely determine the attractiveness of wide scale uptake of sustainable gas in transportation.	Within EN228 there is significant room to blend mixtures of alcohols and ethers and therefore replace more gasoline in the LDV sector. Alcohols in particular could however also be used as diesel replacement (such as ED95, see HDV sections), which in the longer term might be more desirable if the gasoline / diesel ratio in the EU becomes even more unbalanced. The FAME content in diesel can in principle be increased with adapted vehicle and engine technology and used in LDV, HDV and other diesel consuming machinery.	Challenges are mainly around the production process scale and cost effectiveness. This depends largely on production volumes and prices relative to the alternative.	LPG forecourt infrastructure is established, but could be enhanced to stimulate more LPG vehicles. It is possible to use LPG as a dual fuel or blended with DME in CI engines potentially in LDV and HDVs

3.2 Heavy Duty Vehicles

Heavy duty road vehicles (trucks and buses) are predominantly powered by diesel engines currently. This is a consequence of the superior fuel efficiency and low end torque compared to SI engines resulting in better operating characteristics. The heavy-duty vehicle sector is characterised by many different vehicle categories, technologies, sizes and weights, as heavy-duty vehicles are typically customised for specific clients and uses. This range of different vehicle combinations makes it difficult to estimate important parameters such as fuel consumption and CO_2 emissions in a reliable and cost-effective manner. Heavy-duty vehicles were responsible for 27% of road transport CO_2 emissions and almost 5 % of EU greenhouse gas emissions, in 2016[45]. Since 1990, heavy-duty vehicle emissions have increased by 25% – mainly as a result of an increase in road freight traffic – and, in the absence of new policies, they are projected to further increase.

For ICE based powertrains, diesel engines naturally suffer from high engine-out emissions, particularly NOx and Particulate Matter, which so far have been very successfully countered by increasingly sophisticated and costly aftertreatment systems. Cost effective alternative fuels that have cleaner combustion characteristics could therefore play a significant role in powering the HDVs of the future. Currently the focus seems to be mainly on LNG, but many other options could contribute. These could include DME, ethanol or methanol with an ignition improver, HVO or some of the other synthetic paraffinic kerosenes (SPKs), while increased levels of FAME with improved aftertreatment systems could also play a role, even though some of these alternatives entail modifications in the engines and infrastructure and might therefore not be optimal from an overall system standpoint.

In regards to CO_2 emissions standards, it is noted that in May 2018, the Commission proposed a **regulation setting a CO_2 emission performance standards for new heavy-duty vehicles in the EU, as part of the third mobility package**. It would require the average CO_2 emissions from new trucks in 2025 to be 15% lower than in 2019[46]. For 2030, the proposal sets an indicative reduction target of at least 30% compared to 2019. Special incentives are provided for zero- and low-emission vehicles. The proposed regulation applies to four categories of large trucks, which together account for 65-70% of CO_2 emissions from heavy-duty vehicles. The Commission proposes to review the legislation in 2022, in order to set a binding target for 2030, and to extend its application to smaller trucks, buses, coaches and trailers.

It is noted, that the EU will be the last major HDV market to introduce fuel-efficiency standards. Japan established the first mandatory fuel-efficiency standards for HDVs in 2006, following a "top-runner" approach in which the standards are set based on the performance of the best vehicles in the market in the baseline year. Improvements were limited to engine modifications and resulted in modest emissions reductions of 1.2% per year[47]. A second stage, proposed in 2017, incorporates additional technologies such as aerodynamics and tires. It targeted 13-14% reductions on average for trucks and buses but only 3.7% for tractors. China has issued three stages of progressively more stringent standards. The first stage, the "Industry Standard," was implemented in 2012 and covers three segments—tractors, straight trucks, and coach buses. The second stage, the "National Standard," went

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[45] European Environmental Agency -EEA (2018), Carbon dioxide emissions from Europe's heavy-duty vehicles : https://tinyurl.com/y4m3ttnn

[46] Vettorazzi, S. (2018), Setting CO_2 emission performance standards for new heavy-duty vehicles: Initial Appraisal of a European Commission Impact Assessment, European Parliament, EPRS.

[47] Rodriguez F., Delgado F. (2018). CO_2 emissions and fuel consumption standards for heavy-duty vehicles in the European Union. Technical Report.

into effect in 2014. It incorporated city buses and dump trucks and tightened the limits by an average of 10.5-14.5%, depending on vehicle category. The proposal for Stage 3 would tighten fuel-consumption limits by an additional 12.5-15.9% and is scheduled to take effect in 2019. The U.S. Phase 1 and Phase 2 GHG standards for HDVs are arguably the most comprehensive standards yet as they incorporate a larger set of technologies, including separate standards for engines and trailers. The highest fuel-consuming segment, tractor-trailers, will see reductions of about 50% in 2027. In 2017, India finalized its first fuel-efficiency standards for commercial HDVs. Phase 1 goes into effect in 2018, and Phase 2, in 2021. The target reductions are about 11% on average[44].

Current research activities in the ICE based powertrains HDV sector focus strongly on improving fuel consumption for lower cost of operation of the complete vehicle. For the powertrain this focuses on reducing waste energy as well as high efficiency, low polluting combustions systems. These combustion systems are available in various formats and have a large number of names (HCCI, CAI, PPC, LTC and others), but essentially share the aim of efficient combustion at lower temperatures to reduce engine out NOx emissions and are therefore captured here in Low Temperature Combustion systems (LTC). Research into a number of different alternative fuels is ongoing (including DME, ED95, NG) and for OEMs the focus is strongly focused on developing cost-effective system solutions integrating varying levels of electrification with combustion engines depending on typical duty cycles the product will experience. This is also shown in **Figure 13** where "**hybridisation"** and **"transient electric research"** go hand in hand with engine **"right sizing"** and **"high efficiency research narrow operation"**. Research is also taking place on the electrification of roads (e.g. using overhead contact lines)[48].

When it comes to electric powertrains, both electric buses and electric trucks are making good progress with commercial offers available. As mentioned above, BEV are treated in the STRIA roadmap on electrification while FCEV are treated in the present document.

Hydrogen buses projects have flourished across Europe over the past ten years, many of them thanks to the support of EU funding via the FCH JU (for example projects JIVE [49]and JIVE2[50]), and there are early commercial buses on offer.

Hydrogen trucks demo-projects are now also financed via the 2018 programme. Additionally, Hyundai announced at the end of 2018 that it will provide 1600 hydrogen trucks to clients in Switzerland with operations starting in 2019. This type of commercial offer could be a game changer in the landscape of zero emissions HDVs.

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[48] https://www.scania.com/group/en/first-electric-road-nearly-ready-for-operation/ <accessed on April 28th 2019>
[49] https://www.fuelcellbuses.eu/projects/jive
[50] https://www.fuelcellbuses.eu/projects/jive-2

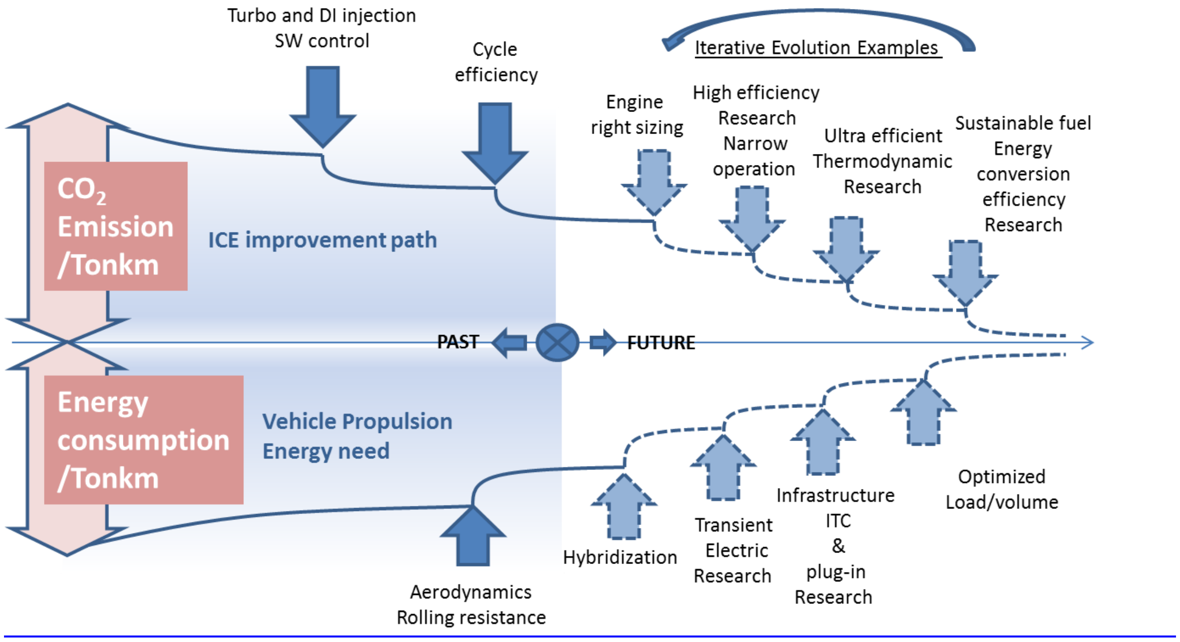

Figure 13- Schematic ICE HD research needs in relation to HD vehicle energy consumption [51]

[51] ERTRAC (2016) "Future light and heavy duty ICE powertrain technologies": https://tinyurl.com/y27xz9qb

Table 8 provides a summary on the state of the art of alternative fuel use in HDVs.

Table 8 – State of the art on alternative fuel use in HDVs

HDVs

	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO)	Liquid petroleum gas and bio-LPG
How much is used and why?	Heavy duty segment currently limited to early stage adoption buses. There is an important interest for hydrogen based heavy duty transport as i) FCEVs offer zero emissions free transport solutions ii) FCs make less noise than ICEs iii) refuelling times are comparable to other liquid and gaseous fuels iv) autonomies and payload are similar to those of conventional vehicles.	There is interest in natural gas for heavy duty transportation. For the HDV sector this is largely driven by the much lower fuel duty per unit of energy compared to diesel and the Euro 6 emissions requirements. HDVs lend themselves much more to captive fleets with more predictable drive cycles that can fit into refuelling routines relying on a less widely distributed refuelling network, or a network at the fleet base e.g. CNG bus. The increase in re-fuelling stations availability has helped the uptake of this technology.	The use of FAME has steadily been increasing to satisfy RED requirements.	Not used in Europe on a large scale yet, except HVO in some countries like Finland.	Negligible use in HDVs.

HDVs

	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO)	Liquid petroleum gas and bio-LPG
How is it used?	Hydrogen use in a vehicle requires the presence of a tank and a fuel cell which allows for the transformation on demand of hydrogen into electrons. Electrons are then supplied to an electric motor directly or can also be stored in a buffer battery before they are channelled to an electric power train. For hydrogen buses and hydrogen trucks, the FC can also be used to produce power to run the climatization system, which is attractive especially for trucks carrying refrigerated food.	Natural gas and bio-methane use in heavy duty vehicles is currently mainly in spark ignition (SI) engines. These engines typically have a lower efficiency than incumbent diesel engines, while compliance with Euro 6 standard is simpler as it only needs a Three Way Catalyst. Natural gas is also used in dual fuel CI engines, but these do not currently meet the Euro 6 methane emission limits. A second generation of dual fuel engines utilising High Pressure Direct Injection is being developed by a number of OEMs targeting Euro 6 compliance while retaining diesel like efficiencies. The gas is either stored in 200 bar on-board pressure tanks (CNG) or in cryogenic liquid form (LNG). LNG has a higher energy density than CNG and is therefore used for long distance haulage. The technology is commercially available in Europe. The technology can also be retrospectively added to the vehicle.	Biodiesel and particularly FAME are extensively used in HDVs through blending (up to 7% by volume) with diesel. Higher blend levels up to B100 are used in dedicated fleets. The use of alcohols with an ignition improver is commercially available from Scania. Volvo has developed DME engines which can be commercialised once the fuel becomes available. The uptake of alcohol and DME engines is currently very limited.	Synthetic fuels can be used as substitutes (in most blend ratio) for diesel, gasoline and jet fuel assuming the finished fuels meet the appropriate standards.	The use in HDVs is currently insignificant, but could possibly be interesting for dual fuel applications.

Trends	A certain number of networks of hydrogen fuelling stations are being developed across Europe. Such hydrogen corridors and ecosystems at the level of a region (H2 Benelux / Zero Emission Valley in Auvergne Rhone-Alpes) or country (H2Germany) allow the development of hydrogen based HDVs applications.	CEN/TC 408 standard for natural gas and biomethane for use in transport and CEN/TC 326 standard for natural gas vehicles - fuelling and operation are being developed and will help increase the uptake of gas and promoting of the LNG infrastructure development. Various projects (such as the LNG blue corridor and GasOn) are currently running in Europe to increase the infrastructure and technology availability. Increasing engine efficiency while maintaining practical engine characteristics and low emissions are the key focus. These include SI lean combustion, HCCI and PPCI and use of heat recuperation to benefit of the higher temperature of SI exhausts. Much research also takes place in further optimising dual fuel engine and aftertreatment technologies. It was reported [52] that the share of natural gas/biomethane mixtures is expected to increase to 8.3 – 12.5 Mtoe by 2020 (5% market share in the transport sector) and 20.8 – 25Mtoe by 2030 (10% market share).	DME and ED95 applications have been developed by Volvo and Scania respectively and are commercially available. So far, the uptake has been limited to mainly buses in Sweden due to infrastructure requirements. VTT is currently researching methanol with an ignition improver (MD95). Some higher biodiesel applications exist also in the field in dedicated fleets.	The technology is at an early commercial stage. Production capacity is already at 5.7 million tonnes GTL per year and close to 3 million tonnes HVO per year. However, this production mainly takes place outside Europe.	LPG is predominantly thought of as a fuel for spark ignition engines. A High Pressure Direct Injection dual fuel system has apparently been developed for application in HDVs (workshop discussion).

[52] COWI for DG MOVE (2015) "State of the Art on Alternative Fuels Transport Systems in the European Union". Available at: https://tinyurl.com/y39d42es

HDVs

	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO)	Liquid petroleum gas and bio-LPG
Vehicle challenges & opportunities	Hydrogen may be better suited for long haul electric HDVs compared to pure battery solutions. Smaller HDVs could be present on the market as BEVs and FCEVs. Several OEMs are working on the development of medium size and large size hydrogen HDVs. The main challenge remains the price of the vehicles. These will drop with an increase in volumes produced.	LNG is a suitable option for long haul HDVs, where CNG is better suited to shorter distance HDVs and LDVs. Natural gas is also used in dual fuel CI engines, but these do not meet the EU VI methane emission limits. A second generation of dual fuel engines utilising High Pressure Direct Injection is being developed by a number of OEMs targeting Euro 6 compliance while retaining diesel like efficiencies. The additional cost of especially the LNG tank can be offset with the lower fuel cost (due to the lower fuel duty). Standardisation of the fuel and increasing the forecourt infrastructure are key enablers to increase uptake. Methane slip from the whole fuel chain is a significant concern and is being addressed with research and technology improvements. Reducing methane emissions from on-board fuel storage and evaporation require further investigation	Higher FAME (TAME) blends have been demonstrated to be possible, but require engine and fuelling system changes and would most likely require aftertreatment considerations. The wider uptake of alcohol based fuels either with a premixed ignition improver, as a dual fuel application or in an optimised SI engine could be of interest. While ED95 technology is mature and a reference fuel standard exists, the other technology would need some further development and the fuels standardising. DME technology is available and relatively mature. ASTM and ISO standards exist which could be translated into a CEN standard.	No real challenges for adoption of these fuels in transport exist as they are direct replacements of the incumbent fuels. Challenges are mainly around sustainable scaling of biomass based systems.	SI engine efficiency improvements are possible due to the high octane of LPG, assuming the standardised composition, which is strongly synergetic with downsizing. Direct injection of liquid LPG could allow for further downsizing, potentially enhancing the thermal efficiency of the engine further. Dual fuel could also unlock further efficiency improvements, but would require significant aftertreatment equipment to meet Euro 6.

HDVs

	Hydrogen	Natural Gas / Bio-methane / E-gas	Alcohols, ethers & esters	Synthetic paraffinic fuel (FT, HVO)	Liquid petroleum gas and bio-LPG
Other technical and infrastructural barriers	Lack of infrastructure remains a barrier to EU wide uptake of hydrogen based HDVs. As mentioned above a series of initiatives are aimed at the development of such hydrogen stations. Early demonstration projects are under way to prove technical and commercial feasibility.	Lack of infrastructure remains the main barrier to EU wide take up of LNG. CNG was covered in the LDV section. Currently only certain MSs such as Spain, the UK and the Netherlands have developed LNG infrastructure. The LNG blue corridor project is aiming to add a significant number in strategic location to develop a practical network across Europe. Methane slip throughout the WTW pathway and variation in the make-up of grid natural gas present further challenges. Transportation competes with power generation and heating for (sustainable) gas. The overall availability of sustainable gas and the exact nature of the regulatory framework will likely determine the attractiveness of wide scale uptake of (sustainable) gas in transportation.	Within EN228 there is significant room to increase ethers. Alcohols in particular could be used as diesel replacement which in the longer term might have more impact. The FAME content in diesel can in principle be increased with adapted vehicle and engine technology and used in LDV, HDV and other diesel consuming machinery. There is currently no DME infrastructure.	No particular challenges besides scale up in production.	There are no real technical barriers for further increasing LPG in HDVs. The infrastructure would need to be adapted / upgraded for HDVs however.

3.3 Rail

The railway network in the EU in 2017 was 207,268 km with 180,092 km of electrified rail lines[53]. The quarterly rail passenger transport performance in the EU-28 during the period of 2013-2017, indicates (**Figure 14**) that after a period of sustained growth, rail transport performance in passenger-kilometres started to feel the effects of the economic crisis at the beginning of 2009. Rail passenger transport nevertheless remained less affected than rail freight transport, and registered a recovery from 2010 onwards.

Figure 14- Quarterly rail passenger transport performance in the EU-28 [54]

All MS rail strategies favour further electrification, but there are routes where electrification is not economically viable, the cost of deploying a power line above the tracks being around 1 MEuros/km. On these routes, locomotives using ICE and fuelled with alternative fuels can play a role. Alternatively, an electric train solution can be implemented consisting of a battery-based solution (for short distance) or hydrogen fuel cell based solution (for long distance).

Rail engines are classed and regulated as Non-Road Mobile Machinery (NRMM). This is currently at stage IV with stage V emission regulation under consideration and can be found in the 2004/26/EC directive. In the 2010 "**Rail Sector Strategy 2030 and beyond**" [55], the European rail sector set a vision to reduce specific energy consumption by 50% by 2050. Also, by 2030, the European railway sector has targeted to reduce total emissions of CO_2 by 50% and of NOx and PM_{10} by 40% and aims at zero emission by 2050. Developing flexible ICE systems able of maximum fuel conversion efficiency, and integrating emissions reduction technologies and hybrid propulsion systems, will contribute to achieve these targets in areas where electrification is not an option.

To meet increasingly ambitious emissions reductions and efficiency gains, rail transport is considering the use of alternative fuels such as liquefied natural gas (LNG) [56, 57], liquid biofuels and synthetic fuels

[53] UIC (2018) Railway Statistics 2017. Available at : https://uic.org/IMG/pdf/uic-statistics-synopsis-2017.pdf
[54] Eurostat Database: https://ec.europa.eu/eurostat/data/database <accessed on May 22nd 2019>
[55] http://81.47.175.201/livingrail/docs/2010_moVing_ToWards_susTainable_mobiliTy.pdf
[56] Railway Technology (2013) "Hydrail and LNG: the future of railway propulsion". Available at: http://www.railway-technology.com/
[57] Railway Technology (2013) "Russian railways: connecting a growing economy". Available at: http://www.railway-technology.com/

in trains running with ICEs, and battery and hydrogen fuel cell based solutions in electric trains, and also looking at improvements in energy efficiency and weight reductions.

Biodiesel (FAME) could also be an alternative fuel[58-59]. However, existing diesel traction engines running with blends in excess of B30 can lead to increased fuel consumption and decreased power, and higher maintenance costs. LNG and biomethane (LBG) offer reductions of particulate matter emissions and tailpipe GHG emissions, but the WTW GHG emissions of LNG depend largely on the levels of methane slip and source of the gas. This technology is considered for new locomotive development rather than for retrofitting of existing ones, due to the extra-space needed for LNG tanks.

Hybrid diesel-electric locomotives that capture braking energy and store it in batteries can offer significantly reduced energy consumption and lower emissions. Different technologies will be suitable for different train types. **Table 9** provides a summary of options for alternative fuel use in rail transport in UK context[60]. It should be noted that H_2 for high speed passenger and freight rail transport considered not to be viable on the basis of energy and power requirements, but viability could vary based on specific regional infrastructure and economic conditions. **Table 10** provides a summary on the state of the art of alternative fuel use in rail transport.

Table 9 – Alternative fuel use in rail transport

		Electric		Autonomous Power			
Future Rolling Stock Category	**Description**	**AC Electric (OLE)**	**DC Electric (third rail)**	**Diesel**	**Hydrogen**	**Battery**	**Biodiesel**
A	Shorter distance self-powered with 75 mph maximum speed	✓	✓	✓	✓	×	✓
B	Middle distance self-powered with 100 mph capability	✓	✓	✓	×	×	✓
C	Long distance self-powered with 125 mph capability	✓	×	✓	×	×	✓
E-A	Electric to 100mph, self-powered to 75mph	✓	✓	✓	✓	×	✓
E-B	Electric to 100mph, self-powered to 100mph	✓	✓	✓	×	×	✓
E-SH	Electric to 100mph with ability to do short hops 'off wire'	✓	✓	✓	✓	✓	✓
F-A	Electric to 125mph, self-powered to 75mph	✓	×	✓	✓	×	✓
F-B	Electric to 125mph, self-powered to 100mph	✓	×	✓	×	×	✓
F-C	Electric to 125mph, self-powered to 125mph	✓	×	?	×	×	?
F-SH	Electric to 125mph with ability to do short hops 'off wire'	✓	×	✓	✓	✓	✓
Freight	Freight loco capable of hauling 2500 tonne trailing load	✓	✓	✓	×	×	✓

"?": question whether one can build bi-mode train with 125mph performance in both diesel and electric mode within space constraints, especially in UK where the loading gauge is small compared to elsewhere

[58] European Biofuels Technology Platform - EBTP (2016) "Strategic Research and Innovation Agenda": https://tinyurl.com/y46xya5f
[59] EC (2013) "Clean Power for Transport: a European alternative fuels strategy". Available at: http://eur-lex.europa.eu
[60] Kent S, Iwnicki, S, Houghton T and Hillmansen S (2018) – Options for Traction Energy Decarbonisation in Rail: Interim Report for WP2.1 Options Evaluation. RSSB.

Table 10- State of the art on alternative fuel use in rail

RAIL

	Hydrogen	Biodiesel	LNG / Liquid biomethane / E-gas
How much is used and why?	The world first hydrogen train has been put into commercial operation since last September 2018 in Saxony, Germany. It offers an alternative to the overhead electrification of rail while keeping an electric train and its advantages (no emission), and with a fuel autonomy of 800 km.	Only trial quantities.	Diesel prices in Europe remain considerably higher than NG on an energy-equivalent basis. LNG is used in pilot demonstrator in Spain, with claims that NOx, CO and PM are reduced by 70%, and GHG by 20-30%. Russian Railways have tested gas-reciprocating traction technology in 2015, while in 2013 trials began of the world's first LNG-powered locomotive (TEM19).
How is it used?	The hydrogen train is a combination of a typical electric power train with additional Li-Ion batteries (to act as a buffer), and hydrogen tanks and fuel cells on the roof to transform hydrogen into additional power when needed. Refuelling the trains is done at a given location (usually the maintenance place) with a dedicated filling station.	AMTRAK (USA) and BNSF Railway (USA) used B20 for one-year tests	TEM19 with gas reciprocating engine has modular design and is equipped with multifunctional microprocessor control and monitoring system. LNG is stored in a removable cryogenic tank.
Trends	Several European rail operators are now interested in this kind of train (SNCF in France, Eversholt Rail in the UK, …) and there are several new types of hydrogen trains in development with different consortia.	Several European rail operators have carried out trials on rail vehicle and engines (e.g. French SNCF, German DB, Czech CD, Hungarian MAV).	Trials have also taken place other countries e.g. Canada, and small scale liquefaction technology, such as GE's MicroLNG, could allow to liquefy natural gas at any point along a gas distribution network. Lower running costs associated with LNG are appealing

RAIL

	Hydrogen	Biodiesel	LNG / Liquid biomethane / E-gas
Vehicle challenges & opportunities	The opportunities are significant as large parts of the railroads in Europe are not electrified and it is not economically viable to electrify them. Hydrogen trains could provide an economic zero emissions alternative with sufficient range. Challenges remain in reducing costs of hydrogen trains, including through volume production.	Challenges include: Lower energy content Poor low temperature starting / operation Poor oxidation stability and water absorption characteristics Opportunities include: Higher cetane number and flash point as well as improved lubricity Biodegradable and low toxicity (these are similar for all vehicles and depend on the blend ratio)	Technology not available for retrofitting the existing locomotives. Modular design significantly simplifies locomotive maintenance and repairs. It takes less time to warm up the engine in the cold weather/regions.
Other technical and infrastructural barriers	There is the need to build an alternative refuelling infrastructure but train refuelling offers scale and could be used to fuel other vehicles (like buses or trucks). For certain tracks (steep ones) specific designs will have to be considered to have additional traction power on-demand.	Incompatibility with certain elastomers and natural rubbers. More rapid lubricating oil degradation. Degradation during long-term storage.	Switching from diesel fuel to LNG would require a new delivery infrastructure for locomotive fuel

3.4 Waterborne transport

Waterborne transport, from recreational craft to large ocean-going cargo ships, is driven primarily by diesel engines (around 99 %), using mainly **heavy fuel oil (HFO)**, which tends to be high in sulphur, and **middle distillate fuel (MGO)**. The waterborne transport sector has internationally recognised standards that define the characteristics of fuel oils and what they can contain, so as to be suitable for use on-board ships (**ISO 8217:2017 being the most widely used standard**). The 2017 update of this standard (previously 2012) included new grades of distillate fuel which allow up to 7% blend of the biofuel Fatty Acid Methyl Esters (FAME). This upgrade brings these distillate fuels in line with the 7% blend in road sectors.

In 2015, shipping emissions represented around 13% of the overall EU GHG from the transport sector and if global shipping was a country it would be the 6th largest GHG emitter in the world. Shipping is amongst the largest emitters of SO_X and NO_x pollutants (i.e. the 15 largest ships producing more SO_x pollution than all the cars in the world[61]). **Figure 15**, illustrates the environmental burdens from shipping activities. By 2050, the internationally agreed target for maritime transport is to **reduce total net GHG emission by at least 50% compared to 2008**[62]. But, the current trend points to an increase in future shipping GHG emissions as a result of projected growth in global trade. Significant measures in relation to **energy efficiency, innovative propulsion and fuel substitution** are required[63].

As with other sectors, there is no silver bullet solution to decarbonisation. It is likely that halving carbon emissions will require a range of options, including new fuel sources and raising technical and operational efficiencies. Shipping has undergone paradigm shifts regarding the usage of fuel before; it went from sail to coal in the mid 1800's, coal to diesel in the 1920s and from diesel to heavy fuel oil (HFO) in the 1950s. Waterborne transport is responsible for emitting approximately 1.1 Gt of CO_2 (3% of global greenhouse gas emissions), as well as 2.3 Mt of SO_2 and 3.2 Mt NOx per year[64]. However, commercial entities are also showing willingness to transition, with for example Maersk (the world's largest shipping container company) recently announcing its intentions to be net-zero carbon by 2050, with carbon-neutral vessels commercially viable by 2030[65]. Also cruise ship companies are facing market pressure to reduce their environmental impacts and have been early adopters of alternative fuels and green shipping technology. Alongside the IMO agreement, various policy measures were suggested for the short- (2018–2023), medium- (2023–2030) and long-term (beyond 2030). Short-term measures include incentivizing speed reduction and optimization, which will have the largest impact, as well as strengthening the **Energy Efficiency Design Index (EEDI)**, incentivizing early adoption of low carbon technologies, developing carbon intensity guidelines for all marine fuels, and research into innovative technologies and low carbon fuels, as well as deployment of available low carbon fuel options. Mid- and long-term measures are to develop zero emission solutions and fuels, such as high power marine fuel cells and hydrogen / ammonia fuel, as well as build upon the short-term measures and develop market-based-mechanisms to incentivize substantial emissions reductions.

[61] https://www.economist.com/finance-and-economics/2017/03/11/green-finance-for-dirty-ships

[62] International Maritime Organization - IMO (2018), Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO Activity related to reducing GHG emissions in the shipping sector : https://tinyurl.com/yxcdgmfn

[63] IEA (2013) "Alternative Fuels for Marine Applications". Available at: https://tinyurl.com/yyxu6d7g

[64] International Maritime Organization –IMO(2012), EEDI – rational, safe and effective, London

[65] Maersk (2018). Maersk sets net zero CO_2 emission target by 2050. In: Moller AP, editor

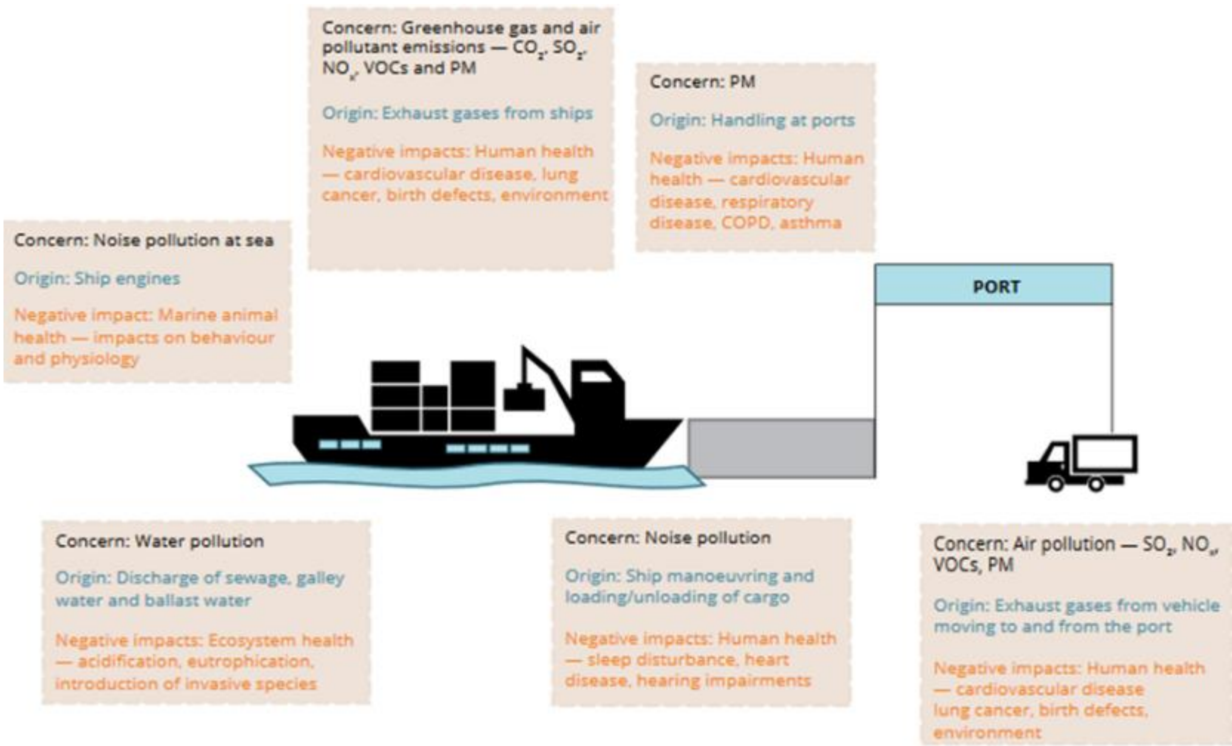

Figure 15- Environmental burdens from shipping activities [66]

Whilst GHG regulations have only started to be developed, IMO SOx regulations have been a driver for alternative fuel use in waterborne transport since 2005. This has been mainly through defined **Sulphur Emissions Control Areas[67] (SECAs)**, but also through global standards, forcing ship operators to either install exhaust after treatment equipment or switch to low-sulphur fuels. In 2020, the IMO global sulphur content standard will go from 3.5% to 0.5%, which will prohibit the use of unabated Heavy Fuel Oil, unless it has been desulphurised at the refinery to make Low Sulphur Heavy Fuel Oil (LSHFO). Additionally, the **EU Directive 2012/33/EU** sets limit at 0.1% sulphur content in waterborne fuel oil for all ships in the North Sea and the Baltic Sea SECAs; at 1.5% sulphur in fuel for all passenger ships operating to or from any EU port, and 0.1% sulphur fuel at berth in ports. European inland navigation is classed and regulated as Non-Road Mobile Machinery (NRMM). This is currently at stage IV with stage V emission regulation under consideration and can be found in the 2016/1628EC directive[68]. Outside of European waters, Canada and the US coastline have the first introduced emission control zone for SOx, NOx and PM in 2016. NOx is also regulated by the IMO with tiered standards for all ships built since 2000. Increasing regulation to reduce air pollutants such as SO_x and NO_x, and concern over potential secondary water pollution from exhaust treatment systems, have caused the shipping industry to think about alternative fuels, with some of the options to reduce air pollutants also reducing GHG emissions.

[66] EEA (2017), Aviation and shipping -impacts on Europe's environment : https://www.eea.europa.eu/publications/term-report-2017

[67] MARPOL annex VI. Established SECA in Baltic, North Sea and English Channel where a phased reduction of SOx emissions was initiated. The allowable amount of fuel sulphur was reduced to from 1.5% to 1.0% in July 2010 and is to be further lowered to 0.1% in January 2015.

[68] EU (2016), Regulation 2016/1628: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1628

Alternative fuels such as biofuels, methanol and methane based gases (CNG, LNG) can help satisfy the above requirements by substituting the fossil petroleum fuels currently in use. However, where dedicated engines are used, fuels will need to be available in sufficient quantities worldwide or regionally for bunkering. So far, the focus is mainly on LNG, but methanol is also receiving significant interest, with Stena Line deciding to retrofit one of its vessels to use methanol[69;70;71]. Whilst LNG and fossil methanol offer advantages over the incumbent fossil petroleum fuels in terms of air quality emissions, they will not meet more stringent GHG reduction targets, and can only be envisaged as interim solutions.

Renewables (such as wind assistance), biofuels, hydrogen and derived fuels (e.g. ammonia, methanol) all have potential to reduce shipping GHG emissions, and range from economically feasible short-term options to less developed long-term options. The most applicable advanced biofuels to international shipping applications are: Fischer-Tropsch diesel (FT-Diesel), pyrolysis and hydrothermal liquefaction (HTL) oil, ligno-cellulosic ethanol (LC Ethanol), bio-methanol, dimethyl-ether (made from bio-methanol) and bio-LNG. Diesel-like fuels, such as SVO, HVO, FAME, FT-diesel and pyrolysis oil can be used in current marine diesel engines with no or small engine modifications and can also use the current storage and bunkering infrastructures.

Alcohols and gaseous fuels like bio-ethanol, bio-methanol, bio-LNG and bio-DME require more significant changes to engine, storage and bunkering infrastructure, incurring additional capital costs. They all require spark ignition engines, dual fuel compression ignition engines or converted compression ignition engines, given their lower cetane number (with the exception of DME) and cannot self-ignite[72]. The sustainable scalability of alternative fuels to achieve a substantial impact is one of the most significant challenges. In the case of biofuels, strong legislative frameworks for bioenergy, e.g. via the EU's Renewable Energy Directive, are a way to mandate sustainable practices.

The **Alternative Fuel Infrastructure Directive** (Directive 2014/94/EU) requires national action plans for LNG bunkering facilities. Current research activities in waterborne transport are concentrated on combustion systems to reduce emissions and fuel consumption. This includes research on dual-fuel engines (gasoil/diesel and natural gas) and advanced fuel injection systems to reduce emissions while maintaining or improving energy efficiency. Partially pre-mixed (and other forms of low temperature) combustion systems combined with exhaust gas re-circulation and waste heat recovery are also topics of research for the same reasons. Methane leakage throughout the fuel supply and storage chain could (partly) offset GHG emissions and requires further research.

More recently, hydrogen has made an appearance in the landscape of alternative fuels for waterborne transport applications, either as a possible blend with existing gaseous and liquid fuels, or as the sole fuel in combination with a fuel cell and electric powertrain. Hydrogen has relatively low volumetric density, when compared to incumbent and other alternative fuels, and requires specialised storage either through compression or liquefaction. This raises questions around the suitability of hydrogen in vessels with high power and energy requirements and used for long range transport. There are costs and energy implications associated with the new equipment and infrastructure associated with storing

[69] DNV GL – Maritime (2014) "LNG as ship fuel. Alternative fuels for shipping". Available at: https://www.dnvgl.com/maritime/
[70] TEN-T Projects (2013) "LNG infrastructure of filling stations and deployment in ships". Available at: https://tinyurl.com/y4pu2gfd
[71] EU (2016) "Significant LNG fuelled Ships". Available at: https://lngforshipping.eu
[72] Maritime Knowledge Center (2018), TNO, TU Delft. Methanol as an alternative fuel for vessels.

hydrogen in these ways, as well as a cost from the revenue lost for any increase in the amount of space needed on board a vessel. For small vessels, several pilot projects are surfacing, like the **Hydroville**[73] in the port of Antwerp, the first certified passenger shuttle that uses hydrogen to power a diesel engine (a project run by CMB and Volvo), or the Energy Observer[74], the first hydrogen autonomous vessel that produces the hydrogen it uses on board, a project backed by several large companies. In the field of larger applications, several major players are working on hydrogen based propulsion systems (Man, Siemens, ABB, etc.). Large cruise ship operators are working also on hydrogen propulsion systems. Recent EU funds are also backing several demo projects with hydrogen as a fuel for river transport applications (2018 FCH-JU program), two ships (one in France and one in Norway) as part of the **FLAGSHIP**[75] project, and a first renewable hydrogen ferry going at sea in Scotland as part of the H2020 project **Hyseas III**[76]. All these projects follow an array of about 30 international and European projects identified by the **European EMSA (European Maritime Safety Agency)** in its 2017 study on the use of fuel cells in shipping[77].

The issues with storage and handling of hydrogen for waterborne transport could be solved by using hydrogen-derived fuels (also known as synthetic fuels), for example ammonia that is made from hydrogen through the Haber-Bosch process. Ammonia (chemically NH_3) is already shipped globally for the fertiliser and refrigerant industries, and can be transported and stored more easily than hydrogen itself. Whilst at the early stage of development, ammonia can be potentially combusted in a large dual fuel marine engine[78], used directly in a specialised fuel cell or dissociated to form hydrogen to be used as fuel. Ammonia is a toxic substance and its use as a fuel in a maritime environment would require development of new regulation to ensure safe use. The emergence of ammonia as a fuel for shipping is focusing interest on research on ammonia engines and fuel cells.

Table 11 provides a summary on the state of the art of alternative fuel use in waterborne transport.

[73] http://www.hydroville.be/en/hydroville/
[74] http://www.energy-observer.org/en/
[75] https://www.fch.europa.eu/page/transport#FLAGSHIPS
[76] http://www.hyseas3.eu/
[77] http://emsa.europa.eu/news-a-press-centre/external-news/download/4545/2921/23.html
[78] https://tinyurl.com/y46u5btk

Table 11 – State of the art on alternative fuel use in waterborne transport

Water-borne	**Hydrogen & ammonia**	**LNG / Liquid biomethane / E-gas, CNG**	**Alcohols & esters**	**Synthetic paraffinic fuel (FT, HVO)**
How much is used and why?	Much like heavy-duty land vehicles, larger marine vessels require high energy and power density that may favour use of hydrogen or a hydrogen-derived fuel over pure battery solutions. Several pilot projects are emerging in the world and in Europe with hydrogen used as a fuel, either in compressed or liquefied form, and either mixed with other gaseous and liquid fuels in combustion engines or used pure in a fuel cell. In parallel to pure hydrogen a certain number of developments are exploring a power to hydrogen to ammonia approach for use is a dedicated fuel cell or engine. Ammonia is liquid at low pressuers and can be more easily transported and stored than hydrogen. Direct synthesis of ammonia is more energy efficient than other power to X fuels except Hydrogen. Ammonia may potentially be usable directly as a retrofit within dual fuel combustion engines as well as with higher efficiency within fuel cells as a more available fuel type	Depending on the combustion and after treatment technology used, LNG can lead to significant emissions reductions. Reductions of 85–90% for NOx, near 100% for SOx and PM and 15-20% for GHG emissions[79] has been claimed, although there is uncertainty in this respect due to methane emissions along the supply chain. Methane slip (the release of unburnt methane) is a challenge but technologies are available to overcome some of this. The first LNG-fuelled ferry based on DNV GL standards was launched in 2000[80]. In EU, 83 LNG-fuelled ships (excluding LNG carriers) are in operation – of which 61 operate in Norway. In 2016, very large cruise ships are on order with LNG dual fuel capability. CNG has a lower power density but is easier to handle and is feasible for recreational and inland craft.	Interest in methanol as ship fuel is growing in response to the need to reduce SOx emissions. In 2015 STENA Line launched the first methanol powered ferry[81]. The NOx emissions from methanol are 45 % of those of conventional fuels and SOx emissions are 8 % of those of conventional fuels (per unit energy). Further reductions are possible with aftertreatment. Ethanol is blended with gasoline in small boat engines [82]. Butanol has similar energy density and octane number as gasoline, which allows higher blends without affecting the energetic performances. Biodiesel blend (B20) was tested with good results in US.	Not yet used in European waterborne transport[63].

Water-borne	Hydrogen & ammonia	LNG / Liquid biomethane / E-gas, CNG	Alcohols & esters	Synthetic paraffinic fuel (FT, HVO)
Trends	Several decisions on emissions standards from key marine authorities are placing hydrogen / ammonia based marine applications in a favourable position. The Norwegian Parliament has enacted a resolution to halt all emissions from ships and ferries in the fjords by 2026, while the International Maritime Organization (IMO) intends to reduce GHG emission by at least 50% of 2008 levels by 2050 and the European Maritime Safety Organization (EMSA) by at least 40% (from 2005 levels) by 2050.	For maritime transport, the implementation of Directive 2012/33/EU of 21 November 2012 as regards the sulphur content of Waterborne fuels is expected to be a driver for the promotion of LNG for ships [83]. 88 LNG-powered ships are under construction, with planned deliveries by 2018[84]. Market studies predict that the LNG demand for Waterborne sector will reach 5.2 Mtoe in 2020 and 8-12 Mtoe in 2030[85]. The alternative fuels infrastructure directive[86]requires national plans to foresee the deployment of LNG fuel infrastructure in ports.	The environmental assessment of methanol produced from biomass has the potential to reduce life-cycle emissions by over 80% for GHG, SOx, NOx and PM, which is similar to BioLNG[63]. There are already demands on methanol as alternative fuel. Methanex has ordered 4 tanker ships on methanol. Waterfront Shipping received 7 new chemical tankers with dual fuel methanol engines in 2016[87]. The technology for biobutanol is not yet mature but US DoE anticipates the potential availability at industrial level.	The Dutch Energy Vision estimates penetration for GTL as a fuel in the inland shipping sector to 11% by 2030 and 19% by 2050, and in recreational vessels to 19% in 2030 and 31% in 2050 [88] . There is an interest in displacing heavy fuel oil with biomass derived fuels produced using pyrolysis and hydrothermal liquefaction technologies.

[79] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/LNG%20Study.pdf
[80] TEN-T Projects (2013) "LNG infrastructure of filling stations and deployment in ships". Available at: **https://tinyurl.com/y4pu2gfd**
[81] IEA (2013) "Alternative Fuels for Marine Applications". Available at: **https://tinyurl.com/y3zstxfc**
[82] EMSA (2015) "Study on the use of ethyl and methyl alcohol as alternative fuels in shipping". Available at: **https://tinyurl.com/y4snmu3r**
[83] EU Directive 2012/33 : **https://tinyurl.com/y284lwfn**
[84] DNV, GL – Maritime (2018). LNG Regulatory update. "Best fuel of the future", Conference and Study Tour. Available at : https://tinyurl.com/y2c65ta9
[85] DNV GL – Maritime (2016) "Engines for gas-fuelled ships". Available at: https://www.dnvgl.com/maritime/
[86] EU, Alternative Fuels Infrastructure Directive : **https://tinyurl.com/y4wzboyf**
[87] https://www.wfs-cl.com/news/2017/04/methanol-fueled-vessels-mark-one-year-safe-reliable-and-efficient-operations
[88] Ditch Ministry of Infastructure and the Environment (2014). "A vision on sustainable fuels for transport". Available at: **https://tinyurl.com/y55lrn8g**

Water-borne	Hydrogen & ammonia	LNG / Liquid biomethane / E-gas, CNG	Alcohols & esters	Synthetic paraffinic fuel (FT, HVO)
Vehicle challenges & opportunities	The technology is still not widespread and requires further development for costs to decrease. However, hydrogen and hydrogen-derived fuels like ammonia offer very large emissions reduction potential. Large waterborne vessels have high propulsion power requirements that will require large fuel cells that have only been demonstrated in stationary applications so far. More energy efficient, zero / low carbon production processes are needed to reduce the cost of ammonia and hydrogen. Toxicity and safety aspects of ammonia need to be considered.	LNG propulsion technology is ready for application and has successfully been deployed on inland vessels since 2011[68]. Whilst LNG contributes substantially to cutting air pollution, this is less clear with respect to GHG's linked directly to CO2 and methane slip. Methane slip must be eliminated due to its large climate warming effect. Standardisation of the filling station for waterborne transport LNG and greater bunkering capacity would allow further development of new LNG-fuelled ships[89] and promote gas (LNG & CNG) delivery in regions where gas is currently unavailable. LNG offers significant environmental benefits in particular when it is blended with liquid bio-methane[90]. Maximising storage efficiency and minimising boil off is a challenge. In comparison to road, marine combustion engines are already highly efficient because of size and loads. Potentially greater efficiencies maybe achievable through electric propulsion and high temperature LNG fuel cells. LNG is considered as a transition fuel, reducing the environmental impact of shipping, prior to the deployment of zero/low carbon solutions. LNG use within fuel cells, may provide a technology pathway towards full hydrogen operation with a more available fuel, that would also offer increased efficiency.	For using biodiesel in existing ships, the fuel system may have to be modified with biodiesel-compatible components for higher blends (above 7%). Biodiesel in high concentrations can dissolve certain non-metallic materials (seals, rubber, hoses, gaskets) and can interact with certain metallic materials (e.g. copper and brass). For new ships and engines this is much less of a concern. Methanol has a heating value close to LNG (LNG with 20.3 MJ/litre and methanol has 19.8), which entails a similar performance [68]. Also, it has a relatively low flashpoint, is toxic (skin contact, inhaled or ingested) and its vapour is denser than air. As a result, changing fuels poses new challenges to operators in terms of handling and safety. The conversion of an existing engine to burn methanol would bear less costs than an LNG retrofit work [68].	

[89] EU (2016) "Significant LNG fuelled Ships". Available at: https://lngforshipping.eu
[90] JRC (2016) "Alternative Fuels for Waterborne and Inland Waterways". Available at: **https://tinyurl.com/yyv8gt7d**

Water-borne	Hydrogen & ammonia	LNG / Liquid biomethane / E-gas, CNG	Alcohols & esters	Synthetic paraffinic fuel (FT, HVO)
Other technical and infrastructural barriers	Work needs to be done to develop the adequate standards and international rules surrounding hydrogen / ammonia use. Several actors are working on this and DNV-GL has recently pre-approved the first hydrogen ferry design for Norway.	LNG demands more space for fuel tanks, leading to a decrease in payload capacity. Relatively high capital cost for the system installation[91]. The current low LNG price compared to the conventional oil fuel is a main economic driver for this new application, in addition to SOx regulation. However, the current lack of LNG bunkering infrastructure presents an uncertain picture for the LNG fuel price. This leads to uncertainty for ship operators on whether they could benefit from the offset between fuel cost savings and large capital investments. There is a limited refuelling infrastructure and an unharmonized regulatory approach for standardisation in MSs, which will be handled by the new standardisation foreseen by CEN/TC 326 standard for natural gas vehicles - fuelling and operation[92]. The availability of adequately trained port, fuelling and crew in the safe use of LNG must be ensured. Safety of LNG during fuelling and collision must be ensured.	The new mandatory notation LFL FUELLED covers aspects such as materials, arrangement, fire safety, electrical systems, control and monitoring, machinery components and some ship segment specific considerations. The availability of adequately trained port, fuelling and crew in the safe use of methanol must be ensured. Conventionally produced methanol refined from natural gas has a higher carbon content than usning natural gas or LNG directly. Synthesised methanol is a less efficient process than hydrogen or ammonia. The scaling of sustainable biodiesel to the quanttities needed with respect to the demand and competition for feedstocks from other sectors such as aviation is a challenge.	

91 TEN-T Projects (2013) "LNG infrastructure of filling stations and deployment in ships". Available at: https://tinyurl.com/y4pu2gfd

92 https://www.dnvgl.com/maritime

3.5 Aviation

Efforts made through technological progress and operational improvements have significantly improved the energy efficiency of air transportation. However, even with the most radical technological progresses, the efficiency gains will not offset the expected traffic growth or allow achievement of the challenging commitments for decarbonisation made by the aviation industry by 2020 and 2050. A global market-based mechanism has been agreed by Member States to ICAO's Committee for Aviation Environmental Protection, which aims to address international aviation emissions, called the **Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).** Under CORSIA, the aviation sector will need to maintain international aviation CO_2 emissions at or below 2020 level. This requirement may be satisfied by the purchase of offset credits from crediting mechanisms, or allowances from emissions trading schemes, such as the UN Clean Development Mechanism (CDM) or the Reducing Emissions from Deforestation and forest Degradation (REDD+) programme. The implementation of this policy means there would need to be a financial incentive for airlines to reduce their international CO_2 emissions[93].

In order to mitigate the cost of offsetting CO_2 emissions to comply with sectoral climate policies such as CORSIA, the aviation industry may reduce its CO_2 emissions directly through improvements in airframe and engine technologies, more efficient aircraft and ground operations and the use of sustainable alternative jet fuels (AJF). Low-carbon synthetic fuels produced from renewable sources are expected to play a key role in meeting aviation sector decarbonisation targets in 2050 [94].

Today the vast majority of commercial aviation flights use Jet-A1 (also known as kerosene). Due to the high cost of aircrafts and the long fleet replacement time, and also to limit infrastructure changes, the aviation sector is likely to rely in future when looking for greener substitutes on liquid fuels similar to kerosene up to 2050 and possibly beyond. All of the alternative jet fuels currently certified or under development are 'drop-in' fuels, which can be blended at a limited percentage into conventional kerosene whilst meeting existing specifications. The composition of these new fuels is currently mostly paraffinic, being known as Synthetic Paraffinic Kerosene (SPK) or iso-paraffins. There are five (5) major fuel routes approved for its use in civil aviation: FT-SPK, HEFA-SPK, HFS-SIP, FT-SPKA/A and ATJ-SPK. In addition, co-processing of up to 5 vol% fats and oils in a refinery to produce kerosene is certified. There are also seven routes currently under approval process, plus other 15 under process[95]. Sustainability of alternative jet fuel production processes depends upon the feedstock and method of production. Drop-in fuels could also be produced from electric power, known as power-to-liquid (PTL) or directly from sunlight.

The alternative fuels mentioned are used blended with conventional Jet-A1 according to the limits established by the standard **ASTM 7566**. Once blended, the fuel is considered as Jet-A1 (ASTM 1655 or DEFSTAN 91-91) and can be used in all civil infrastructures and aircraft that use jet fuel, which is a key advantage to avoid duplication of infrastructures or operations[96]. The blend is needed because the synthetic hydrocarbon fuels do not contain some hydrocarbons naturally present in fossil fuels

[93] International Civil Aviation Organization -ICAO, (2017). What is CORSIA and how does it work? https://tinyurl.com/y6ahgz33 (Accessed March 2019)

[94] International Civil Aviation Organization -ICAO (2013) "ICAO environmental report 2013. Aviation and climate change". Available at: https://tinyurl.com/y28s5z53

[95] CAAFI (2016) "CAAFI – CORE-Jet Fuel Cooperation Workshop". Available at: https://tinyurl.com/y2n9kdpd

[96] ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons". Available at: http://www.astm.org/Standards/D7566.htm

such as aromatics, or other elements such as Sulphur, that are known to play a relevant role for the performance of the aircrafts fuel systems. Overall, these properties make the sustainable fuels cleaner at combustion (clearly for PMs and potentially NOx) and with higher energy content (per unit weight) that translates to some limited energy efficiency gains (due to the reduced weight to be transported and a slightly more efficient combustion). However, the role of those compounds and their interaction with other parameters in the jet fuel are not fully understood, and knowledge is generally based on experience with fossil fuel rather than with these new synthetic alternatives. This means that understanding the optimal properties and limits of blends requires further work.

Most production and use of alternative fuels in commercial aviation has been for demonstration and/or R&I purposes, although this is changing and an increasing number of airports and airlines are operating regular flights on AJF. HEFA-SPK has been blended into the regular kerosene supply at Oslo airport since 2016 [97] and is now available at a number of airports worldwide including Los Angeles[98] and San Francisco[99]. World Energy (which recently purchase AltAir) now runs continuous product of HEFA-SPK at their refinery in Los Angeles (CA). The incentive programs available in the USA and in particular in California for advanced biofuels are supporting World Energy HEFA-SPK production and are also driving the building of another facility for FT-SPK based on municipal solid wastes. At European level, the only incentive for airlines using biojet fuel is the EU ETS for intra-European flights but it is negligible compared with the price gap. Also, aviation is included within some national low-carbon fuel support schemes such as those of the UK and the Netherlands.

Current production capacity for alternative aviation fuels, is still limited globally, and is growing faster in USA than in Europe. This is due mainly to the lack of market due to the high costs of the technology and insufficient policy incentives e.g. compared to road transport. This is very much related to the difference between aspirational and mandatory targets. Also, the limited development of sustainable feedstock supply chains is a constraining factor. The main hurdle for SAF deployment is the cost, and investment required, as the costs are two or three times higher compared to fossil jet fuel. Recent developments in technology are leading to lower production costs and higher availability, as well as higher GHG emissions reductions.

Extensive fuel and engine testing, and issuance of relative certification is compulsory in order to maintain the highest level of flight safety. Work is currently being undertaken both at ASTM level and at national level (through many EU projects, such as the EU JETSCREEN[100] project) to certify alternative aviation fuels.

Pure electric options to fly planes, like battery-based and hydrogen fuel cell-based solutions, remain to this day limited. There are nevertheless pilot projects ongoing, namely for short-distance flights. Airbus has invested together with Roll Royce and Siemens in the development of pure and hybrid electric propulsion. On the hydrogen front, the first hydrogen based small plane has been put in the air in September 2016 by the German DLR centre, while Singapore is home today to the company

[97] ITAKA project (2016) "Press release. ITAKA provides sustainable fuel for worldwide's first biojet supply via hydrant system at Oslo Airport". Available at: **https://tinyurl.com/y2694r3m**

[98] IATA (2019). Sustainable Aviation Fuels Available at: **https://tinyurl.com/y2jaojhe**

[99] **https://tinyurl.com/y5btmw6w** <accessed on 25th of April 2019>

[100] https://www.jetscreen-h2020.eu/

Element One that intends to put a hydrogen based four-seater in the air by 2025. More recently a US company has announced working a 4 to 6 seats piper plane conversion to hydrogen.

Hydrogen is in fact making an entry into aircrafts as an additional fuel which will be used to power certain applications via a fuel cell. One example is to replace the RAM turbine, which is usually located below the cockpit, a small wind turbine that is deployed outside the aircraft when there is a total power outage in order to still have some electricity to fly the plane. Another example is to replace the APU, the Auxiliary Power Unit, which is located usually in the tail of the aircraft and runs on kerosene to power the plane when on the tarmac. A small manned airplane (HY4) has also demonstrated the feasibility of hydrogen-only propulsion.

Table 12 provides a summary on the state of the art of alternative fuel use in aviation.

Table 12 – State of the art on alternative fuel use in aviation

Jet Engines	Hydrogen	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
How much is used and why?	No use of hydrogen in aviation at present	Not used in Europe on a large scale, there is a growing interest in developing these fuels due to substantial potential for decarbonising air transport in the short and medium term[73].The use of sustainable fuel blends has increased from one commercial flight in 2008, to more than 100,000 flights in 2017[101]. Use at airport as non-segregated fuel has started in January 2016 in Oslo[92] increasing the number of flights, but the volumes needed to keep continuous supply are a challenge. There is no continuous production of drop-in fuels for aviation in Europe. Use outside Europe, mostly in USA, has been promoted by military contracts and now starting from private companies.	Used at Lab 'line demonstration project and some Airbus delivery flights, but not used on a continuous basis.	Recently approved, Currently only used in test flights in Europe.[102]	HEFA+ refers to an upgrading from the conventional green diesel (HVO) to the aviation quality standards (cold temperature properties, density). Not yet approved for commercial aviation, but testing is ongoing.	Not used.

[101] https://tinyurl.com/y5btmw6w <accessed on 25th of April 2019>
[102] E.g. used by Lanzatech and Virgin: http://www.lanzatech.com/virgin-atlantic-lanzatech-celebrate-revolutionary-sustainable-fuel-project-takes-flight/

Jet Engines	Hydrogen	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
How is it used?		Synthetic paraffinic kerosene, once it has been blended, can be used as drop-in jet fuel. Maximum blend ratios accepted for commercial aviation are: FT-SPK (50%), HEFA-SPK (50%) and FT-SPK/A (50%)[103]. Once the fuel has been blended and approved according to the ASTM D7566 standard, it can be used in all civil aircrafts and infrastructures using conventional jet fuel without any segregation.	It can be used blended with fossil jet fuel up to 10% v/v [83].	Can be used blended with fossil jet fuel up to 50% v/v [83].	HEFA is approved up to 50%. HEFA + could be used blended with fossil jet fuel up to 15% v/v[104].	It is not drop-in, requires radical change of airframe and combination with electricity. Still not in the market.
Trends	Active research e.g. CLEANSKY programme[105].	The technology is at an early commercial stage and the production capacity is still limited, which is mainly due to economic reasons. However, HEFA is an industrially mature technology. Recently a production facility in Los Angeles (CA, USA) has started continuous production of HEFA, able to produce about 30,000 t of HEFA-SPK per year[106].	The technology is at an early commercial stage with low availability. Developers not focussing on transport market due to low value.	The technology is at an early commercial stage with low availability.	The technology is at commercial stage with high availability. It could be easily adopted with some 'minor' adaptations. HVO (Green Diesel) is well developed for ground transport fuels but HEFA+ is still not certified for aviation use.	Possibilities of using LNG as jet fuel are being explored

[103] ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons". Available at: http://www.astm.org/Standards/D7566.htm

[104] Green Car Congress, Neste and American Airlines collaborate to explore opportunities for renewable fuel use; High Freeze Point HEFA, Available at :**https://tinyurl.com/yyp9fxup**

[105] https://www.cleansky.eu/

[106] Green air online (2016) "United begins regular use of commercial-scale volumes of AltAir's renewable jet biofuel on flights from LAX". Available at: http://www.greenaironline.com/news.php?viewStory=2208

Jet Engines	Hydrogen	SPK (FT, HEFA, FT/A)	SIP	ATJ	HEFA+	LNG
Challenges & opportunities	Liquid fuels are the obliged choice in the short and medium term for long distance air transport, so hydrogen-based solutions will remain limited. There is interest in applications for on-board power and heat using fuel cells. See R&I needs for in later table.	Few technical challenges to fuel use due to their drop-in characteristics at the defined blend ratios. Reaching pure use is still not possible, but could potentially be in the future. Minimum content in aromatics related to fuel system seals is one of the limitations to unblended use synthetic fuels that do not contain aromatics. Lower aromatics result in lower NVPM emissions. Different aerosols, NVPM and soot combustion profiles from SPK suggest different non-CO_2 effects at high altitude that need to be better understood to know the real decarbonisation potential.	SIP is one unique molecule, compared to kerosene, which is a complex mixture of hydrocarbons. May be challenge to get to blends higher than 10%	Same as SPK	Use of low blend ratios of green diesel (as HEFA+ for aviation) SPK if approved could suddenly increase the production capacity and increase the uptake in the short term, but there is still some fuel system testing required to know the limits.	Non drop-in is not feasible in the time frame for a real implementation but it could be a solution for the future.
Other technical and infrastructural barriers	Development and certification of new hydrogen-based systems on board of aircrafts.	Challenges are mainly around the production process scale and cost effectiveness. This depends largely on production volumes and prices relative to the alternative. For new fuels and modification of current blending limits, costly ASTM processes are a barrier. A better understanding of fuel composition limits (fit for purpose) could help to reduce the barrier significantly. There is no other alternative for aviation for decarbonisation or/and fuel independence in the short/medium term. There are some technical constraints for the use of shared civil-military infrastructures as NATO pipelines that need to be tackled to increase the use. The global character of aviation is a challenge regarding competitiveness.				Long time to market, infrastructure

3.6 Summary of trends in alternative fuel R&I

The focus of R&I in powertrains across all transport modes is on increased efficiency and lowering of GHG emissions and of emissions affecting air quality. While continued focus on electrification will help deliver these aims, alternative fuels are also key in achieving these aims. Their impact depends on their characteristics and levels at which they are blended with fossil fuels, and on the development of efficient and clean engines (ICEs and fuel cells).

A variety of alternative fuels are already being tested in buses in public transport systems across Europe. For example, **CityVITAlity and Sustainability (CIVITAS)** initiative projects such as **MOBILIS** and **TELLUS**[107] have tested compressed natural gas (CNG) and biofuels for buses, while a number of cities have trialled hydrogen fuel cell electric buses during projects such as **CHIC**[108] and **HYCHAIN MINI-TRANS**. Many of the vehicles tested during these projects continue to operate under real market conditions after the projects have finished, so delivering continued emissions benefits. Similar projects involving alternatively fuelled cars have also been carried out.

Research is also underway to test the use of alternative fuels in heavy duty vehicles used for freight transport. Projects such as **ENCLOSE**[109] and **BEAUTY** have demonstrated the potential of biofuels to help achieve future emissions limits. These projects have also helped to overcome technical challenges in relation to fuel conversion efficiency and cold start. Another project, **FELICITAS**, investigated fuel cell powertrains and the performance of hydrogen powered vehicles, while **HDGAS** investigated the applicability of liquefied natural gas (LNG). In aircraft, biofuels and synthetic fuels have been investigated. The research projects identified were generally smaller scale projects at an earlier stage of research that developed innovative fuels (such as FIRST). In the shipping sector, a number of research projects are being conducted to develop ships capable of using alternative fuels. Most notably, **HERCULES-2** [110]is developing fuel-flexible engines that will allow for high-performance and low-emissions transport,

Research and Innovation aimed at decarbonizing the different transport subsectors (including aviation, deep-sea maritime freight and HDVs that need energy carriers with high energy densities) needs to continue to focus on the production of advanced biofuels, hydrogen (and possibly ammonia) and synthetic hydrocarbon fuels with more competitive costs, offering long term sustainability. A brief overview of the main R&I activities is provided below by fuel type.

3.6.1 Methane-based fuels

Significant efforts are currently underway to develop High Pressure Direct Injection equipment, which is effectively an improved dual-fuel injection system, and optimised dedicated gas combustion systems. Lean operating dedicated gas engines are being developed for waterborne applications. There is also evidence that dual fuel technology is being developed further to increase diesel substitution rates and minimise methane slip for heavy duty road and waterborne transport. The focus on light duty vehicles is on further downsizing by making use of the high octane of these fuels.

107 https://civitas.eu/content/tellus
108 http://chicproject.eu/
109 http://www.enclose.eu
110 http://www.hercules-2.com/

On-board storage of especially LNG also attracts significant R&D attention across the transport modes in order to make it cheaper, easier to install and lower leakage. Biomethane and power-to-gas technologies could enable a transition to lower carbon content fuels. Focus is also given to the optimization of the production of renewable methane, which can be considered to be the umbrella term for biomethane and power-to-methane produced with renewable electricity. Biomethane and power-to-methane are chemically identical to fossil methane (CH_4) and can be used as substitutes. Currently less than 3% of the transport methane consumption is renewable[111].

The production and use of power-to-methane, which currently is limited to pilot plants in the EU. The future potential can theoretically be considered large, but it is very much dependent on the policy support and the price development and availability of renewable electricity, as the production costs of power-to-methane are very high[112]. The electricity consumption to produce 1 MJ of CNG is 2.58 MJ and 2.59 for LNG, thus large volumes of renewable electricity would be needed. As an example in regards to cost, a study done for the ICCT estimates that a 1.5€/litre subsidy for drop in liquid electrofuels in the 2030 policy framework would deliver around 400 million litres of electrofuels (0.15% of total EU road fuel market in 2030) [113].

A significant number of projects have been conducted focussed on CNG and LNG for both heavy and light duty road transportation. These include the following:

- **LBG: Fuelling- Renewable Transport (2016- ongoing)** [114]: This project supports the transition from fossil fuels to the use of the renewable fuel, bio-LNG, for transport. It forms part of a global project focusing on the realisation of a production facility for bio-LNG and LNG, a network of 20 fuelling stations to sell the produced bio-LNG and LNG in Poland, the Czech Republic, Slovakia and Hungary. It will have an initial fleet of 225 trucks.
- **GasOn (2015-2018)** [115] and **INGAS (2008-2012)** [116] have similar aims to exploit the main benefits of gas-powered engines by developing dedicated, CNG-only engines. INGAS developed technology to allow for a 65 % biomethane gas blend to be used, with the potential for achieving low well-to wheel emissions. GasOn researched methods to achieve future CO_2 emissions targets and reduce air pollutant emissions from vehicles.
- **HDGAS (2015-2018)** [117] and **LNG Blue Corridors** (2013-2017) [118] focused on the use of LNG as an alternative fuel. HDGAS focused on integrating gas engines into heavy-duty vehicles. The technology is expected to deliver CO_2 emissions that are 10 % lower than the current state of the art. LNG Blue Corridors initiated the construction of 14 LNG refuelling stations across Europe and demonstration of 100 LNG heavy-duty vehicles. Liquefied biomethane will also be tested to investigate the potential for CO_2 savings.

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[111] Scarlat, Dallemand & Fahl (2018) Biogas: Developments and perspectives in Europe Renewable Energy Volume 129 p.457-472 .

[112] Malins (2018). What role for electromethane and electroammonia technologies in European transport's low carbon future? - Addendum to What role for electrofuel technologies in European transport's low carbon future? https://tinyurl.com/y3pb65rs

[113] Christensen & Petrenko (2017) CO2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance. Available at: https://tinyurl.com/y62qsw83

[114] https://ec.europa.eu/transport/sites/transport/files/2016-cef-call/2016-cef-country-fiche-sk.pdf

[115] http://www.gason.eu/

[116] www.ingas-eu.org

[117] http://www.hdgas.eu/

[118] http://lngbc.eu/

- **CNG Clean Fuel Box** (2015-ongoing)[119] initiated the deployment of 39 CNG stations and 50 CNG vehicles.

There is also significant activity within industry at the moment including EURO 6 compliant dual fuel combustion systems for HDVs, including methane slip. Methane slip remains an issue throughout the fuel supply chain to the engine, while aftertreatment systems can reduce tailpipe emission to very low levels. R&I efforts are required to reduce the WTT methane emissions, and possibly evaporative emission from on-board fuelling systems.

LNG use in shipping is growing using largely based on dual fuel engines that allow operation on both fuel oil and natural gas.

3.6.2 LPG

Some of the activities discussed in the methane-based fuel section also apply to LPG, specifically around HPDI. For LPG this currently appears to mainly involve the LDV sector even though the technology is equally applicable to HDV and some waterborne applications[120].

LPG-fuelled public buses (including hybrid versions) have been operating in European countries such as Austria (Vienna), Spain (Valladolid) and Romania (Brail and Iasi).[121] However, the fleet in Vienna is now being replaced by alternative technologies.[122]

Recently, Singapore-based owner and operator of LPG vessels BW LPG signed contracts for the delivery and retrofitting of four LPG-propelled dual-fuel engines in its fleet.[123]

3.6.3 Alcohols, esters and ethers

There is a significant amount of work looking at taking advantage of the higher octane of alcohols and ethers in Spark Ignition (SI) engines. The same applies to higher ester blends in diesel for use in Compression Ignition Engines for the Light Duty and Heavy Duty transport modes. A number of academic institutions are researching high efficiency dedicated alcohol engines. DME and ED95 are commercially available products awaiting the roll out of infrastructure. Further work in this area concentrates on improved efficiency, reduced noxious emissions and lowering cost. Work is also underway to research methanol with an ignition improver (MD95), and there is a significant level of activity on dual fuel systems using methanol in the waterborne sector in order to improve efficiency and lower noxious emissions. The rail sector could benefit from the efforts led by other sectors. A number of companies and institutions are developing methanol and ethanol fuelled fuel cell technology for mainly LDVs, HDVs and waterborne applications either as main propulsion or as auxiliary power supply. The focus of this research is around cold start operation, high efficiency, reliability and cost.

Besides from bio-based routes, alcohols and ethers can also be produced using 'green' hydrogen in combination with a suitable source of carbon (e.g. atmospheric CO_2) via a syngas as a basis for making liquid (oxygenated) hydrocarbons including alcohols and single-molecule fuels such

[119] http://www.cleanfuelbox.eu/
[120] European company CVO Technologies s.r.l. presented a motor hatch converted to use LPG (https://tinyurl.com/yyo76req)
[121] https://tinyurl.com/y3ggov87
[122] https://tinyurl.com/yyh5lw2r
[123] https://worldmaritimenews.com/archives/259798/bw-lpg-to-retrofit-4-ships-to-lpg-propelled-dual-fuel-engines/

as methanol, dimethylether (DME), oxymethylene ether, dimethyl carbonate and methyl formate. Such hydrocarbons are being studied as potential synthetic fuels for use in ICEs, although research is still at relatively low technology readiness levels.

3.6.4 Synthetic Paraffinic Fuels

SPKs are largely drop-in and would therefore require less engine development. Significant efforts are taking place in using HVO blended with diesel in mainly LDV and HDV applications, as well as the use of SPFs in aviation. A wide range of bio-based synthetic paraffinic fuels can be produced via different processes. The most common process is Biomass to Liquids via Fischer–Tropsch Synthesis (BTL-FT). In the BTL-FT process, biomass, such as woodchips, is firstly gasified with air, oxygen, and/or steam to produce raw bio-syngas. Then, a cleaning process is applied to the raw bio-syngas to remove contaminants like small char particles, ash, and tar. The cleaned bio-syngas is used in a catalytic reactor to perform FT synthesis to produce renewable liquid fuels.

E-fuels are gaseous or liquid synthetic fuels based on the electrolysis of water to produce hydrogen. Hydrogen can be used in the transportation sector in fuel-cell electric vehicles or can be reacted with CO_2 to form other gaseous fuels like methane or syngas. Syngas can then be transformed into liquid e-fuels like diesel or petrol using Fischer-Tropsch synthesis. An advantage is that no additional investment into new infrastructure (distribution; fuel stations; vehicle) is required for synthetic diesel/petrol[124] . Additionally, e-fuels offer closed-loop carbon cycling via air capturing of CO_2 and a path for the use of renewable electricity in transportation. Renewable electricity sources such as wind or solar power are intermittent and the production of e-fuels is an opportunity to use excess electricity and stabilize the electricity grid. E-fuels used in internal combustion engine vehicles could also contribute to a decrease in particulate matter and nitrogen oxide emissions, depending on the e-fuel produced.

In the e-fuels domain, Audi has been active since 2013 when it started offering renewable Audi e-gas on the market. Audi e-diesel was also produced under the joint pilot programme with Sunfire in Dresden (2014-2016). In collaboration with Ineratec and Energiedienst Holding, Audi are planning to set up a new pilot plant in Laufenburg (Switzerland) with an annual capacity of 400,000 L of Audi e-diesel. In 2018, Audi along with Global Bioenergies in Leuna produced 60 L of e-gasoline (Audi e-benzin) that is free of sulphur and benzene. The combustion and emission behaviour of e-gasoline is being tested in a test engine.[125]

Synthetic fuels such as e-fuels can be counted towards targets in the **2018 Renewable Energy Directive**. The following projects reflect their potential for a creation of a low carbon transportation system.

- **NextGen**.[126](2018-2022): This is a Horizon 2020 project to develop a competitive European technology platform for sustainable liquid fuel production. This project is also known as Sustainable Drop-In Transport fuels from Hydrothermal Liquefaction of Low-Value Urban Feedstock. The project aims to demonstrate that the Hydrothermal Liquefaction pathway

[124] S. Schiebahn, et al. (2015), Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany, Int. J. Hydrogen Energy, 40, pp. 4285-4294

[125] https://www.audi-mediacenter.com/en/press-releases/audi-advances-e-fuels-technology-new-e-benzin-fuel-being-tested-9912

[126] https://www.nextgenroadfuels.eu

(HTL) is an efficient route to produce high-volume, cost-competitive, drop-in synthetic gasoline and diesel fuels, as well as other hydrocarbon compounds.

- **JETSCREEN**[127] (2017-2020): This is a Horizon 2020 project, which has two particular objectives. First, the development of a platform, which integrates distributed design tools and generic experiments to assess the risks and benefits of SPFs for aviation. Second, to optimize alternative fuels for a maximum energy per kilogram of fuel and a reduction of pollutants emissions. The main innovation lies in the gain of knowledge of the detailed composition of SPFs and its potential development in the future.
- **COMSYN** [128] (2017-2021) is currently developing a new biomass-to-liquid production concept that will reduce biofuel production cost by up to 35 %. This research employs Fischer-Tropsch (FT) process for producing synthetic biofuels. To date, the first batch of synthetic diesel from the COMSYN project has been demonstrated in a car during a project workshop.
- **Heat-To-Fuel** [129] (2017-2021): This is an ongoing Horizon program, which investigates FT technology to produce biofuels. The main objective of Heat-To-Fuel is to deliver competitive prices for biofuel technologies while delivering higher fuel qualities and significant reduced life-cycle GHG emissions.
- **HyFlexFuels** [130] (2017-2021) This is a Horizon 2020 project that works on advancing hydrothermal liquefaction (HTL) as key technology for sustainable and competitive production of drop-in fuels from a broad range of biomass feedstocks. HyFlexFuel aims at developing all individual process steps of HTL-based fuel production and at demonstrating their viability under relevant operational conditions. This includes the upgrading of the intermediate product biocrude to final fuels and the valorisation of residual process streams.

However, because of the multiple steps in their production, hydrogen-based synthetic fuels have low overall conversion efficiencies [131] compared to the direct use of electricity or hydrogen. Consequently, their use will only become justifiable in the long term for applications where other, more efficient options cannot be used, such as in aviation or long-haul HDVs or maritime transport.

3.6.5 Hydrogen & Ammonia

Hydrogen, combined in most of the cases with fuel cells, is emerging as a new fuel with multiple benefits.

It is more commonly used in a fuel cell, where hydrogen is completely emission free at point of use, and fuel cells also offer the advantage of being vibrations free and silent. Hydrogen in combination with fuel cells offer zero tailpipe emissions in transport applications where batteries cannot deliver the needed power. In the LDV segment FCEVs offer a user experience that is comparable to ICE when it comes to autonomy (600 km already achieved) and refuelling times (between 3 and 5 minutes). This offers added advantage for vehicles that either must enter densely populated areas or need to offer a high quality of comfort.

[127] https://www.jetscreen-h2020.eu/
[128] https://www.comsynproject.eu/project/
[129] https://www.heattofuel.eu/about/
[130] https://www.hyflexfuel.eu
[131] Nationale Akademie der Wissenschaften Leopoldina, Deutsche Akademie der Technikwissenschaften and Union der deutschen Akademien der Wissenschaften (2017) 'Sektorkopplung' – Optionen für die nächste Phase der Energiewende.

The development of hydrogen as a new possible fuel for transport is being backed by an array of new developments happening at high speed with major (in billions of Euros) investments at world scale: on the one hand major industrial gases and energy players now consider developing hydrogen as a new business and a new energy, and on the other hand an array of vehicles, train and ships suppliers are working on bringing to the market new hydrogen and fuel cell based solutions to their clients. While the costs associated to hydrogen and fuel cells option are still higher than the incumbent technologies, they have the potential to be substantially reduced. In this respect support to the development of key components, the introduction of innovative manufacturing techniques for mass production and an accelerated introduction of FCEVs in different transport segments remains important.

Hydrogen can be produced via different pathways as described in §2.1 and fig.11. While the vast majority of the hydrogen produced today comes from steam reforming natural gas or gasifying coal, considered "grey" hydrogen as it produces CO_2, two new pathways are surfacing that suppress these emissions, which are the production of so called "green" hydrogen via the electrolysis of water with green power, and the production of so called "blue" hydrogen which is a "grey" hydrogen production combined with CCS. While almost all hydrogen used to day in industrial processes is grey, a move to hydrogen to reduce GHG emissions in transport would need to rely on green or blue hydrogen. Green hydrogen cost are expected to become competitive with the cost of hydrogen from steam reforming and with fossil diesel[132].Ammonia is also being studied as a potential future synthetic fuel because it contains high amounts of hydrogen and, despite being highly corrosive, is relatively easy to transport and store, being a liquid at room temperature under modest pressures. However, ammonia is also highly toxic which poses a concern over its widespread use as a fuel. Research is ongoing to develop ways of using ammonia to transport and store hydrogen for use in conventional ICEs, and to minimise its NOx emissions[133] .

A large number of hydrogen demonstration projects have been carried out across Europe and there are ambitious plans (led by the FCH JU)) for further activities in this area in the coming years. Examples of major projects are:

• **CHIC** (2010-2016) [134] was a flagship zero-emissions bus project, which aimed to demonstrate the technology readiness for fuel cell electric buses in European cities. During the project, 23 partners from 8 countries collaborated to enable the operation of 56 fuel cell electric buses and the deployment of 9 hydrogen refuelling stations. Over 8 million kilometres were travelled, with savings of over 4 million litres of diesel and an estimated 6 000 t of CO_2.

• **H2ME** (2015-2020) [135]and **H2ME 2** (2016-2022) [136] aim to develop a European network of hydrogen refuelling stations and significantly expand the fuel cell electric vehicle (FCEV) fleet. In H2ME, activities are focused in Germany, Scandinavia, France and the UK. The learning from this will be used to help other countries develop their own hydrogen mobility strategies. H2ME 2 aims to treble the existing

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[132] Fahili and Breyer (2020). Baseload electricity and hydrogen supply based on hybrid PV-wind power plants, Journal of Cleaner Production, 243
https://doi.org/10.1016/j.jclepro.2019.118466

[133] David W, *et al.* (2014) Hydrogen production from ammonia using sodium amide. *Journal of the American Chemical Society* **136** (38), 13082–13085. https://pubs.acs.org/doi/abs/10.1021/ja5042836

[134] https://cordis.europa.eu/project/rcn/97944/factsheet/en

[135] https://h2me.eu/

[136] https://www.fch.europa.eu/news/launch-h2me-2-expand-hydrogen-refuelling-infrastructure-network-and-vehicle-fleet

fuel cell fleet in Europe by deploying 1 230 new hydrogen-fuelled vehicles. Hydrogen refuelling stations with on-site hydrogen generation via electrolysis will also be tested.

- H2HAUL (2019 – 2024) [137]aims at demonstrating the technology readiness for the heavy duty segment. Major European manufacturers IVECO, FPT industrial powertrain producer and VDL ETS will develop and deploy HD trucks up to 44 tons. A total of 16 trucks will be tested in real-world operations in 4 sites in Europe (Belgium, France, Germany, and Switzerland) to demonstrate that fuel cells trucks could provide an alternative to diesel trucks with equivalent driving range and load capacity. Innovative hydrogen refuelling stations will be deployed as well to demonstrate rapid, high capacity fuelling.

Figure 3 provides an estimate of the overall efficiency of using hydrogen from renewable electricity compared to direct charging and power-to-liquids.

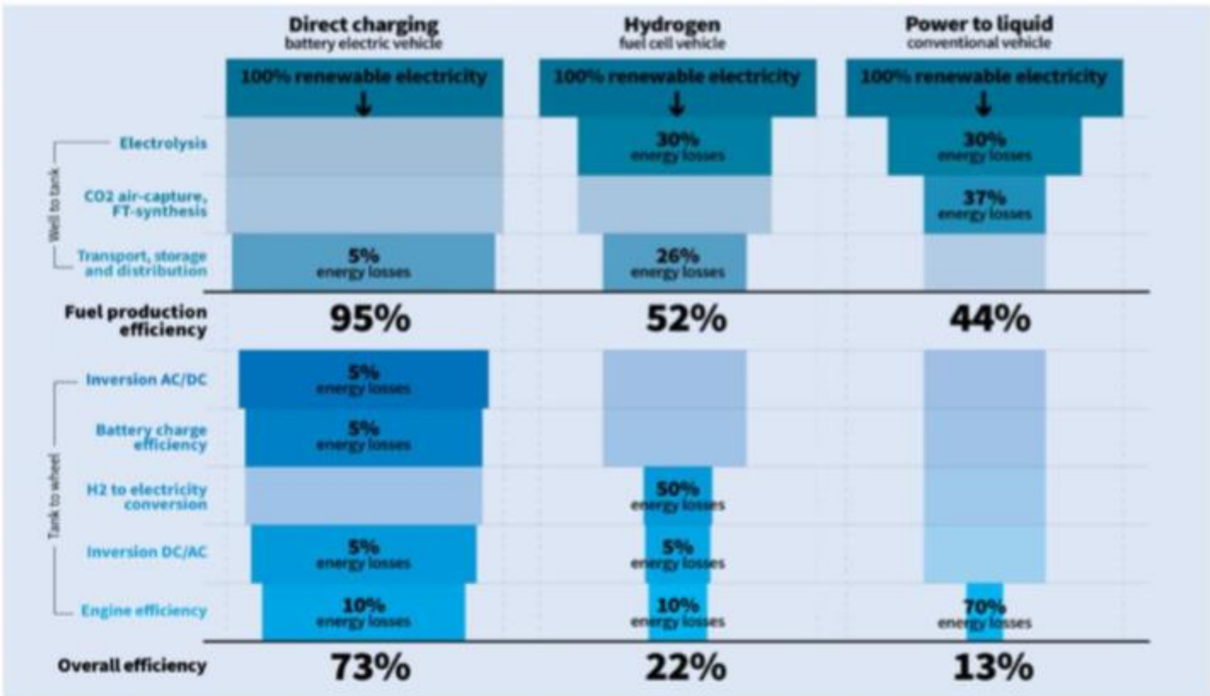

Figure 3: Energy efficiency of different technologies in a passenger car (Electrofuel referred as Power to Liquid)[138]

In the case of power-to-liquids special attention will need to be paid to the source of CO2 used in the production of the fuels – air capture vs point sources – which will have efficiency, cost and GHG implications.

[137] https://www.h2haul.eu/

[138] Transport&Environment (2017): Electrofuels what role in EU transport decarbonisation? https://www.transportenvironment.org/sites/te/files/publications/2017_11_Briefing_electrofuels_final.pdf

4 Potential benefits of alternative fuel use in different transport modes and engines

As already mentioned, 15% of global GHG emissions result from the transportation sector, and it is estimated that the ratio of transport GHG emissions will increase as the transportation of goods grows at a global level[139]. **Table 6** shows the multitude of options that are in use and being considered for different transport modes. The use of alternative fuel use in different transport modes and engines is of vital importance for climate change mitigation. However, emissions reduction is complex due to the vast array of competing alternative fuels and technologies[140]. Uncertainties and trade-offs around economic, environmental and technological aspects, make it difficult to prioritise options for policy-makers. All these aspects, as well as social aspects, which form the pillars of sustainability, need to be considered when assessing the attractiveness of the different options.

Figure 16 illustrates a framework that takes into consideration emissions of GHG (,GHG resulting from automobiles combustion are: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from the tailpipe and hydrofuorocarbon (HFC) emissions from leaking air conditioners), PM_{10}, NOx, CO and HCs as environmental criteria, fuel and vehicle cost as economic criteria, maturity, energy density, availability, and infrastructure as technical criteria, and social acceptability and compliance with policy as social criteria. The definitions of these criteria can be specified as follows:

- **Environmental aspect**: GHG, PM_{10}, NOx, CO and HCs refer to the emissions of greenhouse gases, particulate matter less than 10 mm in size, nitrogen oxides, carbon monoxide, and hydrocarbons per vehicle per km[141].
- **Economic aspect**: fuel cost and vehicle cost refer to the cost of fuels per km and the average vehicle cost, respectively.
- **Technological aspect**: maturity refers to technological maturity of alternative-fuel vehicles; energy density refers to the embodied energy per unit volume; availability refers to the current production and retail availability for vehicles; and infrastructure refers to the perfection degree of the distribution infrastructure for supporting the corresponding alternative-fuel vehicles [142].
- **Social aspect**: social acceptability is used to measure the acceptance of the stakeholders when adopting the alternative-fuel vehicles; and compliance with policy refers to the supporting degree of governmental policies and regulations on some certain alternative-fuel vehicles.

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[139] Pålsson H., Johansson O. (2016), Reducing transportation emissions: company intentions, barriers and discriminating factors, BIJ, 23 (3), pp. 674-703

[140] Gajjar H., Mondol J.D. (2016)Technoeconomic comparison of alternative vehicle technologies for South Africa's road transport system, Int. J. Sustain. Transp., 10 (7) , pp. 579-589

[141] Luo X., Dong L., Dou Y., Li Y., Liu K., Ren J., Liang H., Mai X. (2017)Factor decomposition analysis and causal mechanism investigation on urban transport CO_2 emissions: comparative study on Shanghai and Tokyo Energy Policy, 107 pp. 658-668

[142] Sehatpour M.H, Kazemi A., Sehatpour H.E., (2017). Evaluation of alternative fuels for light-duty vehicles in Iran using a multi-criteria approach. Renew. Sust. Energ. Rev., 72 pp. 295-310

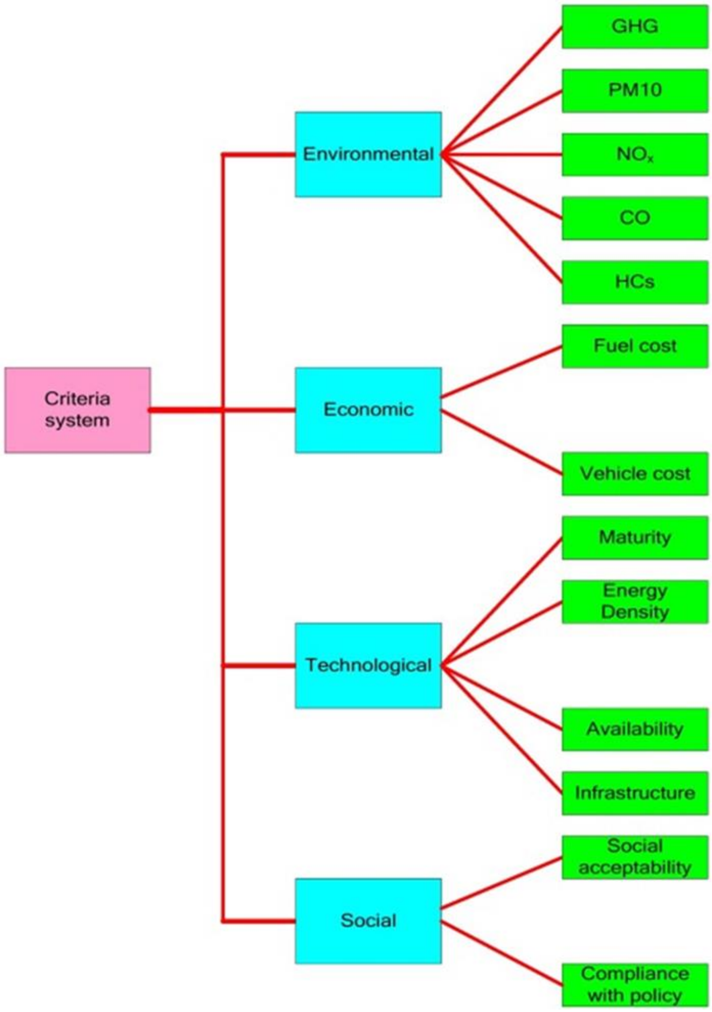

Figure 16– Criteria taken into consideration for the assessment of fuel and technology propulsion options for different transport modes

Furthermore, a useful tool for the assessment of alternative fuels and vehicle technologies - apart from the Multicriteria Analysis - is **Life Cycle Analysis (LCA)**[143]. Analysis of a system under LCA encompasses the extraction of raw materials and energy resources, the conversion of these resources into the desired product, the utilization of the product by the consumer, and finally the disposal, reuse or recycle of the product after its service life. LCA can help to identify the policy objectives relative to climate change mitigation and reduction of other emissions and environmental burdens.

For the WTW[144]. GHG emissions, it is important to understand that the majority of the benefit is likely to come from utilising renewable (low carbon) alternative fuels (WTT). A smaller but not insignificant contribution can be made by increased powertrain efficiency (TTW), which is the focus of this report. TTW noxious (pollutant emissions) contribute to the urban air quality issues experienced in cities across the world. It is however worthwhile noting that correctly regulated and implemented aftertreatment control systems can address this issue. Certain alternative fuels and combustion

[143] Nanaki E.A. and Koroneos C.J. (2012), Comparative LCA of the use of biodiesel, diesel and gasoline for transportation, Journal of Cleaner Production, Volume 20, Issue 1, J, Pages 14-19

[144] For a distinction between LCA and WTW methodologies please see: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC85326/wtt_report_v4a_april2014_pubsy.pdf

systems have inherently lower engine-out emissions that might enable cost-effective aftertreatment systems for potential future pollution limits. This is discussed in more detail in **Section 4.1**.

Figure 17 provides an illustration of the relationship between total WTW energy usage and WTW GHG emissions. The results of the WTW analysis performed by the Joint Research Centre in 2014, are presented for 2020+ vehicles, except for conventional gasoline and diesel where the 2010 results are shown as well to act as a baseline: the dotted lines mark the performance of a 2010 gasoline vehicle. The energy figures include all energy, both fossil and renewable. In general, those options which have low GHG emissions have high total energy use.

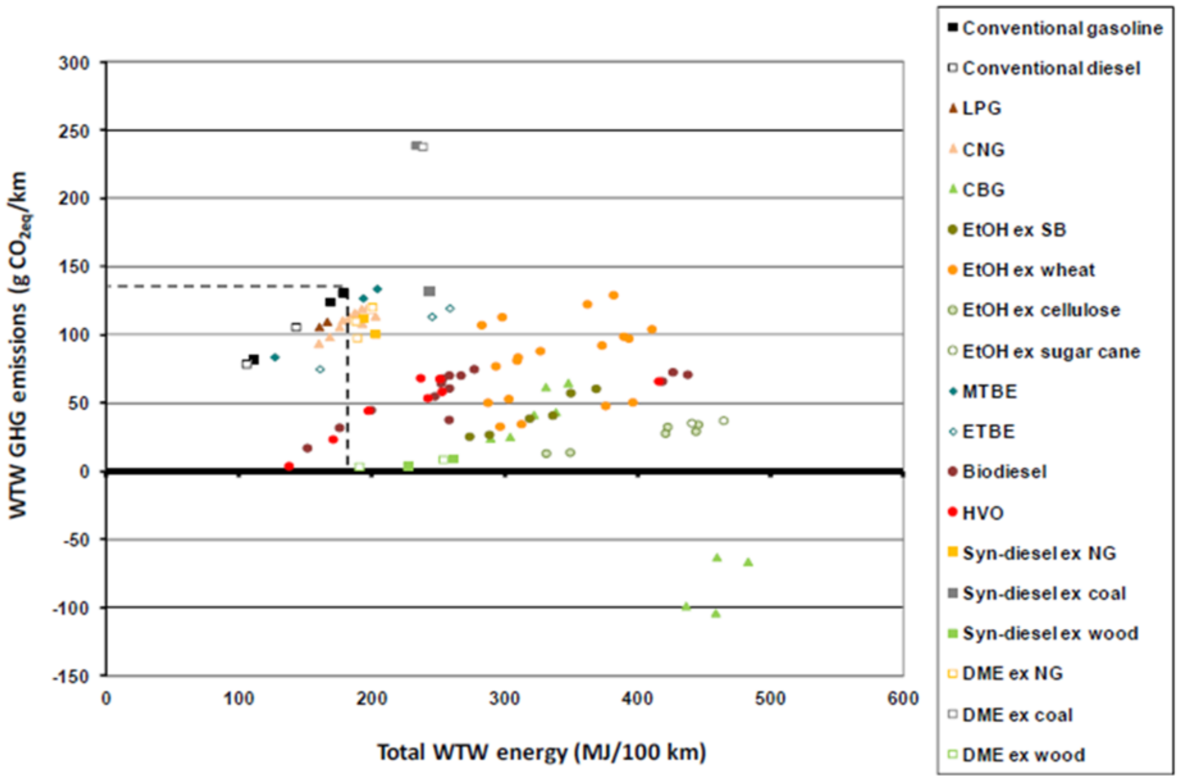

Figure 17- Comparison of specific WTW GHG emissions[145]
Notes *Figures plotted for 2020+ only, except for gasoline/diesel where 2010 is also included*
Dotted lines mark 2020+ gasoline vehicle
Biofuels plotted as neat products

There are then two other factors that are potentially important in prioritising different options: EU competitive position and energy diversification. EU competitive position relates to the extent that any fuel and technology option could provide a competitive advantage to the EU industry. Energy diversification relates to the potential of the option to contribute to the diversification of energy supply to different modes.

4.1 Alternative fuels impact on GHG and noxious emissions

The Life Cycle Assessment methodology is commonly used to evaluate the Well-to-Wheel greenhouse gas emissions of alternative fuels. In regards to the use phase (tank-to-wheel emissions), there are

[145] JRC Technical Reports (2014), WTT Report v.4a, Well-to-wheels analysis of future automotive fuels and powertrains in the European context
https://publications.jrc.ec.europa.eu/repository/bitstream/JRC85329/wtw_report_v4a%20march%202014_final.pdf

two main mechanisms by which the fuel can reduce tailpipe GHG emissions. Firstly, fuels with a higher H/C ratio per unit of energy will automatically have lower exhaust GHG emissions, and those without C like hydrogen will have none. Secondly, increasing the engine efficiency through utilising specific properties of the alternative fuel can bring about further GHG reductions. Engines are typically developed with a particular fuel in mind. The narrower the specification of the fuel the more engine hardware and software can be optimised with respect to engine efficiency (GHG emissions) and pollutant emissions. For road vehicles this effect has been demonstrated over the years with gasoline and especially diesel, however in contrast, increased fuel processing to obtain a narrow fuel specification can in itself be more costly and GHG intensive. A balance between a narrow specification fuel with a fully optimised engine and a wider specification fuel with a less optimised engine would need to be found.

The improvement potential of TTW GHG emissions is important but relatively small (<10%) compared to the WTT improvements that switching to a low carbon, renewable fuel would have (>60%). Switching to alternative fossil fuels brings about limited emissions savings, with natural gas resulting in emissions savings of up to 10% in diesel engines and 20% in gasoline engines (lower or no savings if fugitive methane emissions significant). Options like fossil methanol and fossil gas-to-liquids do not result in emissions savings[146]. Hydrogen produced from fossil fuels with CCS would lead to significant GHG emissions savings. Biofuels GHG emissions reductions depend very much on the source of the biomass feedstock and any external process energy required to convert it to a fuel. GHG emissions savings of biofuels produced from crops can vary widely depending on the crop, its management and any land use changes it may result in. Low input and low (indirect) land use change crops can result in significant savings. Highest savings for biofuels result from biofuels derived from organic waste materials. Finally, hydrogen from renewable resources ("green hydrogen") could lead to highest GHG emissions savings. In this regard it must be noted that there are concrete initiatives pushing for an increased use of green and low carbon hydrogen such as the project CertifHy[147].For pollutant emissions, it is important to understand the difference between engine out and tailpipe emissions. Engine out emissions are not only a function of fuel, but also of the combustion process and combustion system design. Exhaust gas aftertreatment systems are widely used (and can be very effective as demonstrated by heavy duty EURO 6 compliant vehicles) to control tailpipe emissions to "within" the required limits set for the application. Lowering engine-out emissions will therefore not automatically result in lower tailpipe emissions, unless these are likely to be lower than any legal limits aimed at by aftertreatment systems. Lower engine-out emissions could however enable OEMs to meet lower emissions limits at a lower cost. Specifically, fuels without carbon to carbon bonds inherently demonstrate very low levels of particulates. This effect could be utilised to reach a better compromise between NOx and CO_2 emissions in compression ignition engines. Within the marine sector where currently little or no after treatment is used, switching from residual fuel oils to alternative fuels such as LNG or methanol offers the possibility of significant reductions in SOx (>90%), particulates and NOx emissions (>80%). Green hydrogen produces no particulates when used in a combustion engines, and NOx levels comparable to the best results obtained with other gaseous fuels. When used in a fuel cell, hydrogen becomes a 100% emissions free fuel, and is the only one to do so out of the entire range of alternative gaseous and liquids fuels. **Table 13** below summarises

[146] Gilbert P., Walsh G., Traut M., Kesieme U., Pazouki K., Murphy A. (2018), Assessment of full life-cycle air emissions of alternative shipping fuels, Journal of Cleaner Production, Volume 172, Pages 855-866

[147] https://www.certifhy.eu/project-description/project-description.html

promising fuel and powertrain technology combinations with regard to TTW GHG emissions and TTW noxious emissions, with a focus on alternative fuel induced technology improvements in different transport modes. The options below are derived from a literature review and consultation with stakeholders resulting in an assessment of fuel and powertrain technology combinations as captured in ***Appendix 7.3***. All options are expected to be fully commercial in a 10-15 year timeframe.

Table 13 - Benefits of fuel and technology propulsion options

	TTW efficiency	*TTW air quality emissions*
LDV	**Hydrogen in Fuel Cells:** High efficiency use in fuel cells.	**Hydrogen in Fuel Cells:** Enabling FCEVs adoption running on hydrogen produced from green energy sources would lead to zero emission LDV world (= <u>no NOx, no SOx, no particles</u>)
	Alcohols and ethers in SI engine: Use of alternative fuels with higher RON, such as alcohols, ethers and methane, could increase SI engine efficiency by up to 5% in absolute terms. This could allow further downsizing / down speeding. Enleanment either stratified or homogeneous has the potential to significantly increase the engines thermal efficiency and hence lower CO2 emissions.	**Alcohols and ethers in SI engine:** Replacing gasoline and diesel with shorter HC chains potentially reduces engine out PM and NOx which could enable better engine optimisation. Aldehyde emissions would need to be monitored
	Alternative fuels in Fuel Cells: Use of FCs fuelled with hydrogen or alcohols could double efficiency compared to spark ignition engines, depending on operating regime.	**Alternative fuels in Fuel Cells:** Enabling FC introduction based on fuels such as alcohols could lead to significant pollutant emissions reductions of nearly 100% in all emissions compared to SI engines. Aldehydes might be an issue
	Gaseous (methane & LPG) fuels in SI engines: High Pressure Direct Injection systems are under development by e.g. Westport / Prins that aim to reduce CO2 by 10% relative to the current gas SI systems. OEMs are engaged in Low Pressure Direct Injection development, as well as other activities (e.g. GasOn project), with the aim to reduce CO2 by 20% relative to the current best in class SI CNG vehicles.	**Gaseous (methane & LPG) fuels in SI engines**: Replacing gasoline and diesel with shorter HC chains potentially reduces engine out PM and NOx which could enable better engine optimisation
	SPFs: SPFs from a range of sources, including Power to Liquid (PTL), are considered potentially promising, but currently the impact of their specific properties on engine efficiency are not well researched. Properties such as slightly higher energy density compared to conventional fuels would, for example, lead to small efficiency increases.	**SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are potentially promising, but currently the impact of their specific properties on noxious emissions are not well researched.

HDV	**Hydrogen in Fuel Cells:** High efficiency use in fuel cells. **Alcohols and ethers in CI engine:** DME & ED95 engines are commercially available and meet Euro 6. Engine efficiency is similar to diesel currently with further scope for improvement. High Pressure Direct Injection (HPDI) dual fuel systems currently being developed would also be suitable for alcohols & ethers. **Gaseous (methane & LPG) fuels in CI engines**: HPDI systems are under development at e.g. Westport as a dual fuel application aiming at >90% diesel substitution (by energy) and meeting current diesel engine characteristics incl. efficiency. Technology developers also claim such engines would minimise methane leakage. **SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are considered potentially promising, but currently their level of sustainability, cost and impact of its specific properties on engine efficiency are not well researched.	**Hydrogen in Fuel Cells :** Enabling FCEVs adoption running on hydrogen produced from green energy sources would lead to a zero emission HDV world (= no NOx, no SOx, no particles) **Alcohols and ethers in CI engine:** DME & ED95 engines are commercially available and meet Euro 6. No c-c bonds mean that engine-out particulate matter is significantly reduced allowing further improvement in NOx. Aldehyde emissions are understood to be minimal. **Gaseous (methane & LPG) fuels in CI engines**: It is anticipated that these systems will meet EURO 6 limits. **SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are potentially promising, but the impact of their specific properties on noxious emissions are not well researched.

Rail	**Hydrogen in Fuel Cells :** The use of hydrogen in fuel cells is very efficient and leads to zero tailpipe emissions. **Alcohols and ethers in CI engine:** DME & ED95 engines are commercially available and meet Euro 6. Engine efficiency is similar to diesel currently with further scope for improvement. High Pressure Direct Injection (HPDI) dual fuel systems currently being developed would also be suitable for alcohols & ethers. **Gaseous (methane & LPG) fuels in CI engines**: HPDI systems are under development at e.g. Westport as a dual fuel application aiming at >90% diesel substitution (by energy) and meeting current diesel engine characteristics incl. efficiency. Technology developers also claim such engines would minimise methane leakage. **SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are being considered, but currently the impacts of their specific properties on engine efficiency are not well researched.	**Hydrogen in Fuel Cells :** Enabling hydrogen trains adoption running on hydrogen produced from green energy sources would lead to a 100% zero emission rail transport world (= no NOx, no SOx, no particles) **Alcohols and ethers in CI engine:** DME & ED95 engines are commercially available and meet Euro 6. No c-c bonds mean that engine-out particulate matter is significantly reduced allowing further improvement in NOx. Aldehyde emissions are understood to be minimal. **Gaseous (methane & LPG) fuels in CI engines**: It is anticipated that these systems will meet EURO 6 limits. **SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are potentially very promising, but the impact of their specific properties on noxious emissions are not well researched.

Waterborne	**Alcohols and gaseous fuels in (dual fuel) CI engine:** Methanol and natural gas are currently used in dual fuel engines. Engine efficiency is similar than when operated on fuel oil with further scope for improvement of up to 5%. Engine operating fully on gas or methanol are currently under development promising further improvements in efficiency of around to 5% under certain conditions **Hydrogen in Fuel Cells :** The use of hydrogen in fuel cells is very efficient and leads to zero tailpipe emissions. Using ammonia produced from hydrogen is another option available. **SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are being considered, but currently the impacts of their specific properties on engine efficiency are not well researched.	**Alcohols and gaseous fuels in (dual fuel) CI engine:** Methanol and natural gas dual fuel engines have significantly lower NOx, SOx and particulate matter emissions. Engine operating fully on gas or methanol are currently under development promising further reductions in pollutant emissions **Hydrogen in Fuel Cells :** Enabling hydrogen ships adoption running on hydrogen produced from green energy sources would lead to a 100% zero emission waterborne transport world (= <u>no NOx, no SOx, no particles</u>) The same would apply for ammonia-based ships with ammonia produced from green energy sources used in fuel cells. Use in engines would result in NOx and N2O emissions. **SPFs:** SPFs from a range of sources, including Power to Liquid (PTL), are potentially promising, but the impact of its specific properties on noxious emissions are not well researched.
Aviation	**Synthetic paraffinic fuels SPF** Current synthetic jet blended fuels are promising fuels that would allow small efficiency improvements of around 2% in part associated with slightly higher energy density.	**Synthetic hydrocarbon fuels as SPK, SIP or ATJ** Synthetic sustainable jet fuel are promising fuels that would allow NOx, SOx and nvPM improvements, especially linked with the aromatic compounds and sulphur content.

** please note: Time of implementation is sometimes governed by infrastructure availability*

4.2 EU competitive position

Europe's competitive position relative to the rest of the world is in this context defined as the technology leadership of its industry. For alternative fuels this could either mean specific technology required to produce, refine and handle the fuels, or technology that focuses on on-board storage, handling, combustion, aftertreatment and control of these fuels.

Fuel production and infrastructure:

Internal combustion engines

Europe has had and continues to benefit from a leading position worldwide in the development of internal combustion engines.

Europe has also a strong position in the development of LNG refuelling infrastructure for fleets (HDVs, rail and maritime) with several large companies developing and building new infrastructure

e.g. the LNG Blue Corridor project. It also has a strong position in biomethane production technologies via biological and thermochemical routes. There is also significant research and industrial activity for the production of alcohols and SPFs from biomass. Finally, there are several demonstration and early commercial projects for the production of ethanol and butanol from lignocellulosic biomass, methanol from glycerine and from synthesis of H_2 and CO_2, and SPFs. These activities complement the strengths in the traditional refining sector and provide the basis for new alternative fuels to be introduced in internal combustion engines.

Electric powertrains

Electric powertrains have started to enter the mobility space, starting with LDEVs. The USA has a leading role in this field when it comes to addressing the premium cars sector, while Asia, and namely China, has the leading role for the rest of the market. Most electric vehicles are sold in China, Europe being the second largest market. But, Europe is a net importer of electric vehicles (**Figure 18**).

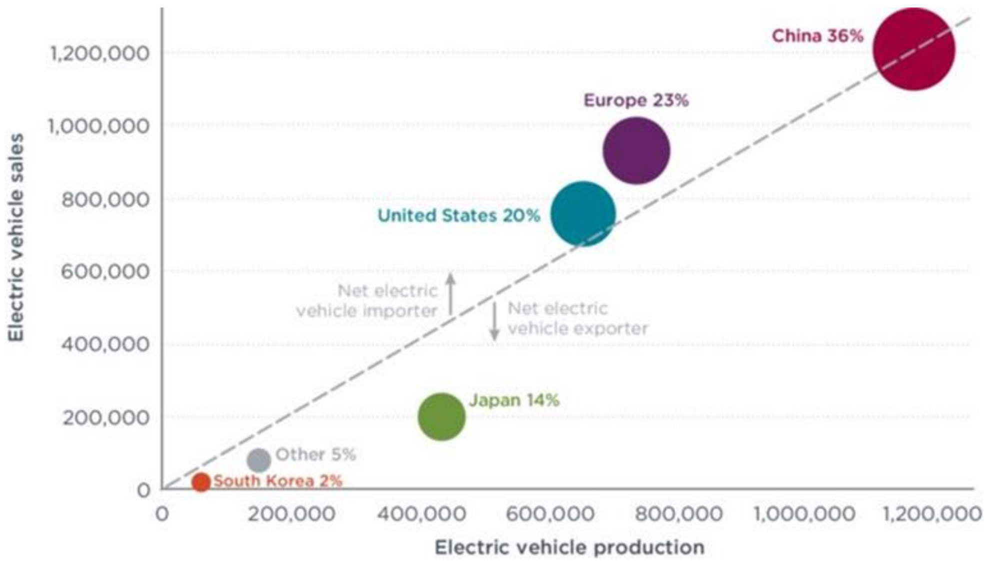

Figure 18 - Cumulative electric vehicles sales and production from 2010 through 2017, in major regions, with circle size proportional to the percentage of global electric vehicles produced[148]

Japan and Korea, and more recently China, are betting heavily now also on FCEVs. Companies like Hyundai and Toyota are already working on the third generation of their fuel cell cars, while some European OEM are in the early days of providing the first FCEVs to the market. European funding has been allocated to stack and fuel cell developments, but the European OEMs need to catch up in technological terms, and there is therefore a danger to lag behind.

European companies are however leaders in the current hydrogen economy with players like Linde and Air Liquide (for production of hydrogen and filling stations), Thyssenkrupp and ITM Power (for the production via electrolysis), and Mc Phy and NEL (for the production via electrolysis and filling stations), all clear elements to take into account to back the emergence of a hydrogen-based mobility sector.

[148] D.Hall, H. Cui, N.Lutsey (2018), Electric vehicle capitals: Accelerating the global transition to electric drive, ICCT: https://theicct.org/publications/ev-capitals-of-the-world-2018

Technological challenges and opportunities

All above alternative fuels routes can present significant challenges for vehicle manufacturers but they can also offer enormous benefits to European citizens at large: clean transport and clean air, noise levels reductions, new jobs, and most importantly a capacity to favour the local production of fuels for transport (especially when hydrogen is concerned either pure or as synthetic fuels) instead of relying on fossil fuels imports. European technological advances would generate new intellectual property which would in turn strengthen Europe's industrial position.

Specifically these would include:

For combustion engines

- On-board CNG/LNG storage and handling for LDVs, HDVs, waterborne inland and marine transport and rail
- Development of synthetic fuels production to act as a substitutive to fossil based fuels
- Gas or alcohol combustion, fuel handling and injection systems for LDVs, HDVs and waterborne transport
- Novel and advanced aftertreatment systems taking into consideration alternative fuel use and the disposal of the resulting residual wastes

For electric power trains

- Develop the new generation of fuel cells for HDVs, trains and ships and favour cross industries collaborations (R&D and applied solutions)
- Work in parallel on the new technological standards and norms to develop as rapidly as possible concrete applications of FCEVs in all HDV, rail and ships segments
- Work on the development at European level of hydrogen corridors for coastal and inland hydrogen-based mobility

As a summary, it is essential to maintain the traditionally strong position the Europe has in transport related manufacturing, as emphasised by the recent EC Communication on **"A European Strategy for Low-Emission Mobility"**. This understanding the drivers and technological shifts that can drastically transform the market over the next decade. Research and innovation in engine technologies compatible with alternative fuels could be an important element in maintaining this competitiveness. This could complement the more drastic and important development needed in electrification through batteries and fuel cells.

Figure 19 illustrates the importance of the European automotive industry globally and in terms of employment, trade balance, innovation spending and tax income in Europe.

EMPLOYMENT		
Manufacture of motor vehicles (EU28)	2.5 million people = 8.3% of EU employment in manufacturing	2016
Total (EU28 manufacturing, services and construction)	13.3 million people = 6.1% of total EU employment	2016
PRODUCTION		
Motor vehicles (world)	98.9 million units	2017
Motor vehicles (EU28)	19.6 million units = 20% of global motor vehicle production	2017
Passenger cars (world)	80.2 million units	2017
Passenger cars (EU28)	17.0 million units = 21% of global passenger car production	2017
REGISTRATIONS		
Motor vehicles (world)	97.9 million units	2017
Motor vehicles (EU27)	17.5 million units = 18% of global motor vehicle registrations/sales	2017
Passenger cars (world)	79.8 million units	2017
Passenger cars (EU27)	15.1 million units = 19% of global passenger car registrations/sales	2017
Petrol (EU15)	49.4%	2017
Diesel (EU15)	44.8%	2017
Electric (EU15)	1.5%	2017
VEHICLES IN USE		
Motor vehicles (EU28)	298.9 million units	2016
Passenger cars (EU28)	259.7 million units	2016
Motorisation rate (EU28)	587 units per 1,000 inhabitants	2016
Average age (EU25)	11 years	2016
TRADE		
Exports (extra-EU28)	€138.6 billion	2017
Imports (extra-EU28)	€48.3 billion	2017
Trade balance	€90.3 billion	2017
ENVIRONMENT		
Average CO2 emissions (EU28)	118.5 g CO2/km	2017
INNOVATION		
Automobiles and parts sector	€53.8 billion	2016
TAXATION		
Fiscal income from motor vehicles (EU15)	€413 billion	2016/2017

Figure 19 - ACEA key figures on the automotive industry[149]

4.3 Low carbon energy diversification

As Europe needs to rapidly decarbonise its transport sector, it needs to look at the availability of the different options and the required transition from one option to another one.

149 http://www.acea.be/uploads/press_releases_files/POCKET_GUIDE_2018-2019.pdf

Current transport systems run on combustion engines (ICEs and turbines), so supplying low carbon fuels (from waste and renewable resources) is an option that needs to be investigated. These fuels will be relevant in a transition to greater electrification, and may have a longer-term future in some heavy-duty applications, especially aviation. Battery based electric powertrains have made significant inroads into LDVs. But there are doubts on what batteries could achieve in heavy duty applications due to the heavy weight of batteries, their limited energy density, as well as the long charging time.

Fuel cells and hydrogen offer a solution for HDVs in road, rail and marine, which could address the limitation of batteries. Also, hydrogen could be produced from a wide range of sources with very low GHG emissions and contribute zero emissions at point of use. In addition, it could be used for the production of synthetic fuels for applications where combustion engines would still be used.

The trend is likely to be towards fully electric power trains in road, rail and marine, with the development of the corresponding infrastructures (BEVs charging and FCEVs hydrogen fuelling stations). However, electrification of heavy duty transport will take time, so improved internal combustion systems and hybrid technologies will continue to offer potential for GHG emissions reduction and air quality benefits, especially if fuelled with low carbon, clean liquid or gaseous fuels. Jet aviation is likely to remain dependent of a liquid hydrocarbon fuel.

4.3.1 Sustainable Renewable fuel availability

The production of alternative fuels is outside the mandate of STRIA, however their availability is critical when assessing future options. The focus in this section is on **advanced biofuels**[150].

4.3.1.1 Biofuels

The consumption of biofuels in the EU has oscillated in the past few years, mainly due to legislative uncertainty and amounted to 14 Mtoe in 2015. However, when referring to the future availability of biomass feedstock to meet the demand for food/feed, industrial products and energy (including biofuels) the recurring theme is "uncertainty". On the one hand biomass supply potential is conditional on the definition of sustainability criteria and dependent on many factors (e.g. productivity increases, technology development, new resources such as marine), and on the other hand, estimating future biomass demand is in any case highly complex as it depends on a great number of variables. The European Commission highlighted[151] the need for further research and analysis on whether there is sufficient supply of sustainable and cost-effective biomass feedstock for all energy uses post 2020. On the global scale, studies also highlight the great variability of estimations of future biomass potential[152].

The **Biomass Futures Atlas**[153] estimated the bioenergy resource in Europe at 375Mtoe in 2020 in a sustainability scenarios and decreasing slightly to 353 Mtoe by 2030. A follow up study, EC funded

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[150] In line with EC communications “A policy framework for climate and energy in the period from 2020 to 2030” and “A European Strategy for Low-Emission Mobility”

[151] EC SWD(2014) 259 final: “State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU”

[152] Saygin et al. (2014). Renewable and Sustainable Energy Reviews 40, 1153–1167; Smith P.et al. 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the IPCC

[153] Biomass Futures (2012) Atlas of EU biomass potentials. Deliverable 3.3: Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources. https://tinyurl.com/y2efe5h6

research project **Biomass Policies**, which considered additional constraints on biomass availability, indicates that the sustainable potential for energy uses could be of the order of 130Mtoe. According to the **Reference Bioenergy Scenario** by the **JRC**[154], the resource potential for Bioenergy in 2020 in the EU-28 is limited to 267 Mtoe. To put this into perspective, final energy consumption in the transport sector in the EU-28 was 359 Mtoe in 2015[155] .

Another report funded by the **EC on advanced biofuels** [156] estimates that biofuels could achieve close to a 50 % share of the overall transport sector energy mix in the long term, achieving 330 Mt of net emission savings or 65 % of the required emission savings needed compared to 1990 levels, without impacting negatively EU's GDP. According to the study, there are sufficient quantities of domestic sustainable biomass from agricultural, forestry, organic municipal wastes and aquatic biomass to meet the proposed 2030 targets and beyond without adverse effects on the environment or other economic sectors. Under the appropriate R&I support, the sustainable biomass availability is estimated at 700 million tons of dry matter per year for 2030 and 1100 million tons of dry matter per year for 2050. Recent R&I developments suggest a large technical potential of aquatic biomass (40 million tons dry matter per year in 2030 and 400 million tons dry matter per year in 2050)[157].

4.3.1.2 Biomethane

In 2017, 150ktoe of biomethane were consumed in transport in the EU[157]. In 2016, there were 456 biomethane plants in Europe; whereas 41 new were constructed – standing for a 9% increase since 2015[158].

The level of total biomethane production foreseen for 2020 in the National Renewable Energy Action Plans is about 12 billion m^3 [159] (about 10Mtoe). The **Green Gas Grids project**[160] estimates that by 2030 methane-based fuels could contribute about 25-30 billion m^3 [161] (up to about 25Mtoe) to transport energy demand, with a 10% contribution from biomethane. Biomethane feedstock availability is subject to the same considerations as for biofuels.

4.3.1.3 Electricity

In the past years the share of renewable electricity generation has continued to increase, nuclear production has remained stable and generation from fossil fuels has fallen significantly. In 2013, half of Europe's total electricity came from low-carbon sources and the European electricity industry has made strong commitments to achieve carbon neutrality by 2050. However, looking at the current trends the European Commission has assessed that the 52% share in 2012 of carbon free gross electricity (from renewables and nuclear) could reach 58% by 2020, 66% by 2030 and 73% by 2050[162].

[154] P. Ruiz Castello, A. Sgobbi, W. Nijs, Ch Thiel, F. Dalla Longa, T. Kober, B. Elbersen, G. Hengeveld (2015) **The JRC-EU-TIMES model** ,Bioenergy Potentials for EU and Neighbouring Countries, JRC , 10.2790/39014
[155] Eurostat (2018) Final energy consumption by sector - code: tsdpc320 http://ec.europa.eu/eurostat/data/database?node_code=tsdpc320#
[156] Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe (2017): https://publications.europa.eu/en/publication-detail/-/publication/448fdae2-00bc-11e8-b8f5-01aa75ed71a1
[157] European Alternative Fuels Observatory : https://www.eafo.eu/alternative-fuels/biomethane/transport <accessed on May 22nd 2019>
[158] European Biogas Association -EBA (2018). European Biomethane Map. Available at: https://tinyurl.com/yxmz9wwo
[159] European Biogas Association – EBA : european-biogas.eu/wp-content
[160] Partners participating in the Intelligent Energy Europe Green Gas Grids Project: www.greengasgrids.eu
[161] Source: EurObserv'ER (2015) "Biofuels barometer". Available at: http://www.eurobserv-er.org/category/all-biofuels-barometers/
[162] European Commission (2019), 2020 climate and energy package. Available at: https://ec.europa.eu/clima/policies/strategies/2020_en

It should be pointed out, that reaching the above mentioned targets are of great significance, taken into consideration the fact that synthetic fuels only deliver climate benefits if produced from low-carbon renewable electricity such as wind and solar power. Even when produced solely from renewable electricity, the production of synthetic fuels can indirectly impact renewable energy usage elsewhere because of the energy accounting methodology in the RED II. If synthetic fuels count toward the 32% renewable energy target in the RED II on the basis of the renewable electricity input rather than the energy content of the fuel, their production will reduce the total amount of renewable energy consumption necessary to meet the 32% target[163].

4.3.1.4 Hydrogen

Low carbon hydrogen can be produced from renewables (including biomass), nuclear energy, and fossil sources with carbon capture and storage (via electrolytic or thermal splitting of water or reforming of methane and syngas). Drivers for green hydrogen production will be the need to store electricity from intermittent renewable energy sources as well as demand from large industrials that use hydrogen as a feedstock (producers of fertilizers, chemicals, fuels, metals, glass, etc.) and will need to reduce their emissions. As the price of electrolysers drops dramatically, like to what is being experienced by batteries, producing green hydrogen becomes increasingly attractive[164]. While infrastructure may take time to develop organically, there are areas where dedicated infrastructure could develop more rapidly e.g. point to point refuelling.

5 Research agenda

This Section presents the research and innovation needs and activities associated with fuel and powertrain combinations in different transport modes. The focus is on gaseous, alcohols and SPF fuels which would deliver benefits to Europe (see **Section 4**). Non-technical challenges to deployment are also discussed where relevant. The R&I challenges are derived from literature and discussions with stakeholders and technology experts.

5.1 R&I needs

5.1.1 LDVs

Alcohol and ether blending into gasoline is a relatively cost-effective solution and is also relevant in vehicles that are partially electrified such as hybrids and range extender vehicles. A more efficient use of alcohols, ethers and gases in spark ignition (SI) engines could be achieved by optimising injection, combustion, aftertreatment systems and their control. By substantially increasing today's blending ratios allowed in LDV petrol engines and optimising the engines for such blending, it would be possible to take full advantage of the higher octane content of alcohols and ethers. Further research is required to understand the extent, impact and especially control of currently non-regulated emissions such as aldehydes. Increasing ether levels could also be beneficial. A 3-year research programme (2015-2018)[165] led by Ford on the use of ethers (DME & OME) has resulted in the

[163] S.Searle and A. Christensen(2018), Decarbonization potential of electrofuels in the European Union: https://theicct.org/sites/default/files/publications/Electrofuels_Decarbonization_EU_20180920.pdf

[164] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

[165] http://www.vka.rwth-aachen.de/cms/VKA/Forschung/Forschungsaktivitaeten/~mhoo/Bundes-und-Landesministerien/?lidx=1

development of the world's first DME-powered passenger vehicle (Ford Mondeo).[166] It is not clear if an OME-powered vehicle has been developed (as envisaged in the project proposal). However, the project did involve testing OME on a full-engine testbed comprising a six-cylinder production engine adapted to run on this synthetic fuel. Test results showed that the Euro 6 level is easily met when using OME, thereby confirming significant reduction in emissions.[167]

Similar synergies can be exploited in gas engines by using **compressed natural gas (CNG), biomethane or methane from PTL**. Direct injection in gas SI engines has the potential to further improve the TTW GHG emissions of such engines. The use of Low and High Pressure Direct Injection (LPDI and HPDI) of CNG in both SI & CI gas engines can achieve higher efficiencies compared to relative incumbent CNG systems and lead to CO_2 reductions by up to about 10%. Further improvements are possible in SI gas engines using lean combustion or Controlled Auto Ignition combustion systems. These advanced combustion systems could make full use of the properties of (bio)methane and lead to efficiency improvements. These combustion systems also lend themselves very well for integration in hybrid applications. More cost effective and easier to package on-board storage systems are required for all gaseous fuels.

Synthetic Paraffinic Fuels are effectively a drop-in fuel, which makes them very attractive and potentially easy to adopt even into an existing fleet., Additional research will help understand the benefits of these fuels in improving engine efficiency and reducing pollutant emissions.

Although **hydrogen fuel cell LDVs** have been commercially developed, they should be the focus of greater attention because of benefits they may have over BEVs e.g. weight, range, refuelling times. Similarly, **fuel cells using alcohol, methane or SPF** potentially provide high efficient and low pollutant engines, but the technology is at an earlier stage of development for transport applications.

Electrification through hybridisation will have an impact on engine size and consequently on the type of engine and its fuel compatibility. A system approach is required for the development of such powertrains. Increased electric propulsion power does mean that **engines** can be further optimised to operate more efficiently and more cleanly within a smaller speed / load operating window as well as have lower transient requirements.

Please note that we have differentiated between challenges (-) and opportunities (+) in the tables below (**Tables 14-18**).

[166] https://www.aboutdme.org/index.asp?bid=593
[167] https://www.greencarcongress.com/2018/09/20180906-tumome.html

Table 14 - LDV summary table of R&I needs

LDV				
Fuel category	**Fuel**	**Powertrain**	**Challenges(-) & opportunities(+)**	**R & I needs**
Natural gas	Compressed natural gas, biomethane or methane (CNG)	SI engines optimised for gas operation	- Limited or no emissions savings compared to gasoline or diesel for fossil natural gas. Would require transition to biomethane to methane produced using renewable electricity - Methane leakage could significantly affect savings - Questions around fine particles emissions from methane combustion + Potential for efficiency improvements in Low and High Pressure Direct Injection of CNG relative to incumbent CNG systems + Further engine thermal efficiency improvements of around 5% through synergies of high octane with downsizing in real world driving conditions + Further reduction of tail pipe pollutant emissions due to lower engine out emissions + On-board storage improvements through conformable, cheaper, lightweight solutions + Transition fuel	• Measurement of evaporative emissions to check if there is a problem, and research on control measures if necessary • Dedicated gas LPDI and HPDI systems • More dedicated CNG engine and combustion system designs • New components for high efficiency and performance SI engines, such as direct injectors, electronic regulators, gas quality sensors and control strategies • Better combustion and after treatment control strategies • Optimised TWC chemistries to reduce tailpipe pollutants and methane further • Conformable CNG cylinders development and vehicle integration • Eliminating methane slip in operational conditions, whilst meeting NOX requirements and maintaining engine efficiency
		SI lean	- Ignition system and control to robustly initiate combustion and maintain good combustion stability at very lean conditions to ensure low engine out NOx emissions - Appropriate and cost-effective aftertreatment systems to meet regulation - Effective air handling and load control + Significantly increase the engine thermal efficiency and therefore CO2 emissions estimated at 10-20% relative to incumbent CNG systems + Synergies with increased electrification	• Development of advanced ignitions systems such as fully controllable multiple spark ignition, corona, plasma etc • Dedicated lean burn gas engines with advanced aftertreatment systems • Fast response and variable air handling systems such as electric superchargers with appropriate control systems to ensure good driveability • Dedicated combustion, fuelling and air handling system design • Fully optimise and integrate the engine with the electric propulsion system (hybridisation, range extender etc)
Liquid Petroleum Gas	LPG, BioLPG	SI	+ High Pressure Direct Injection of LPG + Light weighting of the on-board fuel storage equipment	• Vehicle with a dedicated High Pressure Direct Injection spark ignition engine running on LPG/bioLPG (with optimized compression ratio, injection strategies, use of EGR and any other measure directed to improve engine efficiency such as lean operation) • Injection system for LPG/bioLPG direct injection which prevents vapour lock under hot conditions • Light weight fuel tank for LPG/bioLPG in-vehicle storage with a shape suitable to be integrated as a conventional tank (e. g. under the vehicle trunk)

Alcohols and ethers	Methanol, ethanol	FC	+Higher efficiency compared to ICEs +Liquid fuels potentially easier to deploy compared to hydrogen from infrastructure perspective	• Fuel cells using low carbon synthetic and fossil fuels. Focus on alcohols from renewable energy sources • Reformed methanol HTPEM fuel cell system for FCEVs. Optimization of fuel cell stacks, and integrated systems. Improved efficiency and durability, reduced cost. Scale-up of production capacity. Zero carbon production, reducing cost of zero carbon methanol
	Ethanol, methanol, butanol and other alcohols or blends	SI	- Mature technology when within EN228. No issues reported - Largely mature technology when used blended with gasoline up to E85 equivalent -Gasoline substitution worsens current unbalance + Further engine thermal efficiency improvements of around 5% through synergies of high octane with downsizing in real world driving conditions when optimised for higher blends levels such as E85. (Not Flex Fuel Vehicle) + Thermal efficiency improvement through lean combustion with appropriate NOx control as main powertrain or for hybrid application	• Dedicated fully optimised high alcohol blend engine and combustion system designs • Improved combustion and after treatment control strategies (incl. for currently non-regulated emissions such as aldehydes) • Fully optimise and integrate the engine with the electric propulsion system (hybridisation, range extender engine) • Bi-fuel SI vehicles (octane on demand) using higher octane biofuels in conjunction with lower octane carbon footprint fossil or synthetic fuels
Hydrogen	Hydrogen	Fuel Cell	- Cost of the fuel cell stack and hydrogen tank + Similar driving ranges to conventional ICE based vehicles + Similar refuelling time to conventional ICE based vehicles + No vibrations inside the vehicle leading to an increased comfort for the driver and passengers (no combustion engine) + Reduced external noise footprint of the vehicle linked to an electric powertrain (no combustion engine) + Zero emission at point of use	• Innovation in material science e.g. low-titanium bipolar plates, low-platinum catalyst loading, and alternative catalyst materials (non-noble metal, transition metal oxides, and bio-inspired catalysts) – PEMFCs • Balance of Plant components: humidifiers, compressors, • Improved compressed storage (C-fiber, liner, etc) • Novel storage and fuel cell stack designs • Improved compressors with higher reliability for use at refuelling stations • Innovative materials and structure for SOFCs – focus on auxiliary power • Electrochemical CO_2 separation – SOFCs • Alternative hydrogen storage technologies e.g. metal hydrides and porous sorbents, LOHCs and ammonia. • High-volume and highly automated FC production methods e.g. tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes • Innovative inline quality control for mass production of components • Efficient and reliable hydrogen purification equipment at refuelling stations

5.1.2 HDVs

Methane based gases in either compressed (CNG) or liquefied (LNG) form are currently considered as the main alternative fuel for the HDV sector (which is powered by CI engines). Dual fuel CI engines (engines capable of running on diesel or CNG/LPG with diesel pilot in this case), however, do not currently meet Euro 6 emission limits. Significant research effort into advanced injection systems and /or aftertreatment systems that can operate under low temperature conditions is required to overcome this issue. There is also potential for a more efficient use of methane through the development of high pressure direct injection (HPDI). In new generation HDPI engines, the diesel injection accounts for ~5% of the fuel energy, while the balance is provided by natural gas. Further, recent studies claim that new generation HPDI engines offer similar levels of performance and drivability to diesel[168]. In 2018, Westport Fuel Systems entered into an agreement with Weichai Westport to develop market and commercialise a heavy duty, natural gas engine featuring the Westport HPDI 2.0 in China.[169] Commercial HDPI engines can meet Euro 6 limits, but fugitive methane emissions remain a concern for the rest of the fuel chain.

Engine technology is currently commercially available for **DME and ED95** combustion systems, which provide alternatives to CNG/LNG technology. While these technologies meet Euro 6 emission limits and have efficiency similar to diesel engines, further research into engine efficiency improvement, pollutant control and end-fuel specifications could yield further improvements. The emission of currently non-regulated emissions such as aldehydes needs further research. MD95 could be an interesting option owing to the range of pathways it can be produced from, including renewable electricity.

Similarly to LDVs, **Synthetic Paraffinic Fuels** represent a drop-in solution which could be adopted by the existing fleet. Additional research will help understand the benefits of these fuels in improving engine efficiency and reducing pollutant emissions.

Developing advanced manufacturing techniques for fuel cells can significantly reduce the cost of **hydrogen FC HDVs.** With a significant portion of the capital costs of FCEV HDVs being attributable to fuel cells, reducing their cost is a key priority. **Fuel cells fuelled by alcohols or other alternative fuels** could be of interest, also for ancillary power supply.

Another area for R&I is the development of high efficiency, low pollutant and low cost **engines for use in hybridisation / range extender applications**.

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[168] hhttps://tinyurl.com/y29d9msm
[169] https://www.greencarcongress.com/2018/08/20180829-hpdi.html

Table 15 - HDV summary table of R&I needs

HDV				
Fuel category	**Fuel**	**Powertrain**	**Challenges(-) & opportunities(+)**	**R & I needs**
Natural gas	Compressed or liquefied natural gas, biomethane or methane (CNG, LNG)	SI engines optimised for gas operation	- Limited or no emissions savings compared to gasoline or diesel for fossil natural gas. Would require transition to biomethane to methane produced using renewable electricity - Methane leakage could significantly affect savings - Questions around fine particles emissions from methane combustion+Mature technology that is commercially available + Increase engine thermal efficiency, but unlikely to reach current diesel engine levels + Further reduction of tail pipe pollutant emissions due to lower engine out emissions + On-board storage improvements through conformable, cheaper, lightweight solutions	• Specific hardware and control strategies to limit evaporative methane emissions from the fuel system and crankcase • Dedicated CNG/LNG engine and combustion system designs • Better combustion and after treatment control strategies • Optimised TWC chemistries to reduce tailpipe pollutants and methane further • New components for high efficiency and performance SI engines, such as direct injectors, electronic regulators, gas quality sensors and control strategies • Cheaper and more space efficient (e.g. conformable) LNG tanks development and vehicle integration
		SI lean	- Ignition system and control to robustly initiate combustion and maintain good combustion stability at very lean conditions to ensure low engine out NOx emissions - Appropriate and cost-effective aftertreatment systems to meet regulation - Effective air handling and load control + Significantly increase the engine thermal efficiency of about 10-20% relative to SI gas engine, reaching diesel levels of efficiency + Potentially well suited to being combined with increased electric propulsion (Plug in hybrid, range extender)	• Advanced ignitions systems such as fully controllable multiple spark ignition, corona, plasma, etc • Advanced aftertreatment systems for dedicated lean burn gas engines • Fast response and variable air handling systems such as electric superchargers with appropriate control systems to ensure good driveability • Dedicated combustion, fuelling and air handling system design • Fully optimise and integrate the engine with the electric propulsion system (Plug in hybrid, range extender)
		CI - Dual Fuel	- Methane tailpipe emissions exceed EURO 6 limits currently with HPDI in development to solve this issue - Methane catalysis at low temperatures experienced at regulated test procedures	• Low CH_4 combustion system or CH_4 catalysis.
			+ HPDI technology + Multifuel capabilities to bridge fuel transition + Further thermal efficiency improvements + Increased gas replacement factors + On-board storage improvements through conformable, cheaper, lightweight solutions	• Advanced fuel injection systems (incl. high pressure direct injection – HPDI), regulation components, gas quality sensing and control strategies • Advanced aftertreatment systems at competitive cost • Cheaper and more space efficient (e.g. conformable) zero-vent LNG tanks development and vehicle integration”
Liquid Petroleum Gas	LPG, BioLPG	SI	+ Improved engine efficiency through dedicated engine design with direct injection systems + Further reduction of tail pipe pollutant emissions due to lower engine out emissions + Significant thermal efficiency through lean combustion reaching diesel levels with appropriate NOx control as main powertrain or for hybrid application	• Vehicle with a dedicated direct injection spark ignition engine running on LPG/bio-LPG (with optimized compression ratio, injection strategies, use of EGR and any other measure directed to improve engine efficiency such as lean operation) • Injection system for LPG/bio-LPG direct injection which prevents vapour lock under hot conditions • Advanced aftertreatment chemistries and systems at competitive cost • Integration of LPG/bio-LPG engine in a hybrid vehicle

			+ On-board storage improvements through conformable, cheaper, lightweight solutions	• Light weight fuel tank for LPG/bio-LPG in-vehicle storage with a shape suitable to be integrated as a conventional tank (e. g. under the vehicle trunk)
Alcohols and ethers	DME, OME	CI (incl. LTC etc.)	+ DME engines are mature EURO 6 technology, commercially available through Volvo + Lack of PM allows further NOx reduction and / or improved fuel economy + Dedicated fuel injection technology and control might allow further thermal efficiency improvements and pollutant emission reduction + On-board storage improvements through conformable, cheaper, lightweight solutions	• Dedicated and optimised DME combustion, fuel, control and aftertreatment systems with the aim to even further improve TTW GHG and pollutant emissions • Light weight fuel tank for DME (similar to LPG) in-vehicle storage with a shape suitable to be integrated as a conventional tank (e. g. under the vehicle trunk)
	Ethanol, methanol, butanol and other alcohols or blends	SI, SI lean	- Early stage research at MIT, Ghent University - Driveability and emissions control - Potential for non-regulated aldehyde emissions + Engine thermal efficiency matching or exceeding that of CI diesel engines throughout the operating area + Reduction of tail pipe NOx and PM emissions + Dedicated fuel injection technology and control might allow further thermal efficiency improvements and pollutant emission reduction + Potentially well suited to being combined with increased electric propulsion (PHEV, Range Extender)	• Significant potential was demonstrated during early testing. Further more detailed testing is required to understand the detailed R&I needs • Dedicated and optimised alcohol combustion, fuel, control and aftertreatment systems with the aim to even further improve TTW GHG and pollutant emissions. • Lean SI system development with specific advanced ignition systems, aftertreatment and control systems • Develop high efficiency, low pollutant and low cost engines for use in hybridisation / Range Extender
	Ethanol, Methanol	CI (incl. low temperature combustion systems)	- Ethanol with an ignition improver (ED95) is a mature EURO 6 technology for HDV applications (Scania) + Potential to demonstrate an optimised alcohol based fuel with appropriate additives in CI engine technology + Reduction of tail pipe pollutant emissions + A single liquid fuel diesel alternative that makes the infrastructure issue much easier	• Suitability of other alcohols. Methanol with an ignition improver (MD95) is under investigation at VTT • Dedicated and optimised alcohol (with an ignition enhancer) combustion, fuel, control and aftertreatment systems with the aim to even further improve TTW GHG and pollutant emissions

	Methanol	CI Dual Fuel	- Currently very immature technology in HDV, but principle demonstrated and commercialised in shipping and in principle similar to NG Dual Fuel - Potential corrosion issues - Potential for non-regulated aldehyde emissions + Dedicated fuel injection technology (HDPI) and control might allow further thermal efficiency improvements + Multifuel capabilities to bridge fuel transition + Engine thermal efficiency matching or exceeding that of CI diesel engines throughout the operating area + Further reduction of tail pipe pollutant emissions due to lower engine out emissions. + Lack of engine out PM allows further NOx reduction and / or improved fuel economy	• Significant R&I requirements as this technology is immature • Need for research to assess suitability of this fuel and technology for HDV sector • Assess corrosion issue and develop new materials / additives • Assess the scale of aldehyde emissions & aftertreatment option • Optimised injection equipment for alcohol dual fuel applications • Optimised combustion, aftertreatment & control systems
SPF	SPF	Other	+ To address the EU imbalance between gasoline and diesel demand.	• Naphtha or other higher volatility/ less processed fuels in compression ignition engines using low temperature combustion for improved efficiency with lower emissions and WTW CO_2 reduction • Low temperature combustion in CI using higher volatility synthetic/low carbon e.g. paraffinic fuels for improved efficiency and reduced emissions • Demonstration of the business case for using SPFs in HDVs
Hydrogen	Hydrogen	Fuel Cell	- Cost of the fuel cell stack and hydrogen tank + Similar driving ranges to conventional ICE based vehicles + Similar refuelling time to conventional ICE based vehicles + No vibrations inside the vehicle leading to an increased comfort for the driver (no combustion engine) + Reduced external noise footprint of the vehicle linked to an electric powertrain (no combustion engine) + Zero emission at point of use	• Large demonstration projects to validate the use of the technology for in the HDV segment and refine suitable business models • Balance of Plant components: humidifiers, compressors, • Improved compressed storage (C-fiber, liner,etc) • Novel storage and fuel cell stack designs • Improved compressors with higher reliability for use at refuelling stations • Innovation in material science e.g. low-titanium bipolar plates, low-platinum catalyst loading, and alternative catalyst materials (non-noble metal, transition metal oxides, and bio-inspired catalysts) – PEMFCs • Innovative materials and structure for SOFCs • Electrochemical CO_2 separation - SOFCs • Alternative hydrogen storage technologies e.g. metal hydrides and porous sorbents, LOHCs and ammonia. • High-volume and highly automated FC production methods e.g. tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes • Innovative inline quality control for mass production of components • Efficient and reliable hydrogen purification equipment at refuelling stations

5.1.3 Rail

The use of alternative fuels in ICE technology in rail is considered for those routes where overhead line electrification is not commercially feasible and diesel engines are used. The rail sector is currently not a technology leader in ICE technology and fleet turnover is generally slow. As a consequence the sector relies heavily on adapted engines and other technology originally developed for the on and off-road HDV sector and hence most of the HDV considerations would also apply here.

The main alternatives considered are **LNG** and the increased use of **biodiesel and SPFs** (e.g. HVO). The uptake of LNG as an option, requires the engineering of new locomotives for dedicated LNG engine or dual-fuel engines since this option is not suitable for existing locomotive retrofitting. Furthermore significant efforts are required to roll out dedicated and optimised combustions systems for these fuel types as well the required aftertreatment systems meeting NRMM stage V.

The use of **biodiesel** in engines with blending up to 20% (B20) is considered a mature technology, and such blending does not require significant engine modifications. This option has the merit of decreasing soot emissions, but may increase fuel consumption and NOX emissions, requiring combustion control and aftertreatment systems.

Hydrogen FC trains are appearing as the disruptive option, with the first commercial trains operating in Germany. Hydrogen trains could be used on routes which are difficult or uneconomic to electrify due to route length or lack of space in urban areas. Alstom announced plans to convert a fleet of trains in the UK from electric to hydrogen to avoid the need for line electrification and meet the government target of eliminating diesel trains by 2040[170]. Light rail also presents opportunities for hydrogen, with fuel cell-powered trams being developed and operated in China.

Increased levels of vehicle **electrification** enable engines to be optimised for one or a small number of operating conditions where it is most efficient as is the case in range extender vehicles for example. Additional efficiency improvements can then be leveraged by utilising the unique properties such as octane level of alcohol and methane based fuels.

[170] B.Gerrard, (2018) *French train giant Alstom set to make UK's first hydrogen fleet at British site*, Telegraph,**https://tinyurl.com/yybmy3le**

Table 16 - Rail summary table of R&I needs

Rail				
Fuel category	**Fuel**	**Powertrain**	**Challenges(-) & opportunities(+)**	**R & I needs**
Esters	Biodiesel	CI	- Cold-weather characteristics not suitable for low temperature operation without fuel-line heaters. - Current knowledge shows an increase of NOx when using biodiesel. + Mature technology (US) - The use of B20 in railway engines is acceptable without requiring significant engine modifications. + B20 decreases the hydrocarbon and soot emissions, but may increase the fuel consumption (engine type, tuning level).	• Advanced combustion control and aftertreatment systems • Combining technologies (bi-mode trains) to improve fuel combustion efficiency and pollution reduction. • Advanced combustion technologies for managing NOx released during the combustion.
Natural Gas / alcohol	LNG / methanol	CI-DF	- Limited or no emissions savings compared to gasoline or diesel for fossil natural gas. Would require transition to biomethane to methane produced using renewable electricity - Methane leakage could significantly affect savings - Questions around fine particles emissions from methane combustion - Not suitable for existing locomotive retrofitting - Safety issues related to methane leakage + HPDI technology developed in shipping and trucking for both gas and alcohols would be equally suitable for rail	• Develop high energy efficiency locomotive • Engineering new locomotive for dedicated LNG-gas engine or dual-fuel engines • Develop a fuelling system capable of effective heat recovery for the cryogenic fuel. The temperature of the liquid fuel is −160°C and has to be increased to the temperature of the surrounding environment in a wise manner. The fuel must generally be pressurised at approx. 200 atm while being cold, in liquid state, with avoided cavitation • Develop a method, so as to handle the oil-off gas for better fuel economy • Combining propulsion system for energy saving • Optimise the combustion system to reduce the fuel consumption (automatic controlling devices)
Hydrogen	Hydrogen	Fuel Cell	- Cost of the fuel cell stack and hydrogen tank - Railway standards and safety regulation need to be adjusted to this new fuel + Similar driving ranges to conventional ICE based vehicles + Similar refuelling time to conventional ICE based vehicles + Reduced external noise footprint of the vehicle linked to an electric powertrain (no combustion engine) + Zero emission at point of use	• Balance of Plant components: humidifiers, compressors. • Improved compressed storage (C-fiber, liner,etc) • Novel storage and fuel cell stack designs • Improved compressors with higher reliability for use at refuelling stations • Innovation in material science e.g. low-titanium bipolar plates, low-platinum catalyst loading, and alternative catalyst materials (non-noble metal, transition metal oxides, and bio-inspired catalysts) – PEMFCs • Innovative materials and structure for SOFCs – focus on auxiliary power • Electrochemical CO_2 separation - SOFCs • Alternative hydrogen storage technologies e.g. metal hydrides and porous sorbents, LOHCs and ammonia. • High-volume and highly automated FC production methods e.g. tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes Innovative inline quality control for mass production of components • Efficient and reliable hydrogen purification equipment at refuelling stations

5.1.4 Waterborne

Large scale adoption of alternative fuels within the waterborne sector offers the possibility of significant reductions in airborne pollutants compared to the heavy fuel oils used. The two main alternative fuels that are currently considered for waterborne applications are **methane and methanol**. Both are currently commercially available and mainly used in dual fuel applications with gas oil used as a pilot injection to initiate combustion. Both **methane-based fuels** (LNG/LBG/PTL) and methanol could significantly reduce SOx and PM emissions in particular, as well as NOx emissions. The use of methanol could reduce NOx emissions by up to 60%, but not down to Tier-III level. Further research should be focussed on increasing the methanol / gas substitution rates respectively, engine efficiency and further reducing pollutant emissions, including eliminating methane slip. R&I on dedicated high efficiency lean combustion engines for either methane or methanol based fuels can potentially provide higher efficiency, low pollutant and GHG emission solutions.

Methane slip throughout the fuels chain is a concern for methane based fuels that warrants further research. Technologies for methane slip reduction need to be incorporated in new ship designs. Exhaust gas recirculation (which improves combustion stability), the use of aftertreatment systems with methane oxidation catalysts, or high-pressure direct injection are techniques able to reduce methane slip.

Hydrogen is appearing as an attractive clean fuel which could meet energy density and refuelling logistics requirements, possibly in the form of ammonia, which could be used in fuel cells or engines. Fuel cells fuelled by alcohol, LNG/LBG/PTL or other alternative fuels could be of interest, for both propulsion and ancillary power supply.

Ammonia – a hydrogen carrier – could be employed as a low emissions alternative fuel within the waterborne sector with possible advantages in terms of handling and storage compared to hydrogen. Ammonia engines are not available but are being developed, and in January 2019 Man diesel announced that had started a programme to develop an Ammonia marine engine which could potentially enter service by 2022[171]. Safety aspects around the development of ammonia as a fuel would need to be carefully considered (and norms developed), as well as emissions of nitrogen compounds if it were to be combusted.

Better storage and handling solutions and bunkering logistics are required for LNG and methanol. Wide scale uptake of either fuel is hampered by the limited (global) bunkering provisions.

[171] https://www.ammoniaenergy.org/man-energy-solutions-an-ammonia-engine-for-the-maritime-sector

Table 17 - Waterborne summary table of R&I needs

Waterborne Transport				
Fuel category	**Fuel**	**Powertrain**	**Challenges(-) & opportunities(+)**	**R & I needs**
Alcohols	Methanol	CI-DF	- Immiscible with marine fuels – cannot be used as blends. - Limited potential for CO_2 savings if from fossil source + Reduces emissions of PM by >80% and SOx by >90% depending on the substitution rate + Already used as main fuel in an adapted marine diesel engine with StenaLine. + Reduces NOx emissions by up to about 60% + Methanol and solid oxide fuel cell (SOFC) system for auxiliary power	• Develop engines & injection equipment allowing increased methanol (and other alcohols) substitution rates or have dedicated methanol engine technology that meets / exceeds current marine oil engine efficiencies at low CAPEX cost and low noxious emissions • Advanced aftertreatment systems (NOx) at competitive cost • Future research activities on larger methanol-fuel cells on marine vessels • Tests for assessment of environmental impacts of methanol and SOFC technology for shipping
Natural gas	LNG	SI	- Fuel availability, safety issues for on-board fuel storage, handling systems. - Possibility of abnormal combustion (methane slip) – sensitive to gas composition - Limited or no emissions savings compared to gasoline or diesel for fossil natural gas. Would require transition to biomethane to methane produced using renewable electricity - Methane leakage could significantly affect savings - Questions around fine particles emissions from methane combustion+ Waterborne engines using low pressure LNG have emissions below NOx limit (IMO Tier III) without use of exhaust gas treatment system + Possibility to use the cooling effect of LNG vaporisation for refrigeration of foods (e.g. fish boats), air conditioning on-board, and other cooling effect + Potential for higher efficiency if used in high temperature high power fuel cells	• New engine design for: load efficiency optimisation, reduction of methane slip, adaptation to variable gas composition. • Emission control and energy efficiency measures for ships in the port area. • Waste heat recovery from propulsion engine for overall fuel consumption management on ship. • Investigation on ultrafine PM • Fuel handling and storage (onboard and shore): better storage solution (space, cost), bunkering logistics • High temperature high power LNG powered fuel cell development as possible transition to hydrogen
		CI-DF	- Sensitive to gas composition - Higher NOx emissions than the lean burn type (SI). + Fuel flexible engines - able to switch between fuels in different sailing regions or when some abnormal combustion or leakages occur. Less dependence on the availability of LNG bunkering facilities when sealing in different regions.	• Improvement of energy efficiency of large vessels for coastal and seagoing vessels (increase propulsion efficiency – combined electric propulsion, integrated propeller-rudder configuration). • Advanced injection (HPDI) and combustion systems for greater efficiency • Advanced optimised cylinder lubrication systems. • Advanced catalyst system for aftertreatment (NOx) at competitive cost • Investigation on the impact of switching fuel on emissions level and engine components. • Numerical models for evaluating case by case the integration of energy efficiency systems in new ships designs. • Developments in sensors, condition assessment and adaptive control methods, materials tribology and lubrication improvements

				• Waste heat recovery from propulsion engine for overall fuel consumption management on ship
Hydrogen	Hydrogen / Ammonia	Fuel Cell / Engines	- Cost of the fuel cell stack and hydrogen tank - Marine regulations need to be adapted to this new fuel used on rivers and at sea - High toxicity of ammonia + Similar rang to conventional ICE based ships + Similar refuelling time to conventional ICE based ships + No vibrations inside the ship leading to an increased comfort for passengers (no combustion engine) + Reduced external noise footprint of the vehicle linked to an electric powertrain (no combustion engine) + Zero emission at point of use +/- Long ranges required and fuel bunkering constraints may favour higher energy density liquid option like ammonia next to CH2 and LH2 + Easiness to handle ammonia as a fuel as it is liquid under ambient temperature and pressure	• Demonstration projects to demonstrate the viability of hydrogen and fuel cells in marine environments • Balance of Plant components: humidifiers, compressors • Improved compressed storage (C-fiber, liner,etc) • Novel storage and fuel cell stack designs • Improved compressors with higher reliability for use at refuelling stations • Development of ammonia engines (including dual fuel) and direct ammonia fuel cells • Innovation in material science e.g. low-titanium bipolar plates, low-platinum catalyst loading, and alternative catalyst materials (non-noble metal, transition metal oxides, and bio-inspired catalysts) – PEMFCs • Innovative materials and structure for SOFCs • Electrochemical CO2 separation - SOFCs • Alternative hydrogen storage technologies e.g. metal hydrides and porous sorbents, LOHCs and ammonia. • High-volume and highly automated FC production methods e.g. tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes • Innovative inline quality control for mass production of components • Efficient and reliable hydrogen purification equipment at refuelling stations

5.1.5 Aviation

Aviation strongly relies on energy dense fuels. While radical redesign of aviation powertrains to improve efficiency is progressing, the sector is expected to remain highly dependent on drop-in fuels for at least the next 30 years. **Synthetic Paraffinic Fuels (SPFs)** currently seem the most feasible alternative fuel for the near future. Various routes to synthetic kerosene are already technically available for commercial aviation and up to other 20 are currently waiting to be tested and approved for use. Important areas of research with regards to the use of SPFs in aviation include assessment of the impact on engine components, understanding blending limits and optima, and impact on pollutant emissions. In terms of energy efficiency, the gains that can be expected from using drop-in fuels are small (~2%), but there is an interesting potential for reduction of non-volatile particulate matter (nvPM) (up to 60% reduction in mass and 40% on PM number with a 50/50 blend[172]). Research is also focused on understanding the lower limits for some aromatics species and sulphur for providing optimal performance while reducing SOx and PM emissions. The effect of different blend levels of drop-in fuels on parameters like combustion temperature, efficiency, unburned hydrocarbons and black carbon are a subject of research, and could lead to different high altitude effects compared to conventional kerosene. Further research on the SPFs is needed in relation to chemical composition, allowable and optimal blending levels, and impact on pollutant emissions. Radical aircraft redesign could lead to the consideration of liquefied methane and hydrogen as fuels in the longer term.

According to **FCH Europe's hydrogen roadmap for Europe**[173] synthetic fuels based on hydrogen will play an important role in reducing GHG emissions in aviation. While non-drop-in fuels such as hydrogen cannot be considered in the short term as a mainstream solution for the decarbonisation of jet aviation propulsion, research into this option remains of interest because of the future role of hydrogen as an energy vector in other sectors. This is a long-term option as hydrogen will involve the redesign of the aircraft and propulsion system.

However, in the short-term hydrogen fuel cells could provide a clean auxiliary power source. Using fuel-cell-powered APU is a solution for reducing fuel consumption, pollution and GHG emissions. SOFC is one option for aircraft APU applications due to the fact that it is more tolerant to fuel impurities and can operate using hydrogen generated from kerosene, which could be internally reformed.

[172] EC funded ITAKA project

[173] FCH Europe (2019): Hydrogen Roadmap Europe, available online at : https://tinyurl.com/y4528mma

Table 18 - Aviation summary table of R&I needs

Aviation				
Fuel category	**Fuel**	**Powertrain**	**Challenges(-) & opportunities(+)**	**R & I needs**
SPF	FT-SPK, HEFA-SPK, FT-SKA	Turbofan	- Unknown real blend limits, current limit related with aromatics and sulphur content + Similar composition to incumbent + Mature technology once blended up to 50% v + Blend ratio likely to be enlarged with better knowledge + Lower pollutants (PMs up to -60%, and S) + Potential (lower?) climate effect at altitude	• To know what is maximum blend limit, particularly with regards to minimum aromatics and sulphur content • Need to know effects on maintenance operations (i.e. in flight water generation) with long term use • To know the effects on key emissions varying properties of the fuel, engines, operations and atmospheric conditions to better define the extent of the benefits of the use. • Integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities • Support testing at ASTM for enabling more alternatives
SPF	SIP	Turbofan	- blend limits, probably cannot go higher - fuel composition different to incumbent + Mature technology once blended up to 10% v + Lower pollutants (PMs up to -60%, and S) + Potential lower NOx emissions with better design + Potential (lower?) climate effect at altitude	• Integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities • Support testing at ASTM for enabling more alternatives
SPF	ATJ	Turbofan	- blend limited by fuel gauging system performance - fuel composition different to incumbent + Mature technology once blended up to 30% v + Lower pollutants (PMs up to -60%, and S) + Potential (lower?) climate effect at altitude	• Integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities • Support testing at ASTM for enabling more alternatives
SPF	HEFA+	Turbofan	- Fit for purpose not certified - max (foreseen) blend 10% v - Mature (fuel) technology + Lower pollutants (PMs and S) + Potential (lower?) climate effect at altitude	• Needs to better understand the blend limits and the properties for production and distribution • Integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities • Support testing at ASTM for enabling more alternatives

LNG	LNG	Turbofan	- not drop-in, volume/weight/energy ratio requires different aircrafts, logistics facilities - Increased water vapour emission by 40% (potential climate impact) [AHEAD] - uncertain climate effect (balance) at altitude + Decrease of CO_2 by 25% [AHEAD] + Decrease of NOx by 80% [AHEAD] + Zero PM emissions [AHEAD] + better thermal efficiency	• Breakthrough research on airframe and combination with electrification
Hydrogen	Hydrogen	Fuel Cell for on-board power (APU, kitchen power and heat supply, emergency power) Turbofan	- Cost of the fuel cell stack and hydrogen tank - Need for the development of lightweight resistant hydrogen tanks for use onboard - New regulations for hydrogen use in aviation + Zero emission at point of use + No vibrations inside the plane leading to an increased comfort for passengers (no combustion engine) – for APU + Reduced external noise footprint of the plane linked to an electric powertrain (no combustion engine) – for APU - Redesign of aircraft for hydrogen storage + Potential access to zero carbon fuel	• Develop a light-weight, cost-effective, and safe hydrogen storage technology • Balance of Plant components: humidifiers, compressors, … • Improved compressed storage (C-fiber, liner….) • Novel storage and fuel cell stack designs • Improved compressors with higher reliability for use at refuelling stations • Innovation in material science e.g. low-titanium bipolar plates, low-platinum catalyst loading, and alternative catalyst materials (non-noble metal, transition metal oxides, and bio-inspired catalysts) – PEMFCs • Innovative materials and structure for SOFCs • Electrochemical CO_2 separation - SOFCs • Alternative hydrogen storage technologies e.g. metal hydrides and porous sorbents. • High-volume and highly automated FC production methods e.g. tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes Innovative inline quality control for mass production of components • Efficient and reliable hydrogen purification equipment at refuelling stations • Effective burning of hydrogen as jet fuel requires redesigning the traditional combustion chamber • Airframe redesign for hydrogen storage

5.2 Implementation plan

Reducing GHG emissions in transportation consists of two main elements, namely:

1. The availability of cost-effective sustainable low carbon alternative energy / fuels (well-to-tank - WTT)
2. Improved efficiency in real world utilisation (tank-to-wheel - TTW)

This report deals with the potential impact of alternative fuels on the latter, as well as their potential impact on emissions affecting air quality. Decarbonisation will depend on the full well-to-wheel implications of alternative fuel use, and will need to rely on low carbon and renewable fuels, while alternative fossil-derived fuels could help address in the interim air quality and energy diversification issues.

Figure 19 provides an indicative timeline by which powertrain transitions and market deployment could lead to significant benefits in combination with alternative fuel use. The R&I needs for each transport sector supporting a transition to more efficient power trains that maximise the benefits of alternative fuels are summarised below and detailed in **Tables 14 to 18**.

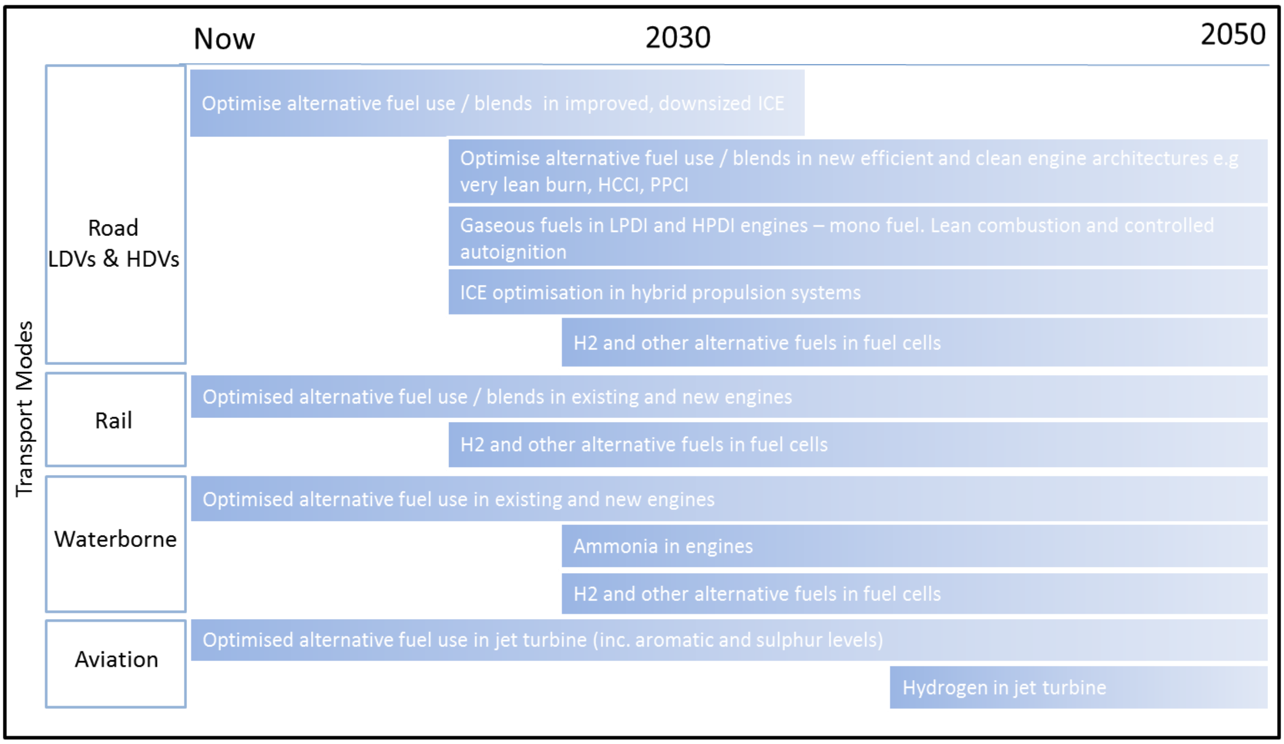

Figure 19 - Overview and timescales of most promising alternative fuel and powertrain combinations

A high-level summary of key elements of a R&I agenda in relation to the different alternative fuels considered is the following:

Alcohols and ethers:

- Optimal levels of alcohols and ethers to maximise WtW emissions savings
- Optimise injection, combustion and aftertreatment
- Downsizing / rightsizing and hybridisation

- Bi-fuel octane on demand engine
- Control aldehyde emissions
- High temperature fuel cells

Methane:

- Direct injection in SI engines
- Lean combustions and controlled auto-ignition
- Aftertreatment to avoid methane slip e.g. exhaust gas recirculation
- Methane slip and leakage in supply chain
- High temperature fuel cells

Synthetic paraffinic and aromatic fuels:

- Optimal levels of SPFs to maximise WtW emissions savings
- Appropriate levels of aromatics

Hydrogen:

- Fuel cell materials, architectures, balance of plant components, manufacturing techniques
- Hydrogen production technologies, storage and refuelling infrastructure

5.3 Synthesis of R&I agenda

The main alternative fuels are gases, alcohols, ethers and drop-in SPFs with specific technology R&I requirements highlighted in the tables and text in **Section 5.1** for each transport mode. The rest of this section provides a synthesis of the R&I agenda in support of the implementation plan above.

LDVs

Increase the uptake of **alcohols, ethers and gases** in spark ignition (SI) engines (taking into consideration their potential for GHG savings), while improving their use by optimising injection, combustion, aftertreatment systems and their control. For compression ignition (CI) engines the uptake of more **biodiesel and especially SPF** (again taking into consideration their potential for GHG savings) would benefit from optimisation of the engine and related technology.

Direct injection in gas SI engines has the potential to further improve the TTW GHG emissions of such engines. Both SI & CI gas engines can achieve higher efficiency combustion systems, such as lean combustion, controlled auto-ignition (CAI) for SI engines and homogeneous charge compression ignition (HCCI) and all manner of low temperature combustion (LTC) systems for CI engines. Implementation of such systems would significantly benefit from narrower fuel specifications, which alternative fuels could provide.

Furthermore, these combustion systems tend to be best suited to and most efficient at a narrower operating window both in terms of speed/load as well as their transient capability. Increased levels of electrification can facilitate this by effectively filling in the operating window gaps. A strong R&I focus on optimisation of the complete system with increased levels of electrification is therefore required.

Although **hydrogen fuel cell LDVs** have been commercially developed, they should be the focus of greater attention because of benefits they may have over BEVs e.g. weight, range, refuelling times. Fuel cells fuelled by alcohols or other alternative fuels could be of interest, considering that a prototype running on ethanol-based fuel cells has already been developed[174]. Developing advanced manufacturing techniques for fuel cells can significantly reduce the cost of fuel cell vehicles. The focus should be on improving manufacturing techniques, such as shifting to high-volume and highly automated production techniques, for example by developing tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes.

HDVs

Alcohol and ether based CI combustion systems are commercially available, but not widespread in part due to lack of infrastructure. There is further development potential in the better utilisation of these fuels with a particular focus on high efficiency high pressure direct injection (HPDI) dual fuel systems as well as LTC systems.

Direct injection in SI gas engines could improve efficiency and tank-to-wheel (TTW) GHG emissions of such engines, approaching CI engine technology, while meeting EURO 6 emissions limits due to the possibility of significantly reducing **methane slip**.

High efficiency combustion systems that operate in a narrower window both in terms of speed/load as well as their transient capability could be developed for HDVs for lighter duty cycles i.e. shorter distances, lower speeds and lower carrying capacity. Increased levels of electrification can facilitate this by effectively filling in the operating window gaps. A strong R&I focus on optimisation of the complete system with increased levels of electrification is therefore required for these vehicles.

Hydrogen fuel cells could be the long-term solution for HDVs, with R&I challenges similar to those listed for LDVs. Fuel cells fuelled by alcohols or other alternative fuels could be of interest, also for ancillary power supply.

Rail

Where overhead line electrification is not commercially feasible the rail sector could benefit from the increased use of blended **biofuels and SPFs**.

Typically, this sector relies heavily on adapted engines and other technology originally developed for the on and off-road HDV sector and hence most of the HDV considerations above would also apply here, including gas engines that could be of interest in future locomotives. The availability of an (overhead) charging infrastructure and well-known duty-cycles suggests that the interaction between ICE and electrification technology is particular promising.

Hydrogen fuel cells could emerge rapidly as the disruptive technology, with a first commercial train already in operation in Northern Germany and several countries (France, UK, etc) working on deployments plans. Principal R&I challenges are similar to road HDV challenges. The Fuel Cell and Hydrogen Joint Undertaking and the Shift to Rail Joint Undertaking recently published (May 2019) a major study on the potential of hydrogen trains in Europe. TCO analyses show that the technology

[174] https://nissannews.com/en-US/nissan/usa/releases/nissan-unveils-world-s-first-solid-oxide-fuel-cell-vehicle

can be cost competitive with the incumbent technologies if favourable conditions such as low electricity prices can be achieved. The overall market potential until 2030 is estimated to be significant, especially for Multiple Units where FCH trains could potentially substitute 30% of diesel purchasing volumes[175].

Waterborne

Large scale adoption of alternative fuels within the waterborne sector offers the possibility of significant reductions in airborne pollutants compared to heavy fuel oils. **Methane (LNG/LBG/PTL) and methanol** in dual fuel applications are commercially available and would be adopted more widely if greater fuelling infrastructure were available, and supply chains, storage and engines could be further optimised to eliminate methane slip, improve efficiency and emissions.

As per the Implementation Plan of Action 8 Bioenergy and Renewable fuels of the SET Plan, **liquid renewable drop-in fuels** are seen as a viable option for the mid-term to long-term (30-40 years)[154].

High efficiency combustion systems that operate on a single fuel in a narrower window in terms of both speed/load as well as their transient capability could be developed for some ship engines.

Hydrogen is appearing as an attractive clean fuel, which could meet energy density and refuelling logistics requirements, possibly in the form of ammonia, which could be used in fuel cells or engines. Fuel cells fuelled by alcohol, LNG/LBG/PTL or other alternative fuels could be of interest, for both propulsion and ancillary power supply.

Aviation

SPFs are the most feasible alternative fuel for the foreseeable future for aviation. Various end-fuels are under consideration, and research will focus on assessing impact on engine components, understanding blending limits and optima, and impact on pollutant emissions. As per the Implementation Plan of Action 8 Bioenergy and Renewable fuels of the SET Plan, **liquid renewable drop-in fuels** are seen as a viable option for the mid-term to long-term (30-40 years). However, it is noted that currently, there is hardly any production of aviation and maritime biofuels in the EU[176].

Hydrogen is also making currently an entry in the aviation space, but mainly so far as a fuel to power auxiliary power units and provide limited energy while on flight.

Discussions are now also starting on how hydrogen could play also a (partial and increasing) role in propulsion chains in the future. In this regard it is worth noticing that the Region Occitanie in France, which hosts major assembly lines of Snecma (engines for planes) and Airbus, has recently tabled (May 2019) a hydrogen plan with 150 MEuros of public funding including support to new hybrid solutions for aviation.

[175] https://fch.europa.eu/publications/study-use-fuel-cells-and-hydrogen-railway-environment
[176] https://setis.ec.europa.eu/system/files/setplan_bioenergy_implementationplan.pdf

5.3.1 Roles and resources

The transport industry and its suppliers are major investors in innovation, to the tune of around 40 billion Euros according to ACEA[177]. Much innovation and related spending has gone into improving vehicle efficiency to meet lower vehicle CO_2 emissions limits.

Alternative fuels should play a major role in reducing CO_2 emissions from transport by substituting fossil fuels, but the role they can play in reducing tailpipe CO_2 emissions by allowing engine efficiency improvements and more efficient hybridisation also need to be recognised for these benefits to be realised. Recognising and realising these benefits requires a **greater interplay between fuel suppliers and the automotive industry**, so that emissions reduction from fuel use and from vehicle operation are no longer seen as separate and the synergies between the two are exploited.

Automotive and fuels supply chains are spread across different countries and integration will be a feature of future research and innovation, stressing the importance of **cross-industry and cross-country collaborations**. European Framework programmes are therefore ever more relevant in this context. So, is also the continued development of **industry research roadmaps that specifically incorporate alternative fuel and vehicle interactions**. In addition, **national and regional industry roadmaps** should highlight national and regional strengths and the opportunity for EU-wide collaboration and complementarity of EU and national / regional funding (**Figure 20**).

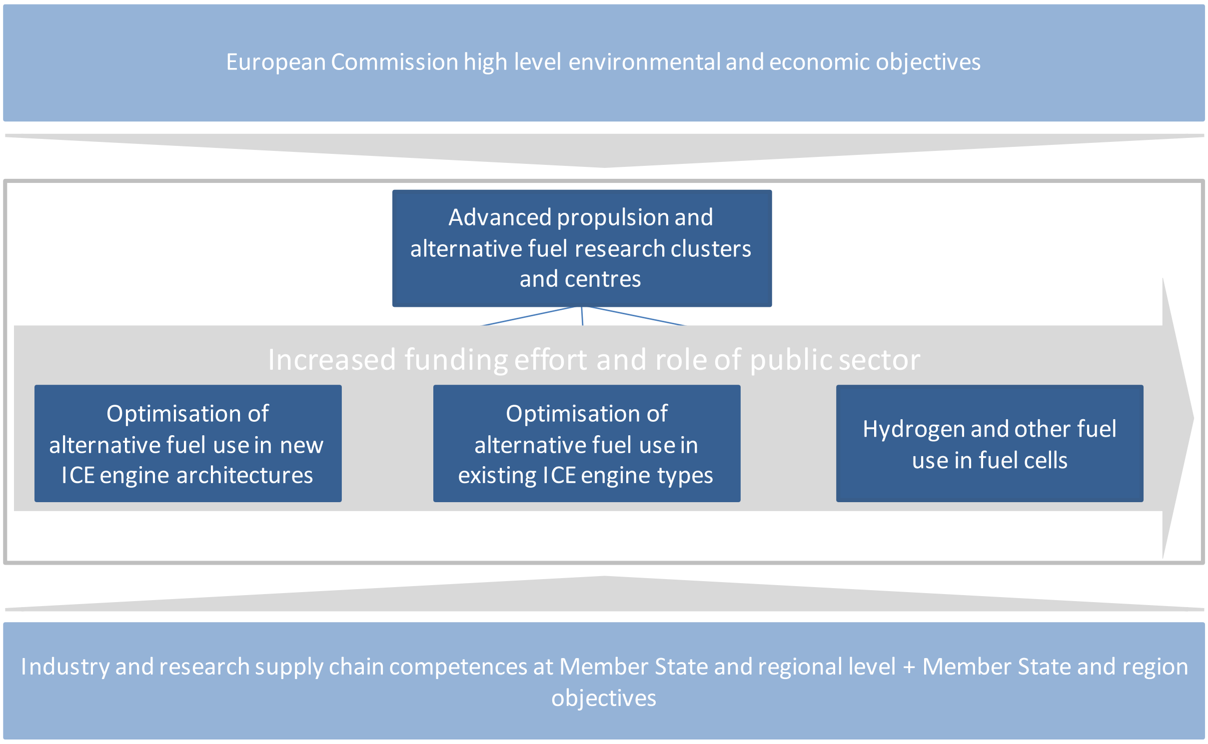

Figure 20 - High level framework for alternative fuel and powertrains R&I

There is also an important role for **harmonised policy and standards** in effectively delivering a clean transport system in Europe, for example through fuel specifications that enable higher levels of alternative fuels to be delivered to the market. The European Commission and cross-industry groups will continue to be instrumental in this area. Research will however also need to deliver

[177] http://www.acea.be/uploads/press_releases_files/POCKET_GUIDE_2015-2016.pdf

technologies which are able to deliver best results under variable conditions e.g. varying blend levels across Europe.

Policy will need to play an important role in steering the research towards meeting specific environmental objectives, as it has successfully done in the case of vehicle CO_2 emissions and HDV noxious emissions. So, the role of policy will be critical in sending signals to the market about the expected importance of alternative fuels. This will drive the private sector to allocate research resources to alternative fuels, which will be complemented by national and European funding to support innovation in the area.

6 High level vision for a Strategic Transport Research and Innovation Agenda on alternative fuels and powertrains

Transport still relies on oil for 94% of its energy needs. Transport emissions represent 32% [178] of the EU's GHG emissions, and remain a source of air quality problems in European cities. Furthermore, Europe imports around 87% of its crude oil and oil products from abroad, with a crude oil import bill estimated at around €187 billion in 2015 [179]. We lay out below a vision of what the Strategic Transport Research and Innovation Agenda in alternative fuels should help achieve.

Climate change and air quality require rapid and deep reductions in emissions across all transport

Sustainable, secure and competitive energy supply and transport services are at the heart of the EU 2050[180] strategy for a low carbon economy. Innovation and deployment of a variety of clean fuels and technologies in transport are essential for a successful transition to a sustainable economy as there is likely to be no silver bullet technology available to replace fossil energy sources. In addition to creating a healthier environment and securing energy supply and mobility services, innovation provides huge opportunities for the European economy. Europe's strategy in relation to fuels and powertrains R&I for transport should have the following objectives:

- Reduce emissions affecting climate change and air quality
- Valorise local sources of energy and reduce our dependence on fuel imports
- Preserve jobs in the transport industry
- Enhance our trade balance

Electrification will be a key element of a low emissions transport sector

Electrification of powertrains has multiple benefits: no emissions at point of use and very low emissions from the rest of the fuel chain if the fuel (either electrons or hydrogen) originates from renewable sources. Therefore, investment in electric powertrains will need to be a central element of a R&I strategy, complemented by R&I in combustion engines and related fuels that can help achieve deeper emissions reductions in the short and long term.

[178] International Energy Agency (2017) : www.iea.org

[179] EEA (2016), Air quality in Europe- 2016 report : www.eea.europa.eu
[180] Clean Planet for all Communication (https://ec.europa.eu/clima/policies/strategies/2050_en)

The bulk of the value to the economy is likely to lie in the development of batteries and fuel cells, and maintaining an automotive industry in Europe will rely on setting up battery and fuel cell supply chains in Europe. Additional economic value could be derived from R&I and solutions that would optimise the interactions between the power grids and the vehicles connected to them (either BEV or FCEV) i.e. developing vehicle to grid solutions before others. Investing in batteries also means investing in battery end-of-life options. The number of EVs in the world could go from 2m in 2016 and to 140m electric in 2030 according to the IEA[181]. This growth could lead to 11m tonnes of spent lithium-ion batteries in need of recycling between 2016 and 2030[182]. However, in the EU as little as 5% of lithium-ion batteries are recycled[183]. This has an environmental and resource cost. Not only do the batteries carry a risk of giving off toxic gases if damaged, but core ingredients such as lithium and cobalt are finite and their extraction can lead to water pollution and depletion among other environmental consequences.

Hydrogen and renewable synthetic fuels will be needed to decarbonise heavy duty road, marine and air transport

Hydrogen and fuel cells are clearly an attractive option to fully decarbonise coaches, trucks, trains and potentially ship powertrains in the long term, providing a full zero-emissions transport solution. This is due to the high-energy requirements of these modes of transport and potential limitations in batteries being able to provide the energy density and refuelling times required. Interest in hydrogen is growing[184,185], but synthetic renewable liquid and gaseous fuels derived from biomass or renewable hydrogen (and renewable CO2) could also contribute to fuel any hard to decarbonise heavy-duty road, rail and marine segments.

For jet aviation, liquid fuels are likely to remain the energy vector of choice for the long term because of the high energy density requirements – hence the opportunity for synthetic liquid fuels. Using compressed or liquefied gases to fuel planes would require airframe changes and have a negative impact on the weight of the plane. As for batteries, their current power and energy densities are not foreseen to suit long distance flights. Small planes operating short distance routes could however be electrified in the future, and hydrogen and fuel-cell based applications could find uses on planes for the production of power, heat and water, as well as providing a zero emission auxiliary power unit when stationed.

The question is then how to produce hydrogen and synthetic renewable fuels with the lowest environmental footprint.

Europe needs to urgently invest in battery and fuel cell development and supply chains

[181] IEA (2018), Global Electric Vehicle Outlook 2018 (https://www.iea.org/gevo2018/)
[182] According to Ajay Kochhar, CEO of Canadian battery recycling startup Li-Cycle
[183] EC (2018), Report on Raw Materials for Battery Applications (https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf)
[184] V. Sefcovcis – November 2018 – FCHJU Stakeholders Forum. “The question regarding the hydrogen economy is not anymore why and if we should develop it, but how”
[185] 14 March 2019 – Cera Week “For the decarbonization of heavy transport, there really is no alternative to hydrogen” – Marteen Wetselaar - COO Shell

Europe has so far not focused enough efforts on batteries and fuel cells for mobility. As a result, Europe is behind other regions in the race to develop and deploy battery and hybrid electric vehicles, and may miss fuel cells being the next big thing. Industry segments, jobs and trade balances are at risk. However, some momentum is being generated by EU-wide activities such as the European Battery Alliance and Fuel Cell and Hydrogen Joint Undertaking[186,187].

In Japan, Honda and Toyota have already launched hydrogen fuel cell cars since a couple of years and are now preparing the arrival of the second generation of these cars on the market. This means their R&D is busy working on the third generation of fuel cells for mobility.

In Korea, no less than $2 billion of investment from the government and $6 billion from Hyundai for the coming 5 years have been announced last December to develop the next FCEVs. Hyundai already has a second generation Nexo FCEV, meaning the company R&D also is also working on the third generation of FCEVs. Additionally, Hyundai has announced it will start delivering 1000 hydrogen trucks to Swiss transport operators beginning in this year.

Finally, billion dollars size investments in new FC production plants are planned in China, with capacities that exceed by far what is anticipated in western countries.

In Europe, some car manufacturers are active developing FCEVs and one has started the commercialisation of a first vehicle (Mercedes). Some tier one suppliers are also active in the space (Bosch is involved in hydrogen trucks, Plastic Omnium is building a 50 MEuros dedicated R&D centre in Brussels, and an alliance was just formed between Michelin and Faurecia). Even though there is nothing comparable so far to what is happening in Asia in terms of FC innovation and production line development efforts, EU OEMs are rapidly warming up to the technology and starting to make important investments.[188]

The transition towards clean transport implies a huge transformation in the automotive industry, which has for decades been a key and prosperous economic sector in Europe. It represents 8 million jobs and over 4% of the EU's GDP [189] . The EU is the second largest producer of cars behind China with 21% of the world production[190]. Focusing on battery and fuel cell R&I, while continuing to develop engine and aftertreatment technologies optimised for future fuels, will ensure the short to long term competitiveness of the industry. The strategic interest in fuel cells goes beyond transport as progress made in that field will have spill over effects on the decarbonisation of heating (also with fuel cells), a sector which accounts for about half of the emissions related to our energy use. FC developments will also benefit electrolysis developments (as electrolysis equipment uses the same or similar core technologies as fuel cells and is key to provide green hydrogen).

[186] https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en
[187] https://www.fch.europa.eu/
[188] Important EU players such as CNH Industrial and Bosch made important investments in Nikola (heavy duty) showing their commitments towards the technology and highlighting how the EU technology leadership can open markets https://www.electrive.com/2019/09/03/iveco-owner-cnh-invests-in-nikola/ and https://www.electrive.com/2019/09/07/bosch-and-hanwha-invest-230-million-in-nikola/
[189] https://ec.europa.eu/growth/sectors/automotive_en
[190] ACEA, 2018

Transforming biowaste into biofuels is an essential complement to electrification

As part of the efforts to valorise local sources of energy and promote an efficient use of resources, organic wastes should be reused to produce low carbon fuels. There is a wide array of technologies, some commercial and many under development, that can transform biowaste into biogases and bioliquids. Investment is needed to develop and improve processes to produce the fuels we will need to fully decarbonize all transports modes (e.g. aviation), as well as investment to scale up the technologies and related biowaste supply chains. This provides an opportunity to limit our dependence on oil imports and export European know-how and technologies abroad.

Green hydrogen could be part of these production paths, making biowaste derived fuels an integral part of the hydrogen economy, and reinforcing the case for their development.

Transition and local solutions will help in the global effort

There is a clear and pressing urgency in the fight against climate change. We have roughly a dozen years left at current greenhouse gas emission rates until we hit the 2 degrees scenario. In addition, air pollution remains one of the main environmental dangers to public health causing around 400,000 premature deaths in the EU each year[191]. The transport sector is a main source of pollution through the combustion of hydrocarbons. Consequently, we need to look at transition solutions that have an immediate effect on reducing pollution, as well as long term solutions.

Improvements in fuel formulations, engine and aftertreatment technologies are important in providing much needed improvements in air quality. As part of this, a move to gaseous fuels in heavy-duty transport could lead to lower pollutant emissions. Fuel formulation and engine improvements can also lead to important GHG emissions reductions, though small in the context of the climate change challenge, unless accompanied by a switch to low carbon fuels. Investing in R&I in these areas remains important. However, battery and fuel cell electric powertrains are likely to be the cleanest and most efficient option for reducing emissions in many transport segments, so should be the focus of R&I funding alongside the development of cost effective and sustainable low carbon fuel production routes.

R&I actions need to focus on the changes that are required to meet longer term environmental, energy security and consumer needs, and on what is strategic in terms of competitiveness, preserving jobs and the trade balance.

A STRIA on alternative fuels, complementing the STRIA on e-mobility, should focus public and private sector efforts on the following R&I:

- **Fuel cells, especially for heavy-duty road and marine application**
- **Cost-effective sustainable hydrogen (and derived fuels such as ammonia) production and storage technologies**

[191] European Environment Agency –EEA (2018), Air quality in Europe—2018 report

- **Bio and non-bio renewable liquid synthetic fuels for applications in road, marine and especially the aviation sectors**

- **High efficiency engines tailored to hybrid applications in medium and heavy-duty vehicles, and optimised for low carbon fuels**

This should be complemented by regulation and goverment programmes stimulating private sector financed R&I on development of the following:

- **Infrastructure needed to deliver alternative fuels**

- **Low carbon fuel formulations based on existing or novel fossil and renewable blend stocks for optimal use in internal combustion engines**

- **Engine aftertreatment technology to deliver level of emissions that pose no significant impact on human health, together with engine and fuel combinations that lead to cost effective solutions**

7 Appendix

7.1 Table of acronyms

APU	Auxiliary Power Unit
BEV	Battery Electric Vehicle
BTL	Biomass-to-Liquid
CAI	Controlled Auto Ignition
CI	Compression Ignition
CI-DF	Compression Ignition Dual Fuel
CNG	Compressed Natural Gas
CO_2eq	Carbon Dioxide equivalent
CO	Carbon monoxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DF	Dual Fuel
DME	Di-Methyl Ether
DPF	Diesel Particulate Filter
EEDI	Energy Efficiency Design Index
EMSA	European Maritime Safety Agency
ETBE	Ethyl Tert-Butyl Ether
EREV	Extended Range Electric Vehicle
EU	European Union
FAE	Fatty Acid Ester
FAME	Fatty Acid Methyl Ester
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch
GHG	Greenhouse Gas
GTL	Gas-to-Liquid
IMO	International Maritime Organization
HC	Hydrocarbons
HCCI	Homogeneous Compression Charge Ignition
HDV	Heavy Duty Vehicle (on roads)
HEFA	Hydrotreated Esters and Fatty Acids
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
LBG	Liquefied BioGas
LDV	Light Duty Vehicle (on roads)
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
LNT	Lean NOx Trap
LPG	Liquefied Petroleum Gas
LTC	Low Temperature Combustion
LULUCF	Land Use, Land-Use Change and Forestry
MD95	95% Methanol 5% Cetane Improver
MGO	Marine Gas Oil
MTBE	Methyl Tert-Butyl Ether
MS	Member State
NDC	Nationally Determined Contributions
NEDC	New European Drive Cycle
NG	Natural Gas
NOx	Nitrogen oxides
NRMM	Non Road Mobile Machinery
NVPM	Non Volatile Particulate Matter
OEM	Original Equipment Manufacturer

(nv)PM	(non-volatile) Particulate Matter
PN	Particulate number
PHEV	Plug-in Hybrid Electric Vehicle
RDE	Real Driving Emissions
RED	Renewable Energy Directive
REx	Range Extender engine
R & I	Research and Innovation
SECAS	Sulfur Emissions Control Areas
SO_2	Sulfur Dioxide
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SI lean	dedicated spark ignition engine running with excess air
STRIA	Strategic Transport Research and Innovation Agenda
SIP	Synthetic Iso-Paraffinic
SPK	Synthetic Paraffinic Kerosene
TWC	Three-Way Catalyst
TTW	Tank To Wheel
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WTT	Well To Tank
WTW	Well To Wheel

7.2 Technical glossary

Technology and fuels	Description	Why is it is being developed?	Benefits
Ethanol and derivatives			
Ethanol	Alcohol fuel, which can be produced from renewable agricultural feedstocks. Can be blended to very high levels into gasoline for use in internal combustion engine vehicles.	Bioethanol is a way to propel vehicles on a renewable, more environmentally-friendly fuel without resorting to alternative drivetrains and changing driver behaviour	Can have lower WTW GHG emissions as long as sustainably sourced, no changes to driver behaviour, high-octane fuel
ETBE	Ethyl Tert Butyl Ether An ether used as a fuel oxygenate, produced via the chemical reaction of ethanol and isobutylene. Most often used as oxygenate to gasoline.	It is used as a sustainable octane enhancer with minimum distillation curve impact	Sustainable octane enhancer. Little impact on other gasoline properties
ED95	An ethanol-based blend of 95% ethanol and 5% ignition improving additives for adapted diesel engines.	A sustainable propulsion fuel for use in engines using the inherently high efficiency diesel cycle	Lower engine out emissions of PM and NOx comparing to diesel
Methanol and derivatives			
MTBE	Methyl Tert Butyl Ether An ether used as a fuel oxygenate, produced via the chemical reaction of ethanol and isobutylene. Most often used as oxygenate to gasoline.	It is used as a (sustainable) octane enhancer with minimum distillation curve impact. It is currently cheaper than ETBE.	Sustainable or cheaper fossil octane enhancer. Little impact on other gasoline properties
DME	Di-Methyl Ether Produced by hydration of methanol for use in CI engines	DME has a similar cetane number and therefore combustion properties than diesel. It can be derived from a variety of sources, either renewable or fossil, which makes it a versatile and possibly low carbon fuel	Similarity to diesel. No carbon to carbon bonds mean no engine out PM emissions
MD95	Similar to ED95 but with methanol	See ED95, if produced sustainably	see ED95
Other Biofuels			
FAME	Fatty Acid Methyl Ester Type of ester derived from transesterification of fats with methanol. Can be blended to high levels into diesel for use in CI combustion engines	FAME, often referred to as biodiesel, is a way to relatively easily and cheaply increase the renewable content of a diesel fuel	Can have lower WTW GHG emissions as long as sustainably sourced

Technology and fuels	Description	Why is it is being developed?	Benefits
FT	Fischer-Tropsch synthesis Liquid biofuels can be produced from syngas, which can be derived from a variety of biomass feedstocks, using FT synthesis	Biofuels are a relatively easily and cheaply increase the renewable content of a diesel fuel	Can have lower WTW GHG emission as long as sustainably sourced, no changes to driver behaviour, higher quality fuel than conventional diesel
HVO	Hydrotreated Vegetable Oil Hydrotreating is an alternative process to esterification to produce diesel from biomass. HVOs are commonly referred to as renewable diesel.	Biofuels are a relatively easily and cheaply increase the renewable content of a diesel fuel	Lower WTW GHG emissions when sustainably sourced
SPK	Synthetic Paraffinic Kerosene or iso-paraffins There are 5 major fuel routes approved for its use in civil aviation: FT-SPK, HEFA-SPK, HFS-SIP, FT-SPKA/A and ATJ-SPK. There are other seven routes currently under approval process, plus other 15 waiting to enter the process. Sustainability of those pathways depends upon the feedstock and way of production.	In the absence of radical re-designs of aviation powertrains, aviation biofuels are considered the primary way to reduce the carbon footprint of the industry	Reduced GHG emissions
Natural gas, propane and derivatives			
CNG	Compressed Natural Gas Methane rich gas stored at high pressure, used as fuel in internal combustion engines	Favourable fuel duty relative to gasoline & diesel. Lower tailpipe CO2 emissions due to higher H/C ratio.	Can reduce GHG emissions slightly if methane slip can be avoided. No PM emissions. Could be used as interim fuel to biomethane
LNG	Liquefied Natural Gas Methane rich cryogenic fluid used as fuel in internal combustion engines	Can be used in dual-fuel operation with heavy duty diesel engines, such as ships, trains and large trucks.	See CNG. Higher energy density by volume than CNG
LPG	Liquefied Petroleum Gas A mixture of light gaseous hydrocarbons. LPG is stored as a liquid under approx. 5bar pressure predominantly for use in SI engines	Can replace gasoline in internal combustion engines with retro-fit technology	Lower pollutant emissions, relatively small GHG emissions benefits, lower cost to drivers if taxes kept low

Technology and fuels	Description	Why is it is being developed?	Benefits
GTL	Gas To Liquids A process by which natural gas is converted in liquid fuels such as gasoline, diesel or jet fuel. Most commonly done through Fischer-Tropsch (FT) synthesis	GTL liquids can be used as direct replacement for conventional fuels.	Possible way of making use of stranded gas and methane that would otherwise be flared
Electricity			
BEV	Battery Electric Vehicles Vehicles propelled by electric motors using electrical energy stored in on-board batteries	BEVs are an alternative to conventional internal combustion vehicles	No pollutant or CO2 emissions on a Tank-To-Wheels basis, and high efficiency. Low GHG emission and OPEX depend on the electricity source
PHEV	Plug-in Hybrid Electric Vehicles Vehicles with two propulsion systems on-board (electric motor and internal combustion engine) that can work simultaneously or in isolation.	PHEVs are transitional between conventional and electric vehicles or a solution for vehicles with limits to full electrification	Working in electric mode provides the same benefits as EVs, but PHEVs offer flexibility and reduce factors such as range anxiety
Fuel Cells			
Hydrogen Fuel Cell vehicles	Fuel cells produce electric current through a chemical reaction, which propels a vehicle using electric motors. Hydrogen is the most common fuel, stored on board in pressurised tanks. Other FC technology using gasoline, natural gas or alcohol is also being developed, but less common	Second most common alternative powertrain solution to the conventional internal combustion engine, after EVs. They could have a higher range than EVs as well as allow quicker recharge times depending on on-board storage and refuelling infrastructure.	Fuel cell vehicles emit no GHGs and pollutants Tank-to-Wheel. Hydrogen as a fuel can be generated in a variety of ways, which include renewable routes.
Diesel			
CI	Compression Ignition Combustion of fuel by high compression of the air inside a cylinder		High efficiency and cost-effective technology
Dual-Fuel	Co-combustion of diesel with another fuel. A small proportion of Diesel (pilot injection) is required to ignite the second fuel	Allows to use other types of fuel in diesel cycle engines	High diesel like efficiency. Same benefits as offered by the alternative fuel used (e.g. LPG, CNG, LNG)
HPDI	High Pressure Direct Injection A technology developed by Westport specifically for natural gas, which injects both the alternative fuels and the small amount of diesel as pilot fuel directly into the cylinder	The technology maximises the use of alternative fuel while maintaining equal horsepower and torque characteristics	Overall benefits the same as with the use of natural gas

Technology and fuels	Description	Why is it is being developed?	Benefits
HCCI	Homogeneous Charge Compression Ignition A type of internal combustion process in which fuel and air are compressed to the point of auto-ignition	High efficiency at low engine out emission levels	Achieves very low levels of NOx emissions without a catalytic converter
MGO	Marine Gas Oil Oil made from distillate only, roughly equivalent to No. 2 fuel oil	With restrictions put on pollutant emissions for inland maritime, low emission fuels allow to avoid expensive retrofit costs	Much less pollutant emissions than HFO
HFO	Heavy Fuel Oil Pure or nearly pure residual oil, roughly equivalent to No. 6 fuel oil	-	The cheapest fuel for marine applications
Gasoline			
SI	Spark Ignition Internal combustion engine in which combustion process is initiated by a spark plug		
CAI	Controlled Auto Ignition Essentially a HCCI for gasoline, where thermal ignition conditions are achieved at the end of compression	see HCCI	See HCCI
Aftertreatment			
TWC	Three way catalyst An emissions control device through catalysing a redox reaction (oxidation and reduction)	Increasingly stringent pollution limits require manufacturers to research into novel catalytic solutions	Decreased amounts of HC and CO (reduced to carbon dioxide and water)
EGR	Exhaust Gas Recirculation Engine technology that takes some exhaust gas and feeds this back into the engine. This has a dilution effect that lowers the combustion temperature ensuring lower levels of NOx		Decreased amount of NOx pollutant emissions
DOC	Diesel Oxidation Catalyst A device utilising a chemical process to break down pollutants into less harmful components		Decreased amount of HC and CO pollutant emissions
SCR	Selective Catalytic Reduction An advanced active emissions control technology that injects urea into the exhaust of the diesel engine.		Breaks down NOx into less harmful N_2.

Technology and fuels	Description	Why is it is being developed?	Benefits
DPF / GPF	Diesel / Gasoline Particulate Filter. A filter that traps particulate matter. When full it needs regeneration through retarding the combustion to generate enough heat to oxidise the PM.		Decreased amount of PM emissions
LNT	Lean NOx Trap Stores the NOx temporarily when in the correct temperature range, but requires regeneration. This requires the engine to run stoichiometric or rich to allow the NOx to be converted to N2		Breaks down NOx into less harmful N2.

7.3 Impact of alternative fuel deployment and development on tank-to-wheel emissions (adapted from 2016 STRIA to include hydrogen)

In this section, alternative fuel and powertrain combinations are scored on their potential to meet key EC objectives by 2050 using the following scoring criteria.

Criteria	Definition	Low	Medium	High
TTW GHG emissions	Engine efficiency improvement potential to 2030 relative to the incumbent technology (e.g. 40% now to 45% in 2030 is 5% improvement)	Under 5%	5 to 10%	Above 10%
TTW noxious emissions	Contribution to TTW noxious (specifically NOx & PM) emissions reduction potential to 2030 compared to incumbent technology (incl. after treatment) on a vehicle basis	No material change	Less than an order of magnitude improvement	More than an order of magnitude improvement
EU competitive ness	On balance, contribution to a competitive advantage for the EU industry	Low potential	Medium potential	High potential

This is repeated for each transport mode. The tables have been compiled based on expert knowledge, survey responses, and discussions held at a stakeholder workshop on 24 May 2016 (see list of stakeholders consulted in Annex 7.4), and have been revised in the current update to include hydrogen.

7.3.1 LDV

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
FC	Hydrogen	Zero emissions	Zero emissions	FC developments for LDVs are at the centre of industrial strategies in the mobility sector in countries like China, Korea and Japan. EU needs to invest considerably to become competitive in this space.
SI	Alcohols, ethers & esters	Slight efficiency improvements of up to 5% through higher RON. Fuels to include are ethanol, methanol and other alcohol mixtures, but also MTBE and ETBE This could allow further downsizing / speeding / enleanment	High Alcohol blends significantly reduce engine out PM and NOx. Note: the emission of non-regulated aldehyde emission could increase	Optimised engine and fuel technology would increase EU automotive industry competitiveness
CI	Alcohols, ethers & esters	Engine efficiency similar to current CI diesel engines	Significant improvement demonstrated from DME and ED95. FAME less so	Optimised engine and fuel technology would increase EU automotive industry competitiveness
FC	Alcohols, ethers & esters	FC has typically a higher engine efficiency especially at part load (real world) conditions	Very low emissions from FC systems	Optimised engine and fuel technology would increase EU automotive industry competitiveness
CI	Gasoline/naphtha	For use of naphtha rather than diesel	Specifically particulates reduction	
SI	Liquid petroleum gas (LPG) & bioLPG	Improvement from compression ratio increase and direct injection	Three way catalyst already very effective Reduction in PM	LPG in direct injection engines fits well in European engine designs and bioLPG production fits with HVO production

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
CI	Natural gas / bio-methane	Efficiency improvement relative to the CI diesel engine is difficult A dual fuel system using a CI combustion process would need to utilised here	DF systems should significantly reduce PM. Engine out NOx might be reduced by finding a better trade-off with CO2. Aftertreatment systems could be optimised further	European countries have developed very up to date technologies for natural gas vehicles, for which Europe still has a leading role.
SI	Natural gas / bio-methane	Higher efficiency of SI engines through the use of gas is possible in the form of downsizing or enleanment New technologies such as HPDI, high pressure direct injection, downsizing with turbo-charging, etc. can lead to higher energy efficiency, and sharp decrease of CO2 emissions: even to 40% compared to the present gasoline engines is possible in prospect.	Natural gas engines emit low levels of regulated pollutants, even without the complex treatment systems used with other fuels, though there are concerns over levels of fine particles. Very low or absent are also other non-regulated noxious substances, in particular unburned carcinogenic substances such as aromatics.	European countries have developed very up to date technologies for natural gas vehicles, for which Europe still has a leading role.
CI	SPFs	Additional tuning possible Difficult to improve CI engine efficiency	Potentially very beneficial for existing fleet CI engine aftertreatment very effective already	Opportunity for EU to develop new innovative fuel technology
SI	SPFs	depends on final product quality (eg RON)	Depends on final quality (eg aromatics content)	Opportunity for EU to develop new fuel innovative technology

7.3.2 HDV

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
FC	Hydrogen	Zero emissions	Zero emissions	FC developments for HDVs have already brought commercial products from Korea and the US to the market. EU is working on several pilot projects. Accelerating development efforts including R&D is key to remain in the race.
CI	Alcohols, ethers & esters	Engine efficiency similar to current CI diesel engines	Significant improvement demonstrated from DME and ED95. FAME less so	Optimised engine and fuel technology would increase EU automotive industry competitiveness
SI	Liquid petroleum gas (LPG) & bioLPG	Improvement from compression ratio increase and direct injection	Three way catalyst already very effective Reduction in PM	LPG in direct injection engines fits well in European engine designs and bioLPG production fits with HVO production
CI	Natural gas / bio-methane	Efficiency improvement relative to the CI diesel engine is difficult. Lower PM & NOx would allow for improved fuel eff.	DF systems do significantly reduce PM. Engine out NOx might therefore be reduced and aftertreatment systems optimised	European countries have developed very up to date technologies for natural gas vehicles, for which Europe still has a leading role.
SI	Natural gas / bio-methane	New technologies such as HPDI, high pressure direct injection, etc. can lead to higher energy efficiency, and sharp decrease of CO2 emissions, thus increasing the CO2 saving compared to HD diesel engines.	Natural gas engines emit extremely low PM, and low regulated pollutants, even without the complex treatment systems used with other fuels. Very low or absent are also other non-regulated noxious substances, in particular unburned carcinogenic substances such as aromatics. Euro 6 SI & CI engines already have very low TTW noxious emissions	European countries have developed very up to date technologies for natural gas vehicles, for which Europe still has a leading role.
CI	SPFs	Difficult to improve CI engine efficiency	SCR+DPF aftertreatment very effective	Europe leading fuel production technology
Turbine	SPFs	Turbo-engines are not efficient in small scale		patent priority and proprietary technology

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
Other	SPFs	Composite piston-turbo cycle allows for very high pressure ratios	lean operation	patent priority and proprietary technology

7.3.3 Rail

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
FC	Hydrogen	Zero emissions	Zero emissions	EU has taken a lead in Hydrogen Train developments with already a commercial offer in operation and more in development. Japan, China, Canada, Korea are working on competitive offers.
CI	Biodiesel	For B20, engine efficiency similar to current fuel. For higher ratio, the performances of existing locomotive diesel engine can be affected.	No change	Developing new engine able to run with more than 20% biodiesel could increase EU competitiveness
SI	LNG	Energy efficiency is in the same range as the diesel engine.	NOx and PM emissions are by 70% lower.	Developing new locomotive offers alternative decarbonisation pathway for the transport sector.

7.3.4 Waterborne transport

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
FC	Hydrogen	Zero emissions	Zero emissions	EU is well placed in the race for waterborne hydrogen based transport with many projects being developed. There is competition starting to come from Japan, Korea and the USA.
CI	Biodiesel	Pressurizing the cylinder helps to reduce the emissions (NOx) and optimise the combustion process. Electronic control injection will improve the degree of fuel atomisation.	No Significant change	Optimised engine technology and fuel handling techniques would increase EU competitiveness
CI, DF	Methanol	Methanol has high octane number - very efficient engine performance. Tests run by different engine designers indicated that the fuel efficiency is the same or better when running on methanol. Advanced injection systems potentially provide further improvements in terms of efficiency	Global reduction of noxious emissions proved by Motorways of the Seas project. NOx emissions during combustion are reduced by approximately 60 % when running on methanol compared to HFO. Significant reduction in SOx Advanced injection systems potentially provide further improvements in terms of pollutant emissions	World's first methanol powered ferry was launched through an EU project.
SI	Natural gas / bio-methane	SI lean burn gas engine has high energy efficiency only at high loads. For the entire load range, energy efficiency can be in the same range as the diesel engine, but the emissions (NOx) are kept low. It Is sensitive to gas quality and not suitable for retrofit existing engine.	Using LNG gaseous emissions meet IMO Tier III. SOx emission is eliminated. PM is close to zero. NOx is reduced by 80-90% due to low flame temperatures during lean burning. SI marine engines emit ultrafine PM.	European manufacturers are world leaders in developing robust engines for LNG-fuelled ships. Bio-methane can be produce locally, offering the perspective of reducing EU energetic dependency.

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
CI, DF	Natural gas / bio-methane	DF has diffusion burning which ensure better capability of burning gases. MAN states that its dual-fuel LNG engine achieves 50 % peak thermal efficiency, compared to diesel engines, with lower fuel consumption. Conversion of existing engines with rebuilding work. Sensitive to gas quality. Advanced injection systems potentially provide further improvements in terms of efficiency	DF systems have very good influence on PM reduction. Aftertreatment (EGR, SCR) of exhaust gases is needed to comply with IMO Tier III-NOx emission limits. Advanced injection systems potentially provide further improvements in terms of pollutant emissions	European manufacturers are world leaders in developing robust engines for LNG-fuelled ships. Bio-methane can be produce locally, offering the perspective of reducing EU energetic dependency.

7.3.5 Aviation

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
FC	Hydrogen	Zero emissions	Zero emissions	EU has developed a first small hydrogen-based pilot plane and has an array of key companies working on hydrogen for aviation. It is too early to tell, but as aviation industry is key to Europe and a sector of leadership, so further efforts are key.
Turbofan	SPK (FT,HEFA)	SPK is less energy dense than conventional jet, but it has higher specific energy Small gain.	Lower nvPM as much as related with a relatively lower aromatics and S content. Lower SOx emissions as synthetic kerosene does not contain sulphur	As there are CO2 global reduction targets for aviation, having available and affordable ways for aviation will be key for sector competitiveness
Turbofan	SIP	Higher energy content per volume, lower per weight. Small gain.	Lower nvPM as much as related with a relatively lower aromatics and S content	As there are CO2 global reduction targets for aviation, having available and affordable ways for aviation will be key for sector competitiveness

Powertrain technology	Fuel	TTW GHG emissions (as a result of engine efficiency)	TTW noxious emissions	EU competitiveness
Turbofan	ATJ	Higher energy content per volume, lower per weight. Small gain.	Lower nvPM as much as related with a relatively lower aromatics and S content	As there are CO2 global reduction targets for aviation, having available and affordable ways for aviation will be key for sector competitiveness
Turbofan	HEFA+	Higher energy content per volume, lower per weight. Small gain.	Lower nvPM as much as related with a relatively lower aromatics content.	No significant technology change, but decarbonisation is a key for competitiveness in aviation.
Turbine	LNG		Lower PM and NOx	

7.4 Stakeholders consulted during 2016 STRIA

- ACI
- Airbus
- Bauhaus
- Becker Marine Systems
- Biochemtex
- British Airways
- CLEPA
- CONCAWE
- Daimler
- DNV/GL
- ENI
- ERTRAC
- FIAT
- Honeywell
- ICCT
- IDIADA
- Italian Ministry of Transport (CPT/IMO)
- JRC
- Lufthansa
- MIT
- Renault
- Repsol
- Rolls-Royce
- SAFRAN
- Scania
- SENASA (Services and Studies for air navigation and aeronautical safety)
- T&E
- Toyota Europe
- UIC
- Volkswagen