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Research and innovation in low-emission alternative energy for transport in Europe

An assessment based on the Transport Research and Innovation Monitoring and Information System (TRIMIS)

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Contents

Abstract

The Strategic Transport Research and Innovation Agenda (STRIA) roadmap on low-emission alternative energy for transport was updated in 2020. This report provides a comprehensive analysis of research and innovation in low-emission alternative energy for transport in selected European Union (EU) funded ongoing projects with end dates from 2019 onwards. It considers the latest developments in the field and includes hydrogen, which is covered in the scope of the updated roadmap on low-emission alternative energy for transport. It identifies relevant researched technologies by fuel type and their phase of development. Results show that *Liquefied Natural Gas* (*LNG) refuelling stations* followed by *biofuels for road transport* and *alternative aviation fuels* are among the researched technologies with the highest investments. Moreover, hydrogen receives the largest share, with 67 projects and the total project value exceeding €1.2 bn. Methane based fuels (e.g. Compressed Natural Gas (CNG), LNG) receive the second greatest attention concerning the number of projects (60) and the level of funding (€944 m), whilst there are only seven research projects still ongoing relating to Liquefied Petroleum Gas (LPG). Alcohols, esters and ethers (31 projects and €241 m) and Synthetic Paraffinic and Aromatic fuels (SPF) (35 projects and €305 m) are in between. So far, road transport has the highest use of alternative fuels in the transport sector. Despite the financial support from the EU, advances have yet to materialise, suggesting that EU transport decarbonisation policies should not consider a radical or sudden change, and therefore, transition periods are critical. It is also noteworthy that there is no silver bullet solution to decarbonisation and the proper use of the various alternative fuels available will be crucial.

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Executive summary

The Transport Research and Innovation Monitoring and Information System (TRIMIS) is the analytical support tool for the establishment and implementation of the Strategic Transport Research and Innovation Agenda (STRIA), and is the European Commission's (EC) instrument for mapping transport technology trends and research and innovation capacities.

Seven STRIA roadmaps have been developed covering various thematic areas, namely:

- Connected and automated transport (CAT);
- Transport electrification (ELT);
- Vehicle design and manufacturing (VDM);
- Low-emission alternative energy for transport (ALT);
- Network and traffic management systems (NTM);
- Smart mobility and services (SMO); and
- Transport infrastructure (INF).

Policy context

The EC adopted STRIA in May 2017, as part of the 'Europe on the Move' package, which highlights main transport research and innovation (R&I) areas and priorities for clean, connected and competitive mobility to complement the 2015 Strategic Energy Technology Plan. The European Green Deal also highlights the European Union's (EU) commitment to accelerate the shift to sustainable and smart mobility, achieving climate neutrality by 2050. As part of the goals of the Green Deal, the EU should in parallel ramp-up the production and deployment of sustainable alternative transport fuels.

The 2030 Climate target plan establishes a greenhouse gases (GHG) emissions reduction by 2030 to at least 55% compared to 1990, including emissions and removals. It acknowledges that all transport sectors - road, rail, aviation and waterborne transport - will have to contribute to the 55% reduction effort. A smart combination of vehicle/vessels/aircraft efficiency improvements, fuel mix changes, greater use of sustainable transport modes and multi-modal solutions, digitalisation for smart traffic and mobility management, road pricing and other incentives can reduce GHG emissions. At the same time, it should help to significantly reduce noise pollution and improve air quality.

More recently, in December 2020, the EU published the Sustainable and Smart Mobility Strategy (European Commission, 2020a). It notes that a comprehensive policy is required to stimulate demand for zero-emission vehicles. Additionally, the 'Clean Hydrogen' partnership could contribute to the development of the relevant technologies. It also acknowledges the potential for hydrogen to support the decarbonisation of heavy duty transport and to contribute to the production of alternative fuels for aviation.

Key conclusions

The findings support one important policy consideration for the future. New technologies and changes in the alternative fuels market need some time to materialise. Thus, policies should not consider a radical or sudden change, and therefore, transition periods are critical. It is also noteworthy that there is no silver bullet solution to decarbonisation, and the proper use of the various alternative fuels available will be crucial. Generally speaking, those fuels with the highest economic potential are already on the market (e.g. Methane based fuels and LPG), but they have a limited overall environmental advantage over conventional fuels (petrol and diesel). On the other hand, fuels with a higher potential to decarbonisation are still not commercially viable, and there is not enough infrastructure for their deployment across Europe (e.g. Hydrogen and SPF). Alternative fuel policies should take into account the current state of the art of low-emission alternative energy for transport. They should evaluate all potential impacts to set realistic targets that ensure the decarbonisation of the transport sector at the highest possible speed to achieve the updated climate target goals.

Main findings

This report presents a comprehensive analysis of R&I in low-emission alternative energy for transport in Europe. Following the previous report on research and innovation in low-emission alternative energy for transport (Ortega Hortelano et al., 2019), the present report focuses on selected EU funded projects from TRIMIS with end dates from 2019 onwards. The report highlights the most relevant researched technologies and their development phase, as well as the policy context and the market activities in Europe. The key conclusions are:

— Under the 7th Framework Programme for Research (FP7) and the Horizon 2020 Framework Programme for Research and Innovation (H2020) about €2.3 bn has been invested in ALT research projects. Road transport has received more funding than any other transport mode.

— In terms of level of investment, the top technology is *LNG refuelling station*, researched in 25 projects. It is in a high maturity phase and it is directly linked to road transport. The second top technology is *biofuels for road transport*, researched in 31 projects. It is characterised by a lower maturity which means that some time is needed for this technology to be deployed in the market. Finally, the third technology is *alternative aviation fuels* researched in 10 projects. The technology is in lower development phases, between Research and Demonstration/Prototyping/Pilot Production.

— Research on methane based fuels (e.g. CNG, LNG) receives a significant economic support (€944 m) through multiple funded (60) projects. Several projects have demonstrated that methane-based fuels have significant economic potential. However, to gain the full benefits of using CNG as a fuel, from the extraction to the powering of vehicles, research will need to be conducted into carbon-neutral natural gas (or methane) production methods.

— LPG technologies are fully developed and as such, they are market driven. In fact, there are only seven research projects still ongoing. The majority of reviewed projects covered a range of alternative fuel types and were not LPG specific. Current research focuses on using LPG in fuel cells for the purpose of auxiliary power. Moreover, some ongoing projects are looking into alternative methods of propane production using renewable sources of CO_2 and electricity.

— Alcohols, esters and ethers come in third place in terms of number of projects (31 projects) and funding received (€241 m). They can reduce carbon emissions and can be blended with fossil fuels (up to certain limits) for use in conventional engines with little modification required. Many of the reviewed projects have been researching production methods of second-generation biofuels (or advanced biofuels) which are manufactured from non-food related biomass. Only one project researched third-generation biofuels' production, which means electrofuels might be scaled up faster than third-generation biofuels.

— Research on SPF also benefit from European funding with €305 m through 35 projects. As it is a relatively new area of research, most of the research focus on novel production processes and evaluation of the commercial viability of these fuels. Moreover, many projects investigate the potential use of waste as feedstock. SPF are mostly investigated in the context of the aviation sector, with some research conducted within the heavy-duty road vehicle market. Research into SPF is still in its early stages, so most of the projects investigate technologies at low technology readiness levels (TRL 1-5).

— Research on hydrogen receives the largest share of total funding exceeding €1.2 bn invested in 67 R&I projects. Hydrogen road vehicle technology is now in the mature stages of development (TRL 6-9) and much of the work focuses on testing the vehicles in real environments. Hydrogen is seen as a good option to decarbonise hard-to-abate sectors, such as road freight transport. The infrastructure for fast and efficient refuelling is necessary for the widespread use of hydrogen vehicles within the European transport system. As a result, the deployment of refuelling stations has been a key area of research.

Related and future JRC work

One of the main tasks of TRIMIS is to assess the development and implementation of new technologies in Europe for each roadmap. This report provides such an assessment for the updated STRIA ALT roadmap (published in 2020). In order to do so, TRIMIS has used data on recent European R&I framework programmes and added hydrogen to the alternative fuels previously studied. It should be noted that transport electrification falls under another roadmap and it is therefore excluded from this report. Two TRIMIS assessments are linked to this report: the research and innovation in low emission alternative energy for transport (Ortega Hortelano et al., 2019), and the research and innovation in road vehicle emissions control (Ortega Hortelano et al., 2020).

Quick guide

This report is divided into eight sections. After this brief introduction, Section 2 outlines the methodological approach applied in the report. Section 3 briefly analyses the content of the updated ALT roadmap. Section 4 reviews the latest updates on the ALT market context. Section 5 sets the policy context for ALT. Section 6 provides an analysis of the Horizon 2020 Framework Programme for research and innovation (H2020) and the 7th Framework Programme for research (FP7) funding calls and how these are distributed across countries, organisations and transport modes. It also identifies key technologies researched in recent framework programmes, as well as the level of their maturity. Section 7 presents an R&I assessment of the most relevant European projects. Finally, Section 8 outlines conclusions and policy considerations for the future.

1 Introduction

In May 2017, the EC adopted the STRIA as part of the 'Europe on the Move' package (European Commission, 2017a; 2017b), which highlights main transport R&I areas and priorities for clean, connected and competitive mobility to complement the 2015 Strategic Energy Technology Plan (European Commission, 2015). The European Green Deal also highlights the EU's commitment to accelerate the shift to sustainable and smart mobility, achieving climate neutrality by 2050 (European Commission, 2019a). As part of the goals of the Green Deal, the EU should in parallel ramp-up the production and deployment of sustainable alternative transport fuels.

The STRIA roadmaps set out common priorities to support and speed up the research, innovation and deployment process leading to radical technology changes in transport. Seven STRIA roadmaps have been developed covering various thematic areas, namely:

- Connected and automated transport (CAT);
- Transport electrification (ELT);
- Vehicle design and manufacturing (VDM);
- Low-emission alternative energy for transport (ALT);
- Network and traffic management systems (NTM);
- Smart mobility and services (SMO); and
- Transport infrastructure (INF).

The STRIA roadmap for low-emission alternative energy for transport([1]) focuses on renewable fuels production, alternative fuel infrastructures as well as the impact on transport systems and services of these technologies for road, rail, waterborne transport and aviation. Electricity is covered in the Transport electrification (ELT) roadmap. The following alternative fuels fall under this roadmap:

- Methane-based fuels (e.g. Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), Biomethane and E–gas). All transport modes can use it, with the exception of aviation.
- Propane and butane based fuels (e.g. Liquefied Petroleum Gas (LPG) and BioLPG), used only in road transport.
- Alcohols, Ethers and Esters (e.g. Ethanol, Butanol, Methanol, Ethanol-based blend of 95 % (ED95)). All transport modes can use it, with the exception of aviation.
- Synthetic paraffinic and aromatic fuel (SPF) (e.g. Hydrotreated Vegetable Oil (HVO) and Gas to Liquid (GTL)). All transport modes can use it, including aviation.
- Hydrogen (e.g. CH_2, LH_2, NH_3). All transport modes can use it. Unlike the former ALT roadmap, the updated ALT roadmap also covers hydrogen.

([1]) https://trimis.ec.europa.eu/sites/default/files/roadmaps/alternative_fuels_stria_april2020_final_version_disclaimer_newcover.pdf (accessed on 29 April 2021)

2 Methodological approach

The main goal of the study is to review EU ALT research projects funded by recent EC research FPs. In order to do so, a methodological approach consisting of two steps was developed, namely:

— The development of a methodology for the project assessment;

— The development of a methodology for the identification and assessment of the technologies researched within FPs.

This chapter is structured as follows. Section 2.1 provides a brief description of the TRIMIS database, Sections 2.2 and 2.3 give a brief description of these steps. Concluding, Section 2.4 sets the scope of the report.

2.1 Database development and labelling

TRIMIS hosts an extensive database of EU and Member State (MS) programmes and projects (currently around 9 000) on transport R&I, which is continuously updated. Projects funded by European FPs are retrieved through an automated data interchange, while projects funded by MS are inserted manually by national contact points. This study focuses on EU-funded projects in the last two FPs, FP7 and H2020. While recent MS projects provide indications on the state of R&I, the use of MS projects would be less reliable since, unlike the European projects, the MS project list is not necessarily comprehensive.

A key step is to identify those projects that fall under the ALT roadmap, following the methodology developed in TRIMIS (van Balen et al., 2019). Many projects cover ALT, therefore only projects that mention a considerable amount of ALT research in the project description have been considered to fall under the ALT roadmap. The projects have been assessed against several other variables, including transport modes and geo-spatial scopes.

2.2 Project assessment

Using the data in TRIMIS, recent programmes that have funded research in vehicle design and manufacturing topics have been identified. All related projects within the last two framework programmes (FP7 and H2020) and other programmes have been included.

Additionally, projects were allocated to the same sub-themes of the roadmap. Table 1 reports the sub-themes identified (left column), and the focus of each sub-theme (right column). By adopting a clustering, it is possible to assess R&I findings focusing on specific areas of interest, give ideas on which areas have been left out until now, and compare developments. A complete table of all projects considered in this report is included in Annex 1.

Table 1. Low-emission alternative energy for transport sub-themes

Sub-theme	Sub-theme focus
Methane-based fuels	This section covers the use of all methane-based fuels, principally compressed natural gas (CNG) and liquefied natural gas (LNG).
LPG	Research projects relating to both liquefied petroleum gas (LPG) and bio-liquefied petroleum gas (bioLPG) for use as an alternative transport fuel.
Alcohols, ethers and esters	This sub-theme covers a broad range of fuels and projects; which tend to have a focus on feedstock cultivation or production of the biofuel.
Synthetic Paraffinic Fuels	This sub-theme covers the research projects addressing synthetic paraffinic alternative fuels (SPF) for use in transport.
Hydrogen	This sub-theme covers the research projects addressing hydrogen and ammonia fuels for use in transport

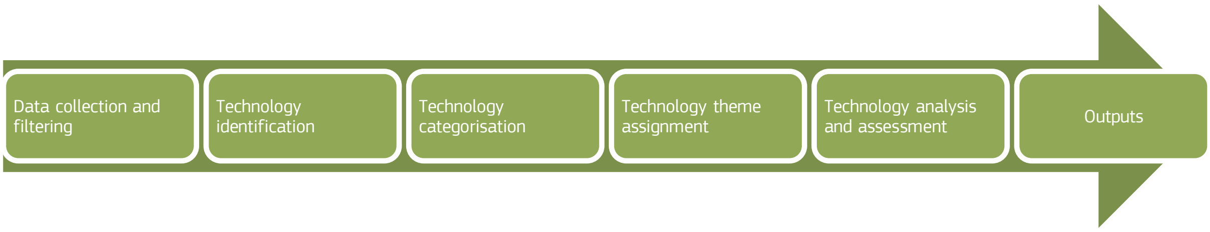
Source: Own elaboration.

2.3 Identification and assessment of the technologies researched within FPs

One of the sub-tasks of TRIMIS is the creation of an inventory and regular reporting on new and emerging technologies and trends (NETT) in the transport sector (Gkoumas et al. 2018, Gkoumas et al. 2020). In doing so, a taxonomy, assessment and monitoring framework is proposed (Gkoumas and Tsakalidis, 2019) which supports innovation management at various levels, thus providing insights to the sector's stakeholders (i.e., researchers, business operators, national authorities and policymakers) while backing the current transport systems' transformation through technological advances.

The TRIMIS technology analysis currently focuses on technologies researched in European FPs, specifically FP7 and H2020 projects from the TRIMIS database. Figure 1 provides an overview of the methodological steps undertaken.

Figure 1. Technology assessment methodological steps



Source: Gkoumas et al. 2018.

3 381 projects fall within the scope. Within these projects, 867 technologies were identified within 45 technology themes through a Grounded Theory approach (Glaser and Strauss, 1967). An iterative approach led to the development of a consistent taxonomy for transport technologies and technology themes.

First, the results of a study that identified technologies within European transport research projects (INTEND, 2017) were analysed by three researchers who have complementary experience in the field of transport innovation and who have individually assessed the technology list. Based on this review, the researchers came up with a standardised approach on what constituted a distinct technology and how to label them (Gkoumas et al. 2018).

All projects descriptions were read and flagged when a technology was mentioned. This filtering exercise was required because EU-funded projects also cover non-technology focused projects like, for instance, those that encourage collaboration between different infrastructure managers. Once a technology was flagged in the project description, another researcher would validate the flagging and write down the technology name.

In a next step, the full list of technologies was evaluated, and the labelling of similar technologies was aligned. The labels were inspired by existing taxonomies, such as those under the Cooperative Patent Classification (CPC, 2019).

When the technology list was established, a number of overarching technology themes was defined. Themes enable a better understanding of how technologies cluster together and which fields of research receive relatively greater interest. An extensive list of themes was created and subsequently reduced to the minimum number of themes under which all technologies could still be logically placed. This process led to a total of 45 themes.

In a final step, all projects were assessed on whether they focused on ALT. If so, the associated technologies and their themes were highlighted. The funds associated with each technology were determined by linking them with the total project budget. If multiple technologies were researched in the project, the budget allocated to the technology of interest was determined by dividing the project budget by the number of associated technologies. The limitations of this attribution approach are acknowledged, but is considered to be transparent and appropriate in the absence of technology-budget reports.

In a consequent step, a set of metrics was established to assess the identified technologies. These metrics indicate the potential for the technology to be further developed.

In the most recent TRIMIS database of January 2021, 124 technologies are linked to the ALT roadmap. From these, ALT is assigned as the primary roadmap to 25 technologies.

Finally, the technology maturity was assessed for all technologies within the four development phases used in TRIMIS. These development phases were built on a similar concept to that of the Technology Readiness Level

(TRL) introduced by the National Aeronautics and Space Administration (NASA) (Héder, 2017). However, the number of readiness levels (or development phases) was reduced from nine to four. This reduction reflects the uncertainty with the allocation of a TRL, due to the limited information available for the status of the technologies researched by a project. The four TRIMIS development phases, and their relationship to the NASA TRL scale, are shown in Table 2.

Table 2: Technology readiness levels (TRLs) and TRIMIS development phase allocation.

TRL	Description	TRIMIS development phase
1	Basic principles observed	Research
2	Technology concept formulated	
3	Experimental proof of concept	Validation
4	Technology validated in lab	
5	Technology validated in relevant environment	Demonstration/prototyping/pilot production
6	Technology demonstrated in relevant environment	
7	System prototype demonstration in operational environment	
8	System complete and qualified	Implementation
9	Actual system proven in operational environment	

Source: TRIMIS, TRL scale based on European Commission, 2014.

2.4 Research scope

Each chapter of this report addresses ALT R&I from different perspectives to give a comprehensive review. Table 3 highlights the approaches used in various parts of the report to facilitate understanding and interpreting the results.

Table 3. Research scope of each chapter and section

Chapter (section)	Type of analysis	Scope
Chapter 3: ALT roadmap	In depth analysis	In depth analysis of the ALT roadmap
Chapter 4: State of ALT	Literature review	Review of trends and business initiatives
Chapter 5: Policy context	Literature review	Review of policy initiatives, focusing on the EU
Chapter 6, sections 1 and 2: Quantitative project analysis	Statistical analysis	Covers FP7 and H2020 projects that commenced between 2007 and 2020
Chapter 6, section 3: Technology analysis	Statistical analysis	Covers FP7 and H2020 projects that developed a technology between 2007 and 2020
Chapter 7: Qualitative analysis	Project reviews	In-depth analysis of H2020 and Connecting Europe Facility (CEF) with end dates from 2019 onwards

Source: Own elaboration.

3 Low-emission alternative energy for transport roadmap

In order to gain a better understanding of the aims and scope of the updated STRIA ALT roadmap(2) (Bauen, A. et al., 2020), this section analyses the challenges, objectives and actions of the roadmap. It should be noted that unlike the previous version of the ALT roadmap(3) (Bauen, A. et al., 2016), the updated roadmap also covers hydrogen.

Electric batteries are now seen as a viable option for many road vehicles. However, aviation, waterborne transport and certain heavy-duty road vehicles are likely to rely on combustion engines and liquid fuels for the majority of applications in the foreseeable future.

In order to decarbonise the transport sector, it is therefore essential in the short- and medium term to increase the use of renewable energy sources and improve the overall energy efficiency of the transport system. This will have the benefit of not only reducing greenhouse gases but also pollutants that are responsible for poor urban air quality.

Nevertheless, increasing the share of low-emission alternative energy in the transport sector poses a number of technical and environmental challenges. The challenges related to hydrogen, can be divided according to the transport mode as follows:

- Road transport. The main challenge remains the price of the vehicles, which thanks to economies of scale should become more affordable after an increase in volumes produced. The ”chicken and egg” problem associated with the deployment of refuelling infrastructure remains. Lack of an appropriate refuelling infrastructure for example remains a barrier to EU wide uptake of hydrogen based Heavy Duty Vehicles (HDVs). In order to facilitate their commercialisation, a number of other issues, such as the standardisation of components and development of protocols allowing faster refuelling operations will need to be developed.
- Rail transport. Challenges remain in reducing costs of hydrogen trains, including through volume production. 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.
- Waterborne. Hydrogen technology is still not widespread and requires further development for costs to decrease. Large waterborne vessels have high propulsion power requirements that will require large fuel cells that have only been demonstrated in stationary applications so far. Whilst to date, the scale of demonstrations remains significantly below that required to be the principle power source within a commercial ship, several design projects are ongoing to test the applicability of integrating FCs within larger vessels. However, due to the magnitude of energy storage and power required in these use cases, the implications for ship design, integration, fuel storage and regulation, no consensus on the optimal strategy for fuel and propulsion has been reached. A lot of work needs to be done to develop the adequate standards and international rules surrounding hydrogen / ammonia use.
- Aviation. Liquid fuels are the only choice in the short and medium term for long distance air transport, so hydrogen-based solutions will remain limited. High power FC (1.5 MW) are yet to be developed in order to address the propulsion of Small, Regional and Short-Medium Range (SMR) commercial aircrafts, as well as key technologies such as liquid hydrogen tanks and fuel systems. Low NOx emitting hydrogen combustion turbines are also needed for larger aircrafts. Development and certification of new hydrogen-based systems on board aircraft will be needed.

The main challenges of all alternative fuels identified within this roadmap can be classified in the following topics:

- Methane leakage
- Fuel storage, handling and injection systems
- Production process scale, cost effectiveness and lack of infrastructure
- Better understanding of blend limits

(2) https://trimis.ec.europa.eu/sites/default/files/roadmaps/alternative_fuels_stria_april2020_final_version_disclaimer_newcover.pdf (accessed on 29 April 2021)

(3) https://trimis.ec.europa.eu/sites/default/files/stria_roadmap_-_low-emission_alternative_energy_for_transport.pdf (accessed on 29 April 2021)

— Others (e.g. regulation)

The development of a new generation of powertrains will require research and innovation efforts to focus on a step change in technology. One that allows greater and more efficient use of alternative energies to reduce greenhouse gases. For energy production, research and innovation efforts will need to focus on novel low emission alternative energies based on renewable and sustainable sources. The main actions for each of the fuels of the roadmap are the following:

Alcohols and ethers:

— Optimal levels of alcohols and ethers to maximise Well-to-Wheel (WtW) emissions savings
— Optimise injection, combustion and after treatment
— Downsizing/rightsizing and hybridisation
— Bi-fuel octane on demand engine
— Control aldehyde emissions
— High temperature fuel cells

Methane:

— Direct injection in Spark Ignition (SI) engines
— Lean combustions and controlled autoignition
— After treatment 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

4 State of low-emission alternative energy for transport

This section reviews the latest updates on the market context about ALT. These subsections are specific for the different transport modes and vehicles, and therefore they will be presented separately. It is important to remind that electricity is covered in a separate roadmap.

4.1 Road transport

To date, by far the greatest use of alternative fuels in transport has been in road transport. Other modes (particularly aviation and maritime) have expectations for a significant expansion of their use of alternative fuels, but it has been extremely limited to date.

A 2015 report on the state of the art of alternative fuels for transport in the EU(4) (DG MOVE, 2015) identified that, in 2012, alternatively-fuelled road vehicles represented 3.4% of the European fleet, although that figure may have included electric and hydrogen-fuelled vehicles. The same report also noted that the use of alternative fuels in heavy-duty vehicles and in aviation were negligible. An update to that report in 2020(5) (DG MOVE and JRC, 2020) noted that, in 2017, road transport depended on oil products for 95% of its energy consumption. It further notes that the share of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) is expected to reach about 14% of the vehicle stock by 2030 and 54% by 2050. The report notes that sales of alternatively fuelled cars grew from 2.6% to 3.6% (of total car sales) in the period from 2014 to 2018, and grew further to 3.9% in the first quarter of 2019. However, BEVs and PHEVs made up a large portion of these alternatively fuelled vehicles. Removing their sales shows that natural gas (NG), LPG, E85 and hydrogen fuelled vehicles formed 2% in 2014 and 1.6% in 2018; sales of these non-electric alternatively fuelled vehicles reduced further by 7.2% in the first quarter of 2019 (relative to their sales in the corresponding quarter in 2018).

Data published by the European Automobile Manufacturers Association (ACEA)(6) indicate that only 1.57% of cars first registered in the EU27 in the first quarter of 2020 were alternatively-fuelled vehicles. This figure had reduced slightly from the corresponding quarter in 2019 (1.65%), but still represented growth over the 2018 value of 1.41%. An update of these figures shows two main points(7). First, in the last quarter of 2020 sales of diesel and petrol cars both had significant losses (-23.0% and -33.7% respectively compared to the last quarter of 2019). As a result, their share decreased from 87.1% to 66% of the car market in the last year. Second, new sales of alternatively-fuelled road vehicles represented the remaining 34%. Out of this, vehicles using E85, LPG and NG, represented only 2.4% of the total new sales. In other words, the large majority of alternative-fuelled vehicles growth is attributable to BEVs, PHEVs and Hybrid electric vehicles (HEV).

More recent data published by the European Alternative Fuels Observatory(8) (EAFO), show that, in 2020, the market share of alternatively fuelled new cars rose to 10.5%; however, the majority of these were battery electric (or plug-in hybrid electric) cars and the share of non-electric alternatively fuelled cars was still about 2%. In the same year, alternatively fuelled cars formed 4.4% of the total fleet; in this case, however, the majority were LPG fuelled (3.2%), with an additional 0.5% for CNG fuelled cars. Similar tendencies are seen in the available figures of 2021: LPG represents 1.5% of the new registrations and CNG just 0.5%. Key aspects of the lack of growth of their use for road vehicles were a lack of attractiveness of alternative fuels to consumers and businesses and a lack of clear market signals.

In the case of bioethanol, although E5 fuel (5% bio-ethanol, 95% gasoline) is widely available across the EU, in 2018 E10 fuel (10% bio-ethanol) was only available in Belgium, Finland, France and Germany(9), despite the majority of post-2002 (spark ignition) vehicles being able to run on it without modification. The roll-out of E10 fuel availability across Europe has continued; recent information(10) indicates that it is now available in 13 EU Member States . For flexi-fuel vehicles, a 2015 report identified that E85 fuel (85% bio-ethanol) was available

(4) https://ec.europa.eu/transport/sites/transport/files/themes/urban/studies/doc/2015-07-alter-fuels-transport-syst-in-eu.pdf (accessed on 29 April 2021)
(5) https://ec.europa.eu/transport/themes/urban/studies/state-art-alternative-fuels-transport-systems-european-union-2020-update_en (accessed on 29 April 2021)
(6) https://www.acea.be/press-releases/article/fuel-types-of-new-cars-petrol-52.3-diesel-29.9-electric-6.8-market-share-fi (accessed on 29 April 2021)
(7) https://www.acea.be/press-releases/article/fuel-types-of-new-cars-electric-10.5-hybrid-11.9-petrol-47.5-market-share-f (accessed on 29 April 2021)
(8) https://www.eafo.eu/vehicles-and-fleet/m1 (accessed on 29 April 2021)
(9) https://www.acea.be/publications/article/e10-petrol-fuel-vehicle-compatibility-list (accessed on 29 April 2021)
(10) https://www.epure.org/about-ethanol/fuel-market/fuel-blends/ (accessed on 29 April 2021)

in four Member States (France, Germany, Netherlands and Sweden), although other sources indicate that it is sporadically available in Hungary, Austria, Spain.

Consumption of biogasoline in the EU in 2016 was 2.6 Mtoe (3.3% by energy content of total gasoline consumption) and consumption of biodiesel (fatty acid methyl esters (FAME) and HVO) was 11.1 Mtoe (5.1% by energy content of total diesel consumption), meaning that overall biofuels accounted for 4.6% (by energy content) of gasoline and diesel consumption in transport. A 2019([11]) report by the United States (US) Global Agricultural Information Network (GAIN, 2019) reported that this had risen to 7.1% in 2018 and forecast a further rise to 7.3% in 2019.

In 2019, the Fuels Europe organisation published their statistical report on the industry (FuelsEurope, 2020). This found that the consumption of LPG had risen from 26.4 million tonnes in 2008 to 30.9 million tonnes in 2018, an increase of 17.0% (or approximately 1.4% per annum).

4.2 Waterborne transport and aviation

For international shipping and aviation, the regulations defining the environmental performance (including CO_2 emissions) of new ships and aircraft are set by international bodies (the International Maritime Organisation (IMO) and the International Civil Aviation Organisation (ICAO), respectively), although their implementation is a matter for national or regional regulatory authorities (including the EU).

In 2013, the IMO implemented regulations on the energy efficiency of new ships, based around an Energy Efficiency Design Index (EEDI) and the requirement to achieve a margin to a baseline level, with the minimum margin increasing over time. The ICAO has also adopted a standard for CO_2 emissions from aircraft, based on their fuel consumption in cruise, normalised by a measure of their floor area (and hence their capacity to transport people and/or freight). The regulation for newly-certified aircraft types enters into force in 2020, while a similar regulation for all newly-manufactured aircraft enters into force in 2028. In addition, ICAO also has implemented regulations regarding the noise produced by aircraft and pollutants. The pollutants included are Nitrogen oxides (NO_x), Carbon monoxide (CO), Hydrocarbons (HC) and, following agreement at the Committee on Aviation Environmental Protection (CAEP) CAEP/11 meeting in February 2019, non-volatile particulate matter emitted by the engines. The regulations covering aircraft noise and engine NO_x emissions have been tightened progressively over time through the introduction of updated regulations.

Within Europe, the policy for the future development of the emissions from aircraft is captured in the Advisory Council for Aviation Research and Innovation in Europe (ACARE) Flightpath 2050([12]) (DG RTD and DG MOVE, 2011), which foresees a 75% reduction in CO_2 emissions per passenger-km by 2050, combined with a 90% reduction in NO_x emissions and a 65% reduction in perceived noise, all relative to a 2000 baseline. These goals are expected to be achieved through a combination of aircraft and engine technology development, operational improvements and alternative fuels; therefore, the advancements in alternative fuels themselves are not expected to provide all the improvements envisaged.

To date, a number of airlines([13]),([14]),([15]),([16]) have flown trial flights using blends of up to 50% biofuels (the maximum allowed under current certification regulations), but widespread adoption of biofuels by the aviation industry is not expected before 2030([17]).

4.3 Rail transport

Shift2Rail (Council of the European Union, 2014) is the first joint undertaking initiative in Europe focusing on R&I and market-driven solutions to speed up the implementation of new technologies into rail product solutions. Its main goal is to promote the competitiveness of the European rail industry and to contribute to a greener mobility. It also seeks technologies to facilitate the completion of the Single European Railway Area (SERA). Finally, Shift2Rail intends to double the capacity of the railway system, increase its reliability and quality of

([11]) https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-15-2019.pdf (accessed on 29 April 2021)

([12]) https://www.acare4europe.org/sites/acare4europe.org/files/document/Flightpath2050_Final.pdf (accessed on 29 April 2021)

([13]) https://www.lufthansagroup.com/en/responsibility/climate-environment/fuel-consumption-and-emissions/alternative-fuels.html (accessed on 29 April 2021)

([14]) https://www.businessgreen.com/bg/news/3063810/ready-for-take-off-virgin-completes-commercial-flight-using-waste-based-biofuel (accessed on 29 April 2021)

([15]) https://www.virgin.com/richard-branson/low-carbon-fuel-breakthrough-virgin-atlantic (accessed on 29 April 2021)

([16]) https://www.reuters.com/article/airlines-biofuels-klm/klm-trials-biofuel-powered-flights-between-amsterdam-and-oslo-idUSL5N1734WP (accessed on 29 April 2021)

([17]) https://www.iea.org/newsroom/news/2019/march/are-aviation-biofuels-ready-for-take-off.html (accessed on 29 April 2021) service by 50%, and halve life cycle costs. It is structured following five asset-specific Innovation Programmes (IPs), ensuring all the different structural (technical) and functional (process) subsystems of the rail system are analysed. The five IPs are the following:

- Cost-efficient and reliable trains, including high capacity trains and high speed trains.
- Advanced traffic management and control systems.
- Cost-efficient, sustainable and reliable high capacity infrastructure.
- IT solutions for attractive railway services.
- Technologies for sustainable and attractive European freight.

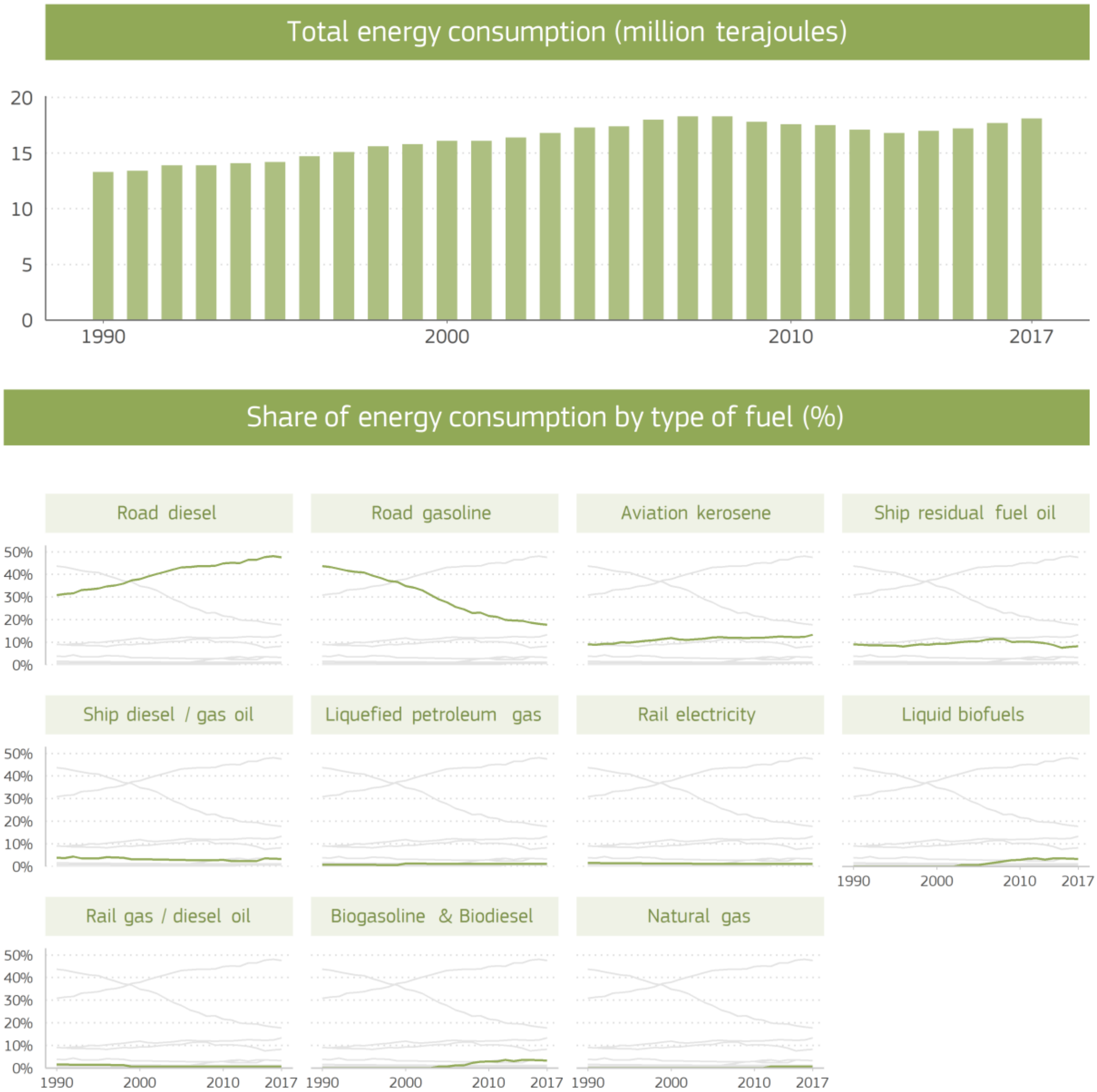
The overall numbers of vehicles has stayed largely constant over time, with some slight indications of a reducing percentage of diesel vehicles (from 47.7% in 2008 to 42.9% in 2017) and a move from locomotives to railcars (the percentage of locomotives reduces from 63.2% in 2008 to 56.0% in 2017([18]).

Although the majority of electric-powered trains use mains electricity via third rail or overhead line systems, there is growing interest in battery-powered trains, in some cases in combination with mains power, to avoid the additional infrastructure costs of providing mains power through particular stretches of the line (through tunnels, for example). Austrian Federal Railways has announced plans to acquire three such overhead line/battery trains, with deployment expected in 2019([19]). There is also some interest in hydrogen fuel-cell powered trains, with orders placed for some for German railways([20]) and being considered for use in the United Kingdom (UK)([21]). In September 2020, it was announced that, after successful testing in Germany between 2018 and 2020, Alstom's hydrogen train will enter regular passenger service in Austria by the end of November 2020([22]). After completing three months of successful test operation on Austrian regional lines, it was approved by the Austrian Federal Railways and are running on the Austrian railways. French National Railway Company has announced that it intends to phase out the use of fossil fuels on its network by 2035, through a mixture of hybrid trains (using biodiesel and electricity), battery electric and hydrogen trains([23]) (Clement, P., 2019). On Thursday 8 April, the SNCF announced the first French order for hydrogen-powered trains from railway manufacturer Alstom for four regions: Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté, Grand Est and Occitanie, Le Monde reports. Partially unveiled on 5 March by the Bourgogne-Franche-Comté region, this order concerns twelve trains (three per region), for a total amount of approximately 190 million euros, according to a joint press release from Alstom, the SNCF and the regions concerned.

Figure 2 presents energy consumption by transport mode and type of fuel. As previously stated, the last few years has seen the slow evolution of renewable transport fuels, with more than 90% of the energy consumption still relying on oil-derived fuels.

([18]) Analysis of Eurostat data, https://ec.europa.eu/eurostat/databrowser/view/rail_eq_locon/default/table?lang=en (accessed on 29 April 2021)
([19]) https://www.railway-technology.com/features/featurepowering-the-trains-of-tomorrow-5723499 (accessed on 29 April 2021)
([20]) https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/worlds-largest-fleet-of-fuel-cell-trains-ordered.html (accessed on 29 April 2021)
([21]) https://www.telegraph.co.uk/cars/news/hydrogen-fuel-cell-trains-run-british-railways-2022 (accessed on 29 April 2021)
([22]) https://www.alstom.com/press-releases-news/2020/9/alstoms-hydrogen-train-enters-regular-passenger-service-austria (accessed on 29 April 2021)
([23]) https://uic.org/events/IMG/pdf/05-sncf_h2_train_ph_clement_diffusion.pdf (accessed on 29 April 2021)

Figure 2. Energy consumption in the transport sector in Europe



Source: European Environment Agency.

5 Policy context

5.1 Alternative fuels in European transport policy

In 2011, the European Commission published its White Paper on Transport (European Commission, 2011), '*Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*'. This laid out the Commission's vision for the future of the European transport system and the policies that would be needed to achieve it.

The first two (of ten) goals presented in the white paper are related to the use of alternative fuels:

- Halve the use of 'conventionally-fuelled' cars in urban transport by 2030; phase them out in cities by 2050; achieve essentially CO_2-free city logistics in major urban centres by 2030;
- Low-carbon sustainable fuels in aviation to reach 40% by 2050; also by 2050 reduce EU CO_2 emissions from maritime bunker fuels by 40% (if feasible 50%).

The roadmap recognised the importance of research in sustainable alternative fuels and also the need to develop the appropriate infrastructure to support the use of such fuels.

In 2019, the new European Commission published the European Green Deal (European Commission, 2019a). This included a commitment to increase the EU's GHG reduction target for 2030 to at least 50%, relative to 1990 levels, and to target zero net emissions by 2050. To achieve this will require a 90% reduction in transport emissions by 2050. This will drive a need to increase the production and deployment of sustainable alternative transport fuels. The report presents an expectation that there will be 13 million zero and low-emission vehicles on Europe's roads by 2025, which will require about 1 million public recharging and refuelling stations. The Commission committed support for the deployment of these public recharging and refuelling stations, where persistent gaps exist. The Commission also indicated an intention to develop new legislation to boost the production and uptake of sustainable alternative fuels for transport.

The 2030 Climate Target Plan (European Commission, 2020b) builds on this by increasing the target to a 55% reduction in greenhouse gas emissions (relative to 1990) by 2030, as a step on a path to climate neutrality by 2050. It acknowledges that all transport sectors will need to contribute to this reduction in emissions and that a smart combination of vehicle/vessels/aircraft efficiency improvements, fuel mix changes, greater use of sustainable transport modes and multi-modal solutions, digitalisation for smart traffic and mobility management, road pricing and other incentives will be needed and that they will also contribute to addressing noise and air quality pollution.

The alternative fuels infrastructure directive (European Parliament and the Council of the European Union, 2014), introduced in 2014, places a requirement on Member States to develop national policy frameworks for the market development of alternative fuels and their infrastructure. In 2019, the Commission started work on evaluating the performance of the directive and assessing options for an update. In the context of the upcoming revision of the alternative fuels infrastructure directive, the Commission will consider options for more binding targets on the roll-out of infrastructure, and further measures to ensure full interoperability of infrastructure and infrastructure use services for all alternatively fuelled vehicles. Adequate information for consumers to end the current lack of transparency on pricing, and facilitating seamless cross-border payments are among the key issues to tackle.

The alternative fuels infrastructure directive is based on the 2009 renewable energy directive (RED) (European Parliament and the Council of the European Union, 2009) which requires the EU to meet a target of 20 % of total energy needs from renewable sources by 2020. In 2019, EU power production from wind and solar power overtook coal for the first time – meaning that they have become as competitive, or even cheaper, than fossil fuels in most places. The directive also required 10% of transport fuels (on an energy basis) to be derived from renewable sources by 2020. Only Finland and Sweden have achieved the 10% share in renewable energy consumption in the transport sector, with Austria and France close to achieving this target. The original RED was succeeded by an updated directive in 2018 (European Parliament and the Council of the European Union, 2018), which extended the overall target to 32% of total energy needs being met by renewable sources by 2030, with a target for transport of 14%. The directive also defines criteria to determine the sustainability of biofuels to ensure they are sustainable and environmentally friendly. In addition, the directive imposes a cap on biofuels produced from crops and includes a specific sub-target to encourage the use of lignocellulosic feedstocks such as pellets, and waste.

In July 2020, the EU published its hydrogen strategy for a climate-neutral Europe (European Commission, 2020c). This recognised that hydrogen will have a key role in decarbonising a large share of the EU energy consumption in achieving the aims of the Green Deal. It presents targets for the future development of renewable hydrogen in the EU, with at least 40GW of renewable hydrogen electrolysers in place by 2030, producing up to 10 million tonnes of renewable hydrogen per annum.

The strategy notes that hydrogen is a promising option for areas of transport where electrification may be difficult. It highlights an early adoption by local city buses and taxis, plus some elements of the rail network, and a longer term potential for fuel cell powered heavy-duty road vehicles. The Fuel Cells and Hydrogen Joint Undertaking (FCH-JU), funded through Horizon 2020, is pushing the European technology capability in this area. Beyond road transport, hydrogen offers a potential application in inland waterways and short-sea shipping and can be a key part of the production of synthetic kerosene for the aviation sector.

More recently, in December 2020, the EU published the Sustainable and Smart Mobility Strategy (European Commission, 2020a). This notes that a comprehensive policy is required to stimulate demand for zero-emission vehicles and that the 'Clean Hydrogen' partnership could contribute to the development of the relevant technologies. It also notes the potential for hydrogen to support the decarbonisation of heavy duty transport and contribute to the production of alternative fuels for aviation. The ReFuelEU Aviation and FuelEU Maritime initiatives will boost the production and uptake of sustainable aviation and maritime fuels. The Communication identifies the requirement to build 1 000 hydrogen stations and 3 million public recharging points by 2030, with the expectation that half and third of them will be built by 2025 respectively.

In aviation, the consumption of fossil fuel, and the consequent emissions of greenhouse gases, has been subject to the requirements of the EU emissions trading system (ETS) since 2012, although the scope was reduced to intra-EEA flights by the 'stop the clock' or postponed deadline derogation, which was introduced in 2013 and remains in place to this day. The regulations for the inclusion of aviation in the EU ETS includes an allowance for biomass to have a zero emissions factor, effectively exempting sustainable biofuels from the requirements to surrender allowances. However, it has been recognised that there are considerable challenges in tracking the sustainability of the biofuel elements of the fuel uplifted to the aircraft (where fuels with a biofuel content are available([24])) and hence defining the levels of exemption that can be claimed by individual operators. The ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which is due to apply from 2021 for all international flights between participating states, will also include an exemption (from the need to purchase offsets for emissions) for sustainable and low-carbon fuels. The EU has not yet determined how the EU ETS will interact with CORSIA (all 27 EU Member States have committed to joining CORSIA from its inception), but it is likely that airlines will need to comply with the requirements for one or the other of the schemes for all flights and, therefore, that there will be additional incentives for airlines to use sustainable fuels in the future.

For maritime transport, the IMO adopted a strategy on reducing GHG emissions from ships in 2018([25]), including the energy efficiency regulations for ships([26]), included in Chapter 4 of Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL). These regulations include provision for rating different fuels by their CO_2 emissions per unit of mass, including lower values for alternative fuels such as LPG, LNG, methanol and ethanol (Table 4).

([24]) The maximum percentage of biofuel in a blend with kerosene is limited by the terms of the ASTM certification for each type of biofuel. The highest blend limit currently allowed is 50%.

([25]) http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx (accessed on 29 April 2021)

([26]) https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx (accessed on 29 April 2021)

Table 4. Fuel carbon factors in IMO ship energy efficiency

Type of fuel	Reference	Carbon content	Cf (t-CO_2/t-Fuel)
Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
Liquefied Natural Gas (LNG)		0.7500	2.750
Methanol		0.3750	1.375
Ethanol		0.5217	1.913

Source: 'Module 2 – Ship Energy Efficiency Regulations and Related Guidelines' ([27]).

The IMO strategy aims at strengthening the EEDI requirements and includes a list on short, medium and long term targets. For the short term (2018-2023), the focus is on broader implementation and possible enhancement of the EEDI and Ship Energy Efficiency Management Plan, while for the medium term (2023-2030) the aim is to include effective uptake of alternative low and zero-carbon fuels and to investigate the effectiveness of market-based measures. For the long run (after 2030) a continuation and broader application of identified measures will be included. In 2020, the IMO Marine Environment Protection Committee (MEPC75) agreed on the introduction of a new package of technical and operational measures covering GHG emissions. (Grosso et al., 2021).

5.2 Alternative fuels in European research programmes

Projects related to the ALT roadmap have been included in EU funding programmes since the FP7 programme. For this present report, the focus has been on projects that have completed since 2019 or are ongoing. Using the data in TRIMIS, the different programmes that have funded research projects in ALT topics that fall into that timeframe have been identified. These programmes, with the number of relevant projects and the funding levels, are shown in Table 5 and Table 6.

([27]) https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx (accessed on 29 April 2021)

Table 5. Numbers and values of ALT projects funded under Horizon 2020

Funding action	Number of projects	Total funding	EU contribution
H2020-EU.1.1. - EXCELLENT SCIENCE - European Research Council (ERC)	1	€1 498 750	€1 498 750
H2020-EU.1.3. - EXCELLENT SCIENCE - Marie Skłodowska-Curie Actions	1	€355 500	€355 500
H2020-EU.2.3. - INDUSTRIAL LEADERSHIP - Innovation In SMEs	1	€71 429	€50 000
H2020-EU.3.3. - SOCIETAL CHALLENGES - Secure clean and efficient energy	28	€324 743 003	€198 367 796
H2020-EU.3.4. - SOCIETAL CHALLENGES - Smart Green and Integrated Transport	46	€701 961 864	€374 329 759
H2020-EU.3.5. - SOCIETAL CHALLENGES - Climate action Environment Resource Efficiency and Raw Materials	4	€13 024 326	€13 024 326

Source: TRIMIS.

Table 6. Numbers (and values) of projects funded through other programmes

Funding action	Number of projects	Total funding	EU contribution
CEF - Connecting Europe Facility	48	€1 123 715 974	€348 429 811
National - Croatia	1	-	-
National - Estonia	3	-	-
National - Finland	2	-	-
National - Netherlands	1	-	-
National - Slovenia	2	-	-

Source: TRIMIS.

The Horizon 2020 programme has funded 81 projects relevant to alternative fuels that either finished in the past two years or are ongoing, with a total budget of €1.042 bn. The greatest contribution has been through the 'Smart, green and integrated transport' action, with significant numbers of projects also funded through the 'Secure, clean and efficient energy' action.

In addition to the current framework programme, Table 6 shows that a significant number of projects has been funded through the CEF programme. Due to the nature of the projects funded under this programme, the average value is higher than under Horizon 2020 (approximately €23 m, compared to €13 m), leading to an overall value of over €1 bn. The analysis for this report has also identified a small number of relevant projects funded by Member States' national programmes, as shown in Table 6.

5.3 Alternative fuels in non-European countries policies

To put European policies on the development and use of alternative fuels in context, it is useful to understand the status of similar efforts in other countries around the world. This section provides a brief review of the policies in countries where the use of biofuels is likely to have the greatest impact; that is, the countries that currently have the highest carbon emissions from transport. Using data presented by the International Energy Agency in the CO_2 emissions from fuel combustion – Highlights 2019 report([28]), the emissions in 2017 for the top 10 non-European countries have been identified. Table 7 presents these emissions.

Table 7. Transport CO_2 emissions for countries with highest levels

Country	Total CO_2 emissions (Mt)	Transport CO_2 emissions (Mt)	Transport CO_2 emissions (% Total)
United States	4 761.3	1 724.0	36.2
People's Rep. of China	9 257.9	880.9	9.5
India	2 161.6	291.4	13.5
Russian Federation	1 536.9	246.1	16.0
Japan	1 132.4	205.1	18.1
Brazil	427.6	203.2	47.5
Canada	547.8	171.5	31.3
Mexico	446.0	151.4	33.9
Indonesia	496.4	141.7	28.5
Islamic Rep. of Iran	567.1	132.0	23.3

Source: Analyses of data from International Energy Agency 'World development Indicators – Highlights 2019' ([29]).

In the USA, California was the first state to pass a low-carbon fuels standard in 2009. The aim of the standard was to reduce the carbon intensity of transport fuels sold in the state by 20% by 2030. The standard operates through a 'cap and trade' system, with the cap reducing steadily over time. Fuels with carbon intensities below the cap generate credits, while those above the cap generate deficits and a requirement to purchase credits. Following the development of the California standard, the US Environmental Protection Agency (EPA) introduced a Renewable Fuel Programme([30]), which aims to promote the use of renewable fuels to replace conventional fuels in transport. The fuels in the Renewable Fuel Programmme include biomass-based diesel, cellulosic biofuel, advanced biofuel and total renewable fuel. The program includes a target of 36 billion (US) gallons of renewable fuel by 2022, an increase from the 33 billion (US) gallons forecasted by 2021. Updates to the programme announced by the EPA in 2019 included a commitment that more than 15 billion gallons of conventional ethanol would be blended into US fuel supplies starting from 2020([31]). The 2020 update also highlighted that the final rule calls for 20.09 billion gallons of total renewable fuel for 2020—an increase of 170 million gallons from the 19.92 billion gallons required in 2019. It is also noteworthy that since 2014, the total renewable fuel statutory target has not been met, particularly for the advanced biofuel portion which falls below the statutory target since 2015.

China is also pursuing an increased promotion of alternative fuels for transport. The China Petroleum & Chemical Corp, the largest oil refiner in China, has indicated that it plans to increase its involvement in biofuels([32]). Since 2016, the company has been producing diesel fuel with a 5 % biofuel content (B5) and has now started selling it commercially alongside its other fuels. The National Development and Reform Commission and the National Energy Administration announced plans in 2017 to promote the use of ethanol blended with gasoline for cars across the country by 2020. They plan to make it available in E10 (10% ethanol) form, with

([28]) https://webstore.iea.org/co2-emissions-from-fuel-combustion-2019 (accessed on 29 April 2021)
([29]) https://webstore.iea.org/co2-emissions-from-fuel-combustion-2019 (accessed on 29 April 2021)
([30]) https://www.epa.gov/renewable-fuel-standard-program (accessed on 29 April 2021)
([31]) https://www.epa.gov/newsreleases/epa-fulfills-another-trump-administration-promise-finalizes-rfs-volumes-2020-and (accessed on 29 April 2021)
([32]) https://www.telegraph.co.uk/china-watch/technology/what-is-biofuel/ (accessed on 29 April 2021)

large scale production of cellulosic ethanol expected to be in place by 2025. However, this mandate was unofficially suspended due to limited ethanol production capacity, a recent drop in corn stocks, and corresponding rising corn prices. Moreover, the COVID-19 pandemic has also significantly lowered fuel consumption and caused some existing ethanol production capacity to shift from fuel production to medical-grade ethanol production([33]). China has also been focusing on the development of low-cost hydrogen production and the promotion of hydrogen fuel cell cars([34]), with targets of 50 000 fuel cell vehicles on the road by 2025 and 1 million by 2030.

Russia has recently indicated that it is considering implementing climate legislation to regulate carbon emissions([35]). However, the legislation will not include specific targets for individual sectors and there has been no indication of any promotion of alternative fuels for transport.

In India, Rajasthan([36]) was the first state to implement a national policy on the use of biofuels that was approved in May 2018([37]). The new policy expanded the scope of feedstocks that could be used for producing biofuels (to include sugar-containing materials like sugar beet, starch-containing crops such as cassava and damaged food grains and potatoes unfit for human consumption). The policy also offers financial support to bio-refineries involved in producing advanced biofuels. The Asian Development Bank has recently approved a €1.9 m technical assistance package to support advanced biofuel development in India([38]).

Brazil has long maintained a policy of promoting the use of bio-ethanol derived from sugar cane as a fuel in cars, in blends of up to 100% (i.e. pure ethanol). The policy was originally instigated to reduce dependence on oil imports, but is now also employed as a contribution to meeting its obligations under the Paris Agreement([39]). The RenovaBio programme is targeted at reducing emissions from gasoline by over 10% by 2028. This will include incentivising fuel distributors to increase the biofuel content of the fuels that they sell. Brazil is the largest soybean market in the world, accounting for around 113 million tonnes([40]). The regulation centres on tradable carbon credits, based on the reductions in emissions represented by the individual biofuels. However, the required certification processes are still to be developed.

In July 2018, Japan published its fifth strategic energy plan([41])(Agency for Natural Resources and Energy, 2018). This noted a continuing heavy reliance on imported oil for transport in the country and recognised the importance of diversifying the fuels used. The plan identified LPG as a fuel for which they had been heavily dependent on a single source (the Middle East), but the increased availability of shale gas from North America had reduced the risk. It also recognised the environmental benefits of LPG (over petroleum fuels) and its importance for the transport sector. Further, the plan recognised the importance of developing biofuels for cars (as they would be expected to continue to use internal combustion engines for some time in the future) and the Government intended to introduce '*preferential measures for the introduction of the domestically-produced next-generation bioethanol*'. They would also consider supporting first-generation bioethanol (based on food) where appropriate and the introduction of biodiesel in the future. They also intended to support the use of biofuels in aviation and the use of LNG and LPG as fuels for international shipping. In addition, in 2016, Japan published a 'Strategic roadmap for hydrogen and fuel cells', which included targets for about 200 000 fuel cell vehicle by 2025 and 800 000 by 2030([42]).

In June 2019, Environment and Climate Change Canada published a proposed regulatory approach for a clean fuel standard([43]) (Environment and Climate Change Canada, 2019). This aims to achieve reductions in annual greenhouse gas emissions of 30 million tonnes by 2030. Under the proposed regulation, the provision of credits for low-carbon fuels will be based on their life-cycle emissions. Transport fuels included in the standard include

([33]) http://www.biodieselmagazine.com/articles/2517189/report-chinaundefineds-biodiesel-production-up-despite-lower-consumption#:~:text=Domestic%20biodiesel%20production%20is%20expected,752%20million%20liters%20in%202019 (accessed on 29 April 2021)

([34]) https://fuelcellsworks.com/news/china-petroleum-and-chemical-corp-to-focus-on-hydrogen-refueling-stations/ (accessed on 29 April 2021)

([35]) https://www.climatechangenews.com/2019/03/22/russia-floats-first-law-regulate-carbon-emissions/ (accessed on 29 April 2021)

([36]) https://www.thehindu.com/todays-paper/tp-national/tp-otherstates/rajasthan-first-state-to-implement-biofuel-policy/article24568039.ece (accessed on 29 April 2021)

([37]) https://www.indiatoday.in/education-today/gk-current-affairs/story/biofuels-rajasthan-national-policy-1302788-2018-08-01 (accessed on 29 April 2021)

([38]) https://biofuels-news.com/news/bank-backs-biofuel-development-in-india/ (accessed on 29 April 2021)

([39]) https://knect365.com/energy/article/e5560843-78a9-4034-81f7-25319afe103c/what-to-expect-from-brazils-renovabio-programme (accessed on 29 April 2021)

([40]) https://biofuels-news.com/news/brazil-expects-bumper-soybean-crop/ (accessed on 29 April 2021)

([41]) https://www.enecho.meti.go.jp/en/category/others/basic_plan/5th/pdf/strategic_energy_plan.pdf (accessed on 29 April 2021)

([42]) https://www.meti.go.jp/english/press/2016/0322_05.html (accessed on 29 April 2021)

([43]) https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/pricing-pollution/Clean-fuel-standard-proposed-regulatory-approach.pdf (accessed on 29 April 2021) natural gas (and renewable natural gas), hydrogen, propane (and renewable propane) and electricity. The Forward Regulatory Plan 2019 to 2021, of the Environment and Climate Change Canada includes several initiatives relating to air emissions and greenhouse gases.

6 Projects and technology assessment

This section provides an overview of ALT projects financed by FP7 and H2020. The first subsection contains basic quantitative data about the number of projects and EU contribution. The second section presents main organisations involved in implementation of ALT projects and distribution of funds between particular countries (27 EU Member States and the UK). The UK was still a member of the European Union in the period covered by the analyses, and therefore the UK results are included in the report. Furthermore, the UK continues to participate in programmes funded under the 2014-2020 Multiannual Financial Framework (MFF) until their closure([44]).

6.1 Framework programmes analysis

During the period coved by the presented analysis, 262 research innovation projects related to alternative low-emission alternative energy for transport (hereinafter ALT projects) have been financed under FP7 and H2020 (Table 8), including 72 (27.48%) which are still ongoing at the time of writing this report. In total, €2.3 bn has been invested, including €1.4 bn (58.15%) of EU funds and almost €1 bn of own contributions of beneficiary organisations.

Table 8. Basic statistics of ALT projects within FP7 and H2020

Status	Number of projects	Total EU contribution (in € million)	Total projects cost (in € million)
Finished	189	844.3	1 401.6
Ongoing	72	492.5	897.3
Total	262	1 336.8	2 298.9

Source: TRIMIS.

Figure 3 shows the share of EU contribution in a total project cost and a number of projects funded within different programmes, splitting all the projects between those funded within H2020 3.4 (Horizon 2020: Smart, Green and Integrated Transport) Programme, other H2020 programmes, FP7 – Transport programme and other FP7 programmes. The size of the dots depicts total EU contribution. Note, that for a clarity of the chart, 33 Small Medium Enterprise (SME) Phase 1 projects (SME-1) were excluded. The figure shows that highest number of ALT projects have been financed within H2020 3.4 Programme. Similarly, the highest amount of EU contribution has been directed to beneficiaries throughout the H2020 3.4 Programme.

([44]) https://www.gov.uk/government/publications/continued-uk-participation-in-eu-programmes/eu-funded-programmes-under-the-withdrawal-agreement (accessed on 29 April 2021)

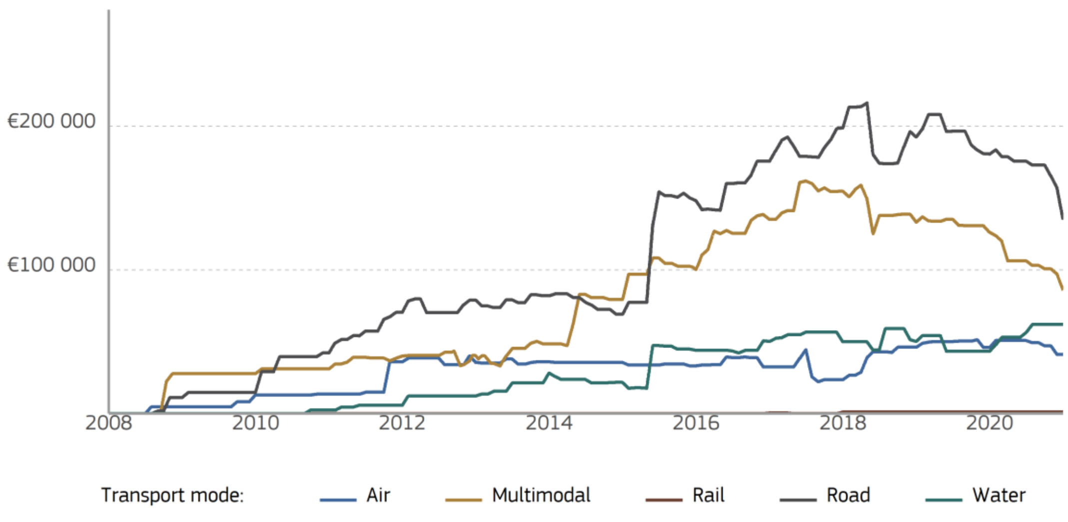
Figure 3. ALT Projects distribution according to Parent Programme, size of EU contribution and its share in total project costs

* without SME-1 projects.

Source: TRIMIS.

Figure 4 shows the average daily total funding of ALT projects spitted across particular transport modes. It assumes that funds are equally distributed through projects duration. It shows that during the almost entire FP7 and H2020 programmes duration, the larger share of funds has been directed to road-related ALT projects, followed by multimodal ones. Waterborne and air-related projects attracted lower amount of EU contribution. There are almost no rail-related ALT projects – only two H2020 projects are listed in the TRIMIS database, including one SME-1.

Figure 4. Average daily R&I funding of ALT projects by transport mode



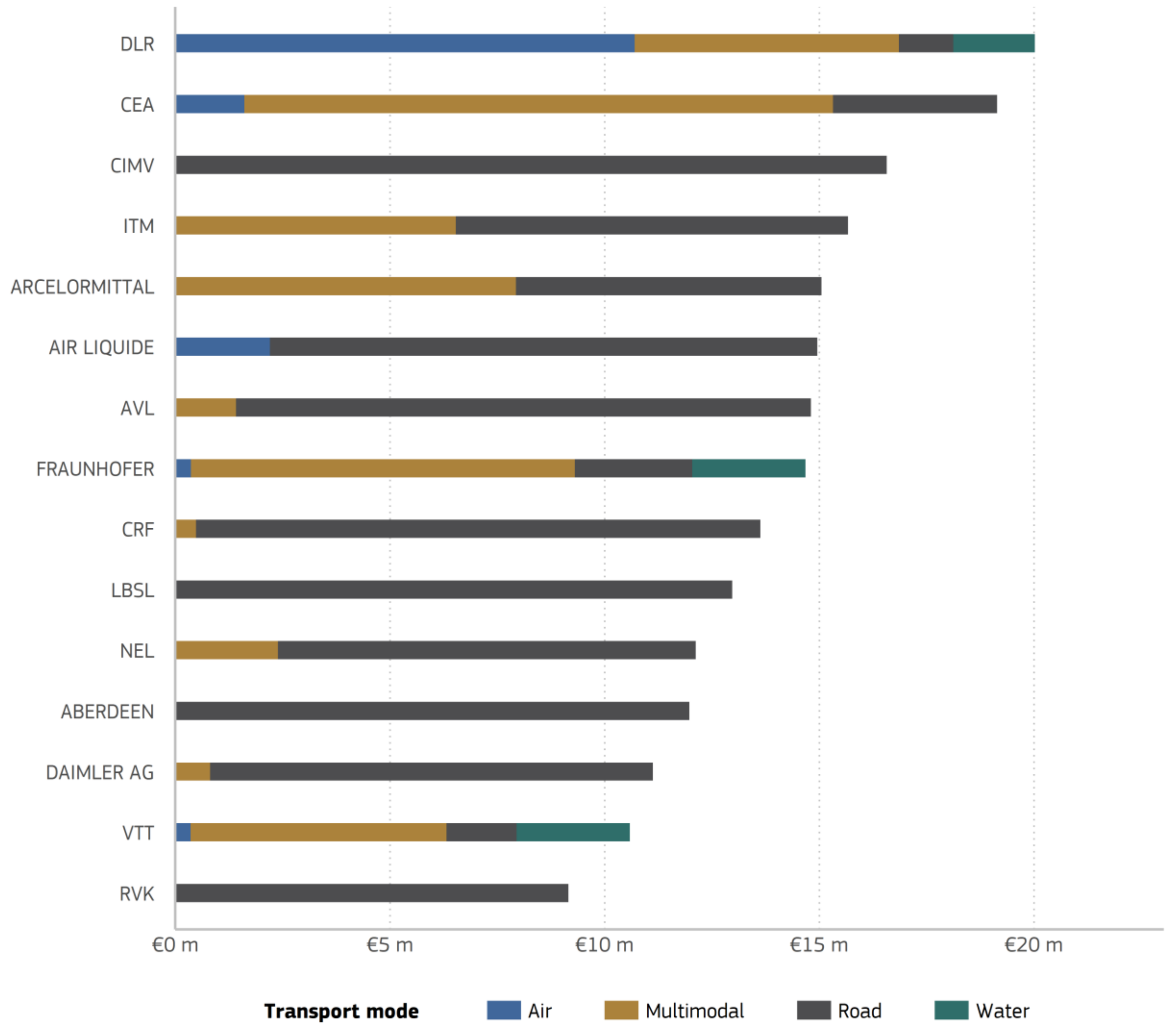
Source: TRIMIS.

The highest average daily funding on road projects exceeded €200 000 in the beginning of the year 2018. The highest total average daily funding of all ALT projects taken together exceeded €455 000 (April 2018). Since then, total funding, as well as funding directed to projects related to all transport modes (except waterborne) has decreased.

6.2 Geographical and organisation analysis

A total of 1 561 unique organisations have been involved in FP7 and/or H2020 ALT projects, including 1 435 located in 27 Member States and the UK. The top 15 beneficiaries are presented in the Figure 5. The beneficiaries specialise in one particular transport mode ALT projects (e.g. the French CIMV, German RVK or Aberdeen City Council (UK) – road), in the mix of road and multimodal ALT projects (e.g. the British ITM POWER Ltd. or the Belgian ARCELORMITTAL) or in the diverse types of projects, except rail ones (e.g. German DLR). The top 15 beneficiaries received approximately €212 m of EU contribution, which is above third part of all EU contribution and approximately 16.6% of total costs of all ALT projects.

Figure 5. Top-15 ALT funding beneficiaries, including division between transport modes

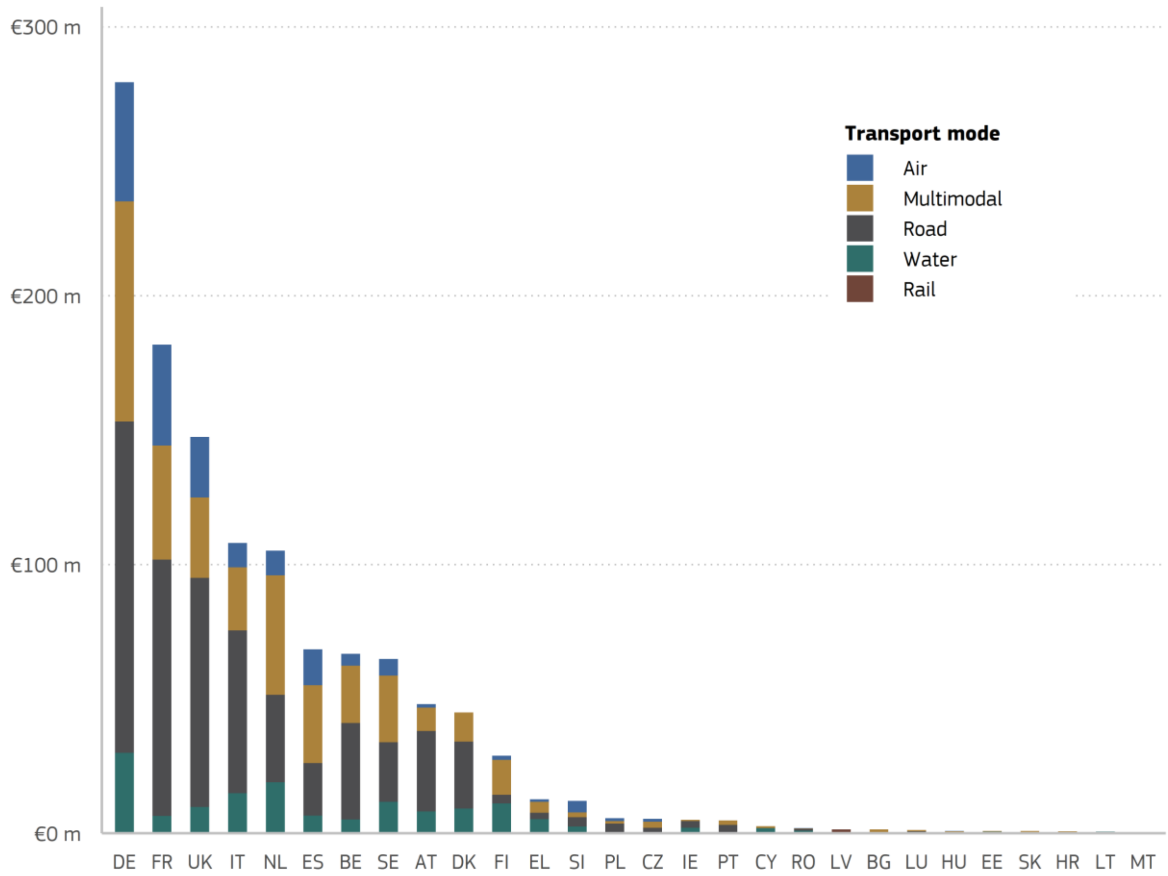


Abbreviations: DLR: Deutsche Zentrum für Luft- und Raumfahrt e.V.; CEA: Commissariat à l'énergie atomique et aux énergies alternatives; CIMV: Compagnie Industrielle de la Matière Végétale; ITM: ITM Power (Trading) Limited; ARCELORMITTAL: Arcelormittal Belgium NV; AIR LIQUIDE: Air Liquide Advanced Technologies; AVL: Anstalt für Verbrennungskraftmaschinen List ; FRAUNHOFER: Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.; CRF: Centro Ricerche Fiat S.C.p.A.; LBSL: London Bus Services Limited; NEL: Nel Hydrogen AS; ABERDEEN: Aberdeen City Council; DAIMLER AG: Daimler AG; VTT: Teknologian tutkimuskeskus VTT Oy; RVK: Regionalverkehr Köln GmbH;

Source: TRIMIS.

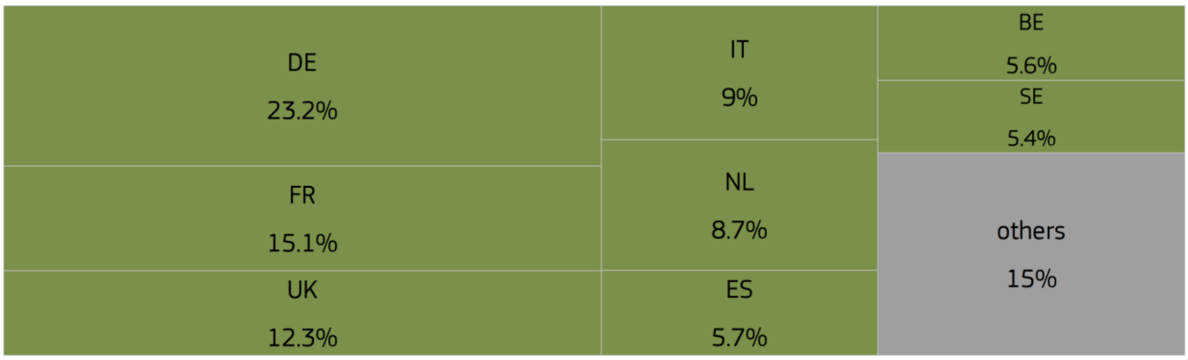
Figure 6 shows the distribution of EU contribution between particular countries split between particular transport modes. The highest value of funding has come to German beneficiaries – in total nearly than €280 m. Three other countries have attracted more €100 m contributions each: France, the UK, Italy and the Netherlands. Beneficiaries from these four countries has concentrated almost 70% of all EU funds for designated to ALT projects (Figure 7).

Figure 6. ALT funding by MS, including division between transport modes



Source: TRIMIS.

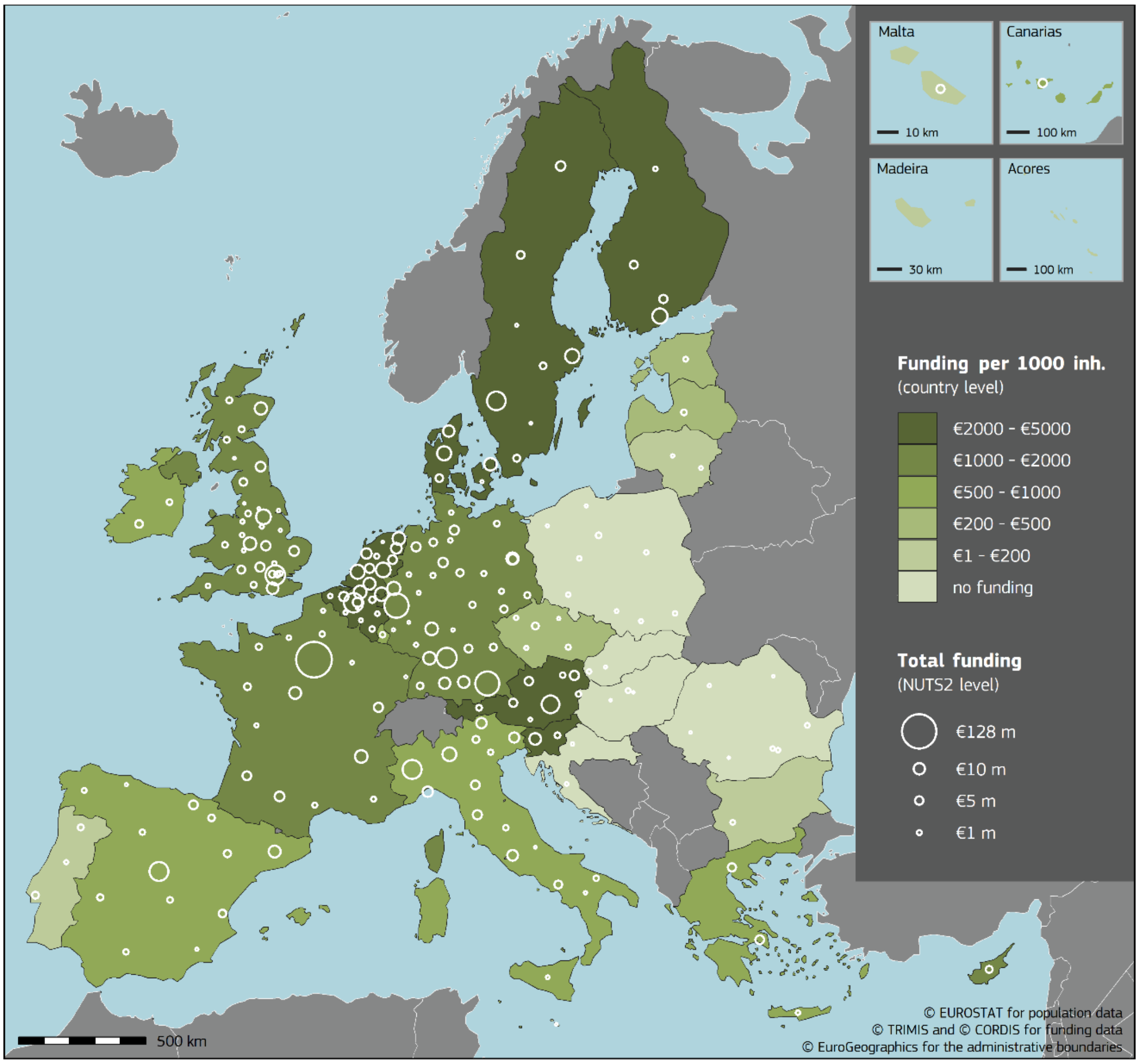
Figure 7. MS shares of ALT funding



Source: TRIMIS.

Figure 8 provides more detailed insights on geographical distribution of ALT funding in both, absolute terms (i.e. total funding acquired by organisations located within a given NUTS2 region) and relative terms (i.e. funding in relation to the population, at the national level). The map shows the high concentration of funding in several regions in France (Île de France; €128 m), Germany (Köln, Oberbayern, which contains metropolitan area of München and Stuttgart, among others; €56 m, €54 m and €36 m respectively) followed by Inner London – West (UK), Brussels (BE) and Comunidad de Madrid (ES). Moreover, there is also high spatial concentration of funding in the regions of the south and south-west Germany, southern part of the UK, the Netherlands, Belgium (in particular its central and northern part).

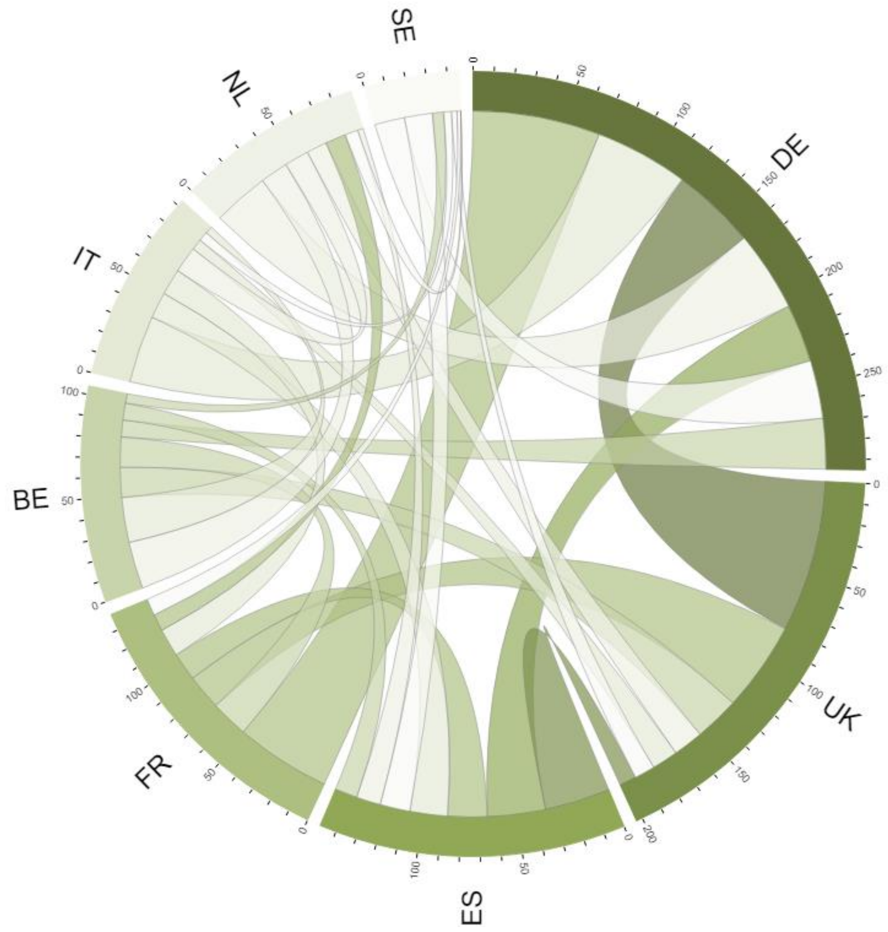
Figure 8. Geographical distribution of ALT funding



Source: TRIMIS.

Finally, some of the ALT projects have been involving many organisations from several countries. Figure 9 shows the main collaboration links between project partners located in different countries. In the directed chord diagram the width of the arc at ends indicates number of project partners located in a given country in all projects with involved organisation located in another country (i.e. the one located at the other end of the arc). Germany, being the country which attracts the highest share of ALT R&I funding, has also the highest number of involved project partners. The strongest links, with the highest number of beneficiaries from both countries includes Germany and the UK (45 and 81 partners involved, respectively), Germany and France (68 and 51) and Germany and Italy (50 and 36).

Figure 9. Main links between project leader and project partners located in different countries



Source: TRIMIS.

6.3 Top technologies identified in the roadmap

As reported in Section 2.2, 25 technologies are identified that are that are exclusive to the ALT roadmap. 14 technologies are linked to road transport, seven to waterborne transport (sea and inland), two to aviation, one to multimodal and one to rail. Out of the 25 technologies, only 14 derive from more than one project: thus, 11 technologies are linked to unique projects. Looking into technologies that are linked not only to ALT but also to other roadmaps, the number rises significantly to 124, with VDM being a notable case (84 technologies linked both to ALT and VDM).

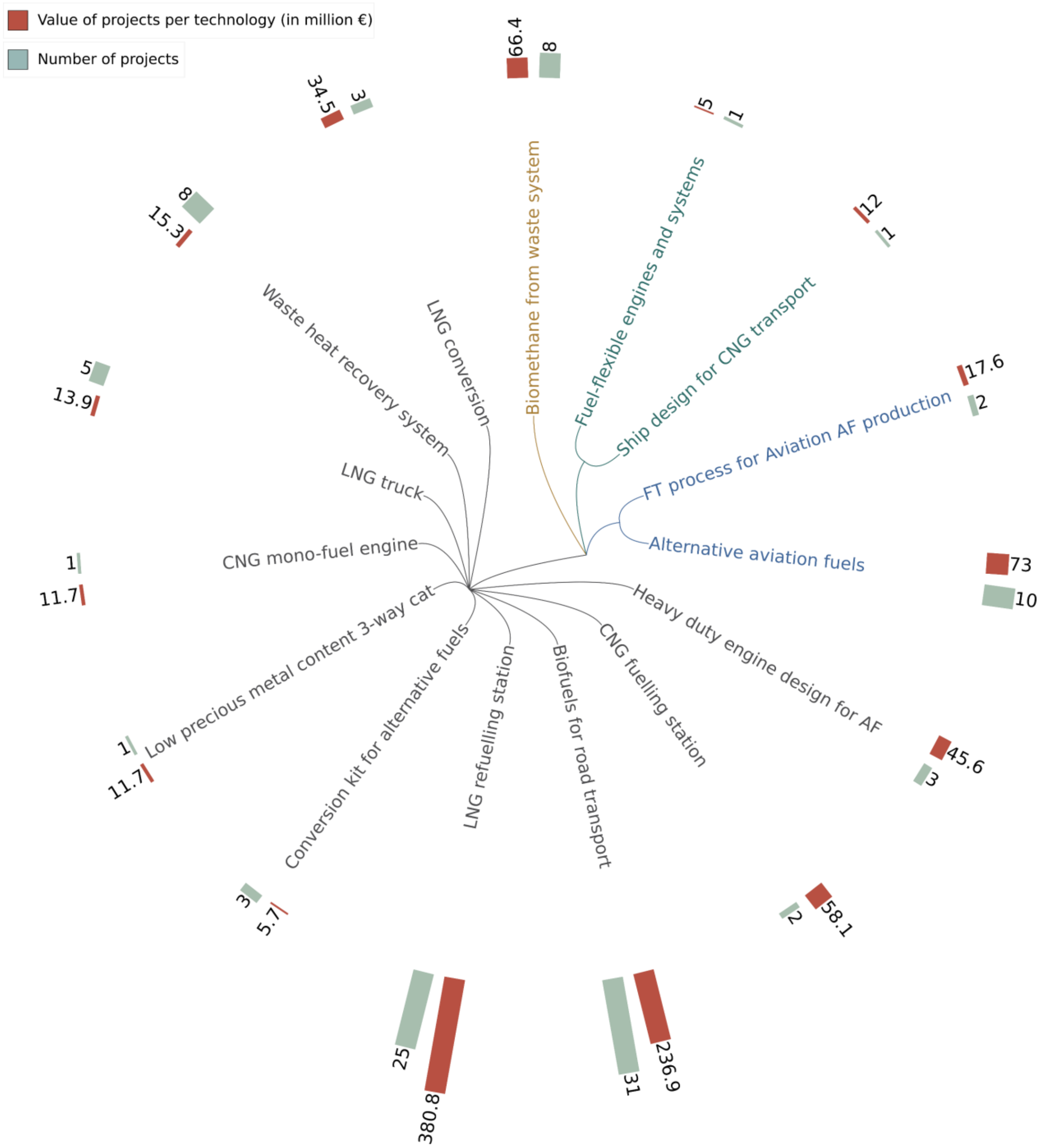
Focusing on the technologies exclusive to ALT, the radial structure of Figure 10 highlights key metrics on the overall top 15 technologies, in terms of the total value invested per technology.

The metrics analysed are:

- "Value of projects per technology": the total value of all projects that have researched the technology (i.e., the total investment, by both the EU and industry, in the development of the technology);
- "Number of projects": the number of projects that have researched the technology;

These two metrics highlight the combined effort that has been put into the technology.

Figure 10. Top 15 technologies for the ALT roadmap



Bars not in scale. LNG: Liquefied natural gas; AF: Alternative Fuel; LNG: Compressed natural gas; FT: Fischer-Tropsch). Brown branches: road transport; blue branches: aviation; green branches: waterborne transport; dark yellow: multimodal transport.

Source: Own elaboration.

The top technology in terms of budget is *LNG refuelling station*, researched in 25 projects and linked to road transport. The high budget for this technology derives from the projects that research it: 24 of the 25 projects are linked to CEF calls, while only one is linked to FP7 (the LNG Blue Corridors project). For the same reason, the technology is marked with high maturity in the TRIMIS database (21 projects researched the technology at a Demonstration/Prototyping/Pilot Production maturity phase, with four projects still ongoing in 2021).

The second top technology is biofuels for road transport, researched in 31 projects. 27 of the projects that research this technology are from H2020 calls, making that the maturity of this technology is rather lower. In fact, 14 projects, all of them from H2020 calls and 10 still ongoing in 2021 research the technology at a research maturity phase. Six projects are in a validation phase, and seven in a Demonstration/Prototyping/Pilot Production phase in the TRIMIS database. In fact, among the projects, one (Photofuel) declares an initial TRL 3, one (ABC-SALT) an initial TRL 4, while, four projects (CONVERGE, BioRen, BABET-REAL5, COZMOS) declare an initial TRL 5.

Finally, the third technology with the highest budget is *alternative aviation fuels* researched only in 10 projects (four from FP7 and six from H2020 calls). Six of the 10 projects researched the technology from a low development phase (research), while two (namely, the still ongoing BIO4A and HEAVEN H2020 projects), declare an initial TRL 6, leading to these technologies being tagged as Demonstration/Prototyping/Pilot Production in the TRIMIS database.

Although with limitations linked to the approach followed for clustering technologies in technology themes and building a taxonomy, the exercise of linking several technology metrics with organisational data, can be useful for identifying technology value chains, including opportunities, as well as providing indications on overspending and inefficiencies. In the future, efforts will be made to have a better coverage of technologies researched within projects, indexed in higher aggregation levels.

7 Research and innovation assessment

This section presents an analysis of the research being performed, the results being achieved and the implications for future research and policy development under five sub-themes. In line with the fuel categories included in the ALT roadmap, the sub-themes selected for this analysis are:

— Methane-based fuels (CNG, LNG and bio-based equivalents);

— LPG (and bio-based equivalents);

— Alcohols, ethers and esters;

— Synthetic paraffinic fuels.

— Hydrogen & ammonia

Table 9 shows the numbers of projects and levels of funding identified from an analysis of the projects in TRIMIS under each of these sub-themes for recent and ongoing projects. The selection of these projects was based on those assigned to the 'Low emission alternative energy for transport' STRIA roadmap in TRIMIS, with end dates from 2019 onwards. Note that the LPG sub-theme has significantly less research being conducted than the other sub-themes, consequently the number of projects and funding value assigned to it are comparatively small.

Table 9. Alternative fuel type summary table

Alternative fuel type	Total project value (in € million)	Total EU contribution (in € million)	Number of projects
Methane-based fuels	944.1	383.7	60
LPG and bioLPG fuels	66.6	55.3	7
Alcohols, ethers and esters fuels	241.9	202.9	31
Synthetic paraffinic fuels	305.1	248.0	35
Hydrogen & Ammonia	1 289.1	533.5	67

Source: Own elaboration.

In addition to the split of projects by types of fuel being researched, it is possible to assess the number of projects and levels of funding by the funding source. The results are shown in Table 10. Note that, whereas a project may research multiple fuels (and, therefore, is counted multiple times in Table 9), each project is counted under only one funding source in Table 10.

Table 10. Alternative fuels research by parent programme summary

Parent programme	Total project value (in € million)	Total EU contribution (in € million)	Number of projects
CEF - Connecting Europe Facility	1 123.7	348.4	48
Horizon 2020	1 041.6	587.6	81
Other funding sources	no data	-	6

Source: Own elaboration.

In total, 135 projects were reviewed as part of this assessment, with the majority of projects falling under the umbrella of the Horizon 2020 programme. The total value of all the Connecting Europe Facility (CEF) projects is, however, slightly larger than Horizon 2020, as the projects are of a much larger size; average value circa €23 m for CEF vs. circa €1 m for Horizon 2020. The projects designated under "Other funding sources" were those that were funded under a national programme rather than an EU wide framework. The funding data for these projects was unavailable hence no information has been provided in Table 10.

7.1 Sub-theme 1 – Methane-based fuels

This section covers the use of all methane-based fuels, principally CNG and LNG. There is also research into biomethane as a transport fuel. These fuels have lower carbon emissions (per unit of energy) compared to petrol or diesel; this is due to the lower carbon content of the fuel([45]),([46]). The downside is that the energy density of CNG is lower than that of diesel or gasoline and therefore for the same requested work from the engine, more CNG fuel is required than either diesel or gasoline. Research from three recent projects (PEMSFORNANO, DOWNTOTEN and SUREAL 23) suggests that NG engines might have higher particle number (PN) emissions than diesel engines; which remains a crucial issue to be addressed if gaseous fuels are introduced as a viable alternative to diesel. The research projects in this area generally focus on issues such as the development of engine technology, fuel storage and charging infrastructure.

7.1.1 Overall direction of R&I

Many of the methane-based research projects reviewed in this assessment relate to the deployment of refuelling infrastructure. This is a necessary measure to support the uptake of methane-propelled vehicles and so is expected to be a focus area of the research. The Trans-European Transport (TEN-T) CORE network appears to be key geographic area of investigation for the deployment of refuelling stations. This is consistent with the Alternative Fuels Infrastructure Directive (AFID), that places mandatory targets for 2025 on the number of CNG and LNG refuelling stations along the TEN-T CORE network([47]).

In terms of funding, there is quite an even distribution across the various methane fuel types, though biomethane has the largest share. This is encouraging as biomethane (if produced sustainably) has the potential to reduce lifecycle emissions significantly compared to fossil-fuel CNG/LNG.

Some of the studies reviewed point towards the economic benefits that alternative methane-based fuels could provide. One such study determined that the socio-economic cost-benefit ratio of the construction of a biomethane refuelling station could in the region of 5.5 in favour of the benefits. Power to gas (PtG) has great potential in a future energy system which requires large-scale energy storage coupled with intermittent renewables. A study outlined below has conducted economic analysis of PtG's potential which concludes that it could play a key role in a future European energy system.

7.1.2 R&I activities

The projects included in this sub-theme assessment have conducted research into a range of methane-based alternative transport fuels. There is quite an even distribution of funding across the fuel types, with biomethane taking the largest share. This could be expected as biomethane has the benefit of significantly reduced lifecycle carbon emissions compared to fossil-fuel methane.

([45]) http://european-biogas.eu/wp-content/uploads/2016/05/BiomethInTransport.pdf (accessed on 29 April 2021)
([46]) https://www.sustainablegasinstitute.org/wp-content/uploads/2019/01/SGI_White_Paper_Briefing_note_2019_v3-1.pdf (accessed on 29 April 2021)
([47]) https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32014L0094 (accessed on 29 April 2021)

Table 11. Methane-based alternative fuel type summary table

Fuel type	Total project value (in € million)	Total EU contribution (in € million)	Number of projects	Average project value (in € million)
LNG	220.8	106.6	19	15.8
CNG	149.4	45.5	5	29.8
LNG/CNG	120.9	48.0	12	12.1
Biomethane	259.7	60.8	7	37.1
Not specified / mixture of fuels	193.5	122.7	17	12.1
Total	944.1	383.7	60	8.2

*Please note that the multiplication of average project value and number of projects may not equate to the total project value, some projects lacked information on funding and so were excluded from the average calculation. *Source*: Own elaboration.

A selection of research projects in this area is described below. These projects have been selected as they show good examples of innovation in methane-based fuels and have some results available to report at time of writing.

- STOREandGO (2016-2020) is a PtG project that has built three innovative PtG plants in Germany, Italy and Switzerland that will generate green methane from renewable electricity. Both catalytic and biological methanation processes have been trialled. The ambition is to generate gas with over 90% methane by volume for injection into mains gas grids and for liquefaction into LNG as a transport fuel. Alongside construction of the trial plants, the project has also conducted a range of multidisciplinary research such as developing a set of tools, databases and studies on PtG. The research includes a life cycle assessment (LCA) on PtG technologies, identifying potential locations for large-scale renewable energy store PtG plants in Europe and an examination of the legal framework
- Green Region for Electrification and Alternatives fuels for Transport (GREAT) (2015-2019) installed three CNG/LNG refuelling stations in Sweden for heavy trucks and published two reports on the development of business models and the development of policy measures to support alternative fuels.
- LNG motion (2016-2020) aims to increase LNG availability along the TEN-T core network corridors by developing a network of LNG stations in a large-scale pilot trial. Also, 200 trucks will be equipped with LNG and will use the stations along the corridors. Using data collected form the 200 LNG fuelled trucks and operation of the stations, the gathered data will be used to create a social cost-benefit analysis, an LNG business case for the EU transport sector and to formulate best practices and lessons learned regarding permitting.
- GASVESSEL (2017-2021) is an ongoing project that intends to increase EU gas security by sourcing gas from resources that are otherwise wasted, namely, stranded gas reservoirs and flared gas (which represents about five times the volume of the gas currently used in Europe). It aims to achieve this with a novel ship design that has a new pressurised containment system for the transportation of CNG.
- The LeanShips project (2015-2019) involves eight demonstration actions that combine technologies for efficient, less polluting new and retrofitted vessels. One such demonstration project is a CNG propelled tugboat with a novel natural gas engine developed by MTU company. The engine has thus far performed well, and its behaviour matches that of a traditional diesel engine.
- The GAINN4MOS project aims to improve what is known as the Motorways of the Sea network of the TEN-T by carrying out engineering studies of LNG ship retrofits, LNG infrastructure and bunkering stations for LNG.

7.1.3 Achievements

PtG is an attractive proposition, as it simultaneously addresses the issues of renewable power intermittency and of providing sustainable fuels for transport and other end uses.

STOREandGO undertook a lifecycle analysis of the Synthetic Natural Gas (SNG) produced from its demonstration sites. The study found that the lifecycle emissions of SNG from PtG has high variability depending on geographical location, system configurations, electricity generation mix and carbon dioxide (CO_2) sourcing. In its most optimistic scenario, it found that the lifecycle emissions of SNG could be as low as 0.4kgCO_2e/m^3, whereas fossil-fuel natural gas is 2.4kgCO_2e/m^3. The study also concluded, however, that SNG produced from an Italian electricity mix had lifecycle emissions as high as 14.1 kgCO_2e/m^3, which is almost six times that of fossil-fuel natural gas.

The STOREandGO project also modelled the European energy system in the year 2050 using a tool developed at the Joint Research Centre based on cost optimisation. The objective was to identify the role that PtG can play in the future and to identify the drivers and barriers for the technology. The study covered 55 scenarios, 21 of which showed that a synthetic methane capacity between 40GW and 200GW might fit into the future European energy system. This corresponds to between 5% and 30% of the future overall gas demand respectively.

To support the uptake of alternative methane-based fuels, the necessary refuelling infrastructure must be in place to fulfil the demands of the vehicles. A significant proportion of research is, therefore, being conducted into determining the optimal locations for CNG/LNG refuelling points.

- At time of writing, the GAINN4MOS project has confirmed the completion of 15 engineering studies (14 were proposed in the project objectives), the full results of all projects have yet to be published but some summary results have been provided. One study investigated the feasibility of an LNG/CNG supply station near the Port of Koper, Slovenia. It concluded that the forecast demand of LNG from heavy-duty road transport alone was enough to justify the investment of the supply station.
- LNG Motion conducted a cost benefit analysis (CBA) into the construction of refuelling stations supplying CNG and fuelling stations for LNG from both biomethane and natural gas for heavy duty transport, logistics and public transport along the TEN-T network. The CBA concluded that supplying biomethane and a blend of biomethane and natural gas to refuelling stations had a significant societal benefit when compared to a business as usual scenario (i.e. diesel refuelling stations). The cost benefit ratio was determined to be 5.5 for the biomethane scenario, this indicated that the implementation of biomethane refuelling stations is desirable from a socio-economic perspective.

Research is being conducted into methane-based fuels for the maritime sector, work has investigated novel methods of large-scale transportation of methane in ships and methane-based fuels as a form of propulsion.

- GASVESSEL has successfully implemented a decision support model that is able to calculate CNG cost and tariffs for natural gas sourced from a variety of locations using their novel CNG maritime transportation method. The model incorporates optimisation algorithms and is flexible so that it allows the user to explore different parameters suited to a specific location. A study used the model to investigate eight location scenarios across for three regions: East Mediterranean, Barents Sea and the Black Sea. The cheapest region identified was Cyprus/Lebanon in the East Mediterranean, the CNG tariff for midstream transportation was determined to be €0.0170/m^3.
- The LeanShips project found that a novel CNG engine for the propulsion of ship tugboat performed very well in trials. The results reported that the gas engine has the potential to replace diesel propulsion systems without lowering the expectations regarding transient behaviour and other engine performance indicators. Positive results were found from the emissions measurement tests; it is stated that the International Maritime Organisation's Tier 3 requirements could be met without any additional aftertreatment.

7.1.4 Implications for future research

The economic benefit of switching to alternative methane-based fuels has been identified in some of the studies above. The LNG Motion study has predicted a great socio-economic benefit in the construction of biomethane refuelling stations, which is to be expected given the carbon emission reductions that could be achieved. GAINN4MOS identified that there is enough LNG demand from heavy-duty vehicles to justify the construction of a refuelling station. Future work could involve demonstrating field trials of methane refuelling infrastructure to support the potential shown in the research.

STOREandGO highlighted the huge position that PtG technologies could play in the future European energy system; further research into this promising area is well justified given its potential.

- STOREandGO undertook economic analysis of PtG technologies and attempted to predict the cost of the electrolysers and methanation systems in years 2030 and 2050. The study predicted learning rates of the technologies to plot learning curves up to 2050. The calculated cost reduction potentials showed that the cost (in terms of €/kWh$_e$) of electrolysers in 2050 could be a quarter of that in 2017. The cost of methanation technologies (in terms of €/kWh$_{SNG}$) in 2050 could be half of that in 2017. The study concluded, however, that many simplifications were made in the economic model, including; not accounting for inflationary effects and no changes to technology efficiencies. The study indicates that there is good potential for cost reduction in PtG technologies; however, further detailed economic analysis is required to give greater confidence in this conclusion.

The LeanShips project gives a promising outlook for maritime CNG engines as the novel solution performed very well in trials. The study suggests that its results now need to be validated by conducting real life environment sea trials.

7.1.5 Implications for future policy development

In a number of the studies discussed above, the researchers have explicitly expressed that further policy support is required for methane-based fuels to reach their potential. For instance, to gain the full benefits of using CNG as a fuel, from the extraction to the powering of vehicles, research will need to be conducted into carbon-neutral natural gas (or methane) production methods. Although the use of CNG achieves only a limited level of decarbonisation, biomass digestion and power-to-gas technology to produce biomethane (or synthetic methane) have the potential to reduce CO_2 emissions by 100%. Some of the projects mentioned are still in progress but even so they have identified gaps in research:

— In its review of business models for alternative fuels, the GREAT project suggested three clear areas where policy needs to support the LNG heavy-duty transport market: increasing LNG/liquefied bio-gas (LBG) demand in heavy-duty transport, scaling up the LNG/LBG infrastructure (fuelling station network) and providing LNG/LBG at a competitive price (compared to diesel).

— The LeanShips study suggests that the novel CNG engine will not be taken up due to lack of incentives. The report suggests that “the future is to work with a committed launching consortium, which will together take the full financial risk of realising new technology and pushing for real life market demonstration.”

Methane-based fuels have significant economic potential as demonstrated in STOREandGO and LNG Motion. The concerns related to the lack of policy support raised in the projects above, coupled with the economic potential of methane-based fuels gives good incentive for supportive European policy.

— The STOREandGO energy system modelling indicated a high potential for PtG in Europe by 2050 (between 5% and 30% of the future gas demand). The study states that the current political framework is not ready for market uptake of power-to-gas and does little to support the implementation of PtG. Given the indicated high potential of PtG and its suitability to complement intermittent renewable electricity generation, there is a strong incentive to provide policy support to this technology.

— The results from LNG Motion’s cost benefit analysis concluded that the construction of biomethane refuelling stations for heavy-duty transport along the TEN-T network would provide great socio-economic benefit (the cost benefit ratio was determined to be 5.5).

Annex 1 lists the projects that were reviewed under this sub-theme in preparing the report.

7.2 Sub-theme 2 – LPG and bioLPG fuels

This sub-theme assessment contains the research projects relating to both LPG and bio-liquefied petroleum gas (bioLPG) for use as an alternative transport fuel. Conventional petrol cars can be converted relatively cheaply to run on LPG, which can offer quick carbon emission savings.

7.2.1 Overall direction of R&I

As an alternative fuel source, LPG and bioLPG has undergone little research; the majority of projects reviewed covered a range of alternative fuel types and were not LPG specific. There has been research into using LPG in fuel cells for the purpose of auxiliary power and some ongoing projects are looking into alternative methods of propane production using renewable sources of CO_2 and electricity.

7.2.2 R&I activities

There were just seven projects that were identified for review in the LPG sub-theme, some of these were large-scale projects that encompassed multiple fuel types. In Table 12, the total funding of the LPG sub-theme has been provided, it has not been broken down into LPG and bioLPG, as no projects were identified that were specific to bioLPG.

Table 12. LPG/bioLPG fuel type summary table

Fuel type	Total project value (in € million)	Total EU contribution (in € million)	Number of projects	Average project value (in € million)
Total	66.5	55.3	7	9.5

Source: Own elaboration.

The project below has been selected as it shows a good example of innovation in LPG fuels and has results available to review at time of writing.

— PROMETHEUS-5 (2016-2019) aimed to develop a small scale (5kWe) power generation proton exchange membrane (PEM) fuel cell unit that can also act in a Combined Heat and Power (CHP) mode (5kWe, 7kWth). The device can work with a variety of fuels (LPG/Natural Gas/Biogas) and has a high electrical efficiency (35%, based on lower heating value), compared to conventional diesel/gasoline generators at this size range. It also has the added benefits of reduced vibration, noise and reduced pollutants (NO_x, SO_x). The product is aimed at stationary applications as well as for auxiliary power units on boats and trucks.

The projects below are still ongoing and do not have any notable results to report as yet; however, they highlight research being undertaken related to this sub-theme and so have been included.

— Conventional biofuels compete with the land resources that are needed for agricultural production of food and for maintaining biodiversity; eForFuel (2018-2022) intends to use just renewable electricity, microbial growth and CO_2 to produce sustainable propane and isobutene (for LPG and isooctane respectively). The production process, requiring only CO_2, electricity and water, aims to generate sustainable biofuel in a way that is independent of agricultural or forestry land use. eForFuel aims to establish and demonstrate a unique integrated electro-bioreactor, which automatically integrates different steps: CO_2 electro-reduction, formate production and formate bioconversion to hydrocarbons that can serve as fuels that can be used in existing engines.

— COZMOS (2019-2023) is developing a novel process that will produce propane from renewable sources of CO_2 and hydrogen using a novel catalytic process. The catalyst will allow combined reactions, that currently run at disparate temperatures and pressures, to operate in a temperature/pressure 'sweet spot', which is claimed to reduce infrastructure and provide energy and production cost savings. This process will be demonstrated using the off-gases from energy intensive steel and refinery industries, it is hoped to achieve TRL 5.

7.2.3 Achievements

Just one project was identified as having notable results, the achievements of this project is shown below.

— The PROMETHEUS-5 project has resulted in the fuel cell power unit (the H2PS-5) being proposed for field testing by telecom service providers (to provide back-up power for telecommunication systems) in both

Greece and India. It is also due to be trialled by the operator of the natural gas distribution in the city of Athens. The company that owns the H2PS-5 is hoping to commercialise the product in 2021.

Some interim reporting has been detailed below for the ongoing projects, which yet have to produce notable results.

- eForFuel has thus far developed a conceptual and basic design of its novel electro-bioreactor (EBR), with detailed architecture of its hardware control and software. The construction of its prototype is currently under progress and the consortium have agreed on the initial definitions, settings and system descriptions for the LCA.
- COZMOS has thus far conducted work into their LCA, techno-economic assessment, stakeholder engagement and end-user interests. The researchers have been spreading awareness of the project at various conferences.

7.2.4 Implications for future research

There is a limited number of LPG/bioLPG research projects; therefore, it is difficult to draw any conclusions for future research. The PROMETHEUS-5 project was a notable success, however, and is due to undergo the next stage of its research. Field testing of its fuel cell power unit (the H2PS-5) is to take place and based on the success of this next stage of research, the product may be commercialised. The H2PS-5 is aimed at auxiliary power unit (APU) applications in transport; therefore, LPG research may be directed towards using the fuel as an auxiliary power source rather than for propulsion.

7.2.5 Implications for future policy development

LPG and bioLPG may have a role to play in decarbonising transport; however, there is little research in this area. PROMETHEUS-5 has demonstrated the use of LPG in a PEM fuel cell for the purpose of auxiliary power in transport, and not for the purpose of propulsion. This suggests that LPG's role in a future transport system is likely small and may find a place complimenting other fuels rather than acting as the primary source of propulsion.

Annex 1 lists the projects that were reviewed under this sub-theme in preparing the report.

7.3 Sub-theme 3 – Alcohols, ethers and esters fuels

Alcohols, ethers and esters can be produced from renewable sources and offer low-carbon alternatives to conventional fossil fuels in transport. This sub-theme covers a broad range of fuels and projects; which tend to have a focus on feedstock cultivation or production of the biofuel, rather than vehicle technologies for using the fuel. The fuel types being researched cover a range of transport modes and feedstocks. A benefit of using alcohol, ethers and esters is the ability for the fuel to be blended with conventional fossil fuel (up to a certain limit, which depends on the fuel type) with minimal changes to the vehicle components.

7.3.1 Overall direction of R&I

The research identified in this review was largely focused on the production of alcohols; mostly bioethanol. The typical production method of such biofuels is from lignocellulosic biomass feedstocks (mainly food-crops), these biofuels are termed first-generation biofuels. A key problem with first-generation biofuels is that because they use food-crops as feedstocks, their harvesting competes on land-use with food production.

Many of the production methods being researched in the projects reviewed are methods that aim to mitigate the land-use issue by using resources that are not as dependant on land. Such methods include: biocatalytic production which requires only sunlight, CO_2 and water, and the torrefaction of waste wood biomass.

Other research includes looking into alternative business models that allow ethanol to be produced in smaller scale plants, whereas currently it is restricted to large scale plants that are in close proximity to an abundant biomass feedstock. Smaller plants that can produce ethanol at a cost competitive price will increase the number and variety of feedstocks available for use.

7.3.2 R&I activities

A total of 31 projects, with a combined research value of €241 m, were reviewed for this sub-theme (see Table 13).

Alcohols received a significant proportion of the funding and amounted to almost half of the total number of projects. These projects were largely focused on the production of bioethanol, which is commonly used as a road transport fuel. A small number of projects also investigated the production of biobutanol, which has the benefit of higher energy density than bioethanol. The most common production method investigated in the research was from lignocellulosic biomass feedstocks, which is to be expected as this is the conventional production method. Some alternative ethanol production methods have been investigated, such as biocatalytic production, which requires only sunlight, CO_2 and water. Also, one project investigated the torrefaction of biomass, which converts woody biomass into a biocoal; carbon monoxide exhaust fumes from the combustion of the biocoal is then microbially fermented into bioethanol.

No projects investigating the use of esters, such as Fatty Acid Methyl Esters (FAME), were identified in this review. FAME fuels are used in road transport and it has been researched as a fuel for aviation, but no such research was seen in this review. Ethers are usually additives rather than a fuel due to their low energy density; just two ether projects were identified in this review.

Table 13. Total funding and number of projects for alcohols, ethers and esters research projects

Fuel type	Total project value (in € million)	Total EU contribution (in € million)	Number of projects	Average project value (in € million)
Alcohol	89.4	80.1	14	6.4
Ester	0	0	0	0
Ether	10.7	10.3	2	5.3
Other	141.8	112.5	15	10.9
Total	241.9	202.9	31	8.4

*Please note that the multiplication of average project value and number of projects may not equate to the total project value, some projects lacked information on funding and so were excluded from the average calculation. *Source*: Own elaboration.

A selection of research projects in this area are shown below. These projects have been selected as they show good examples of innovation in alcohol, ether or ester fuels, and have results available to review at time of writing.

— Biocatalytic production of liquid fuels requires only sunlight, CO_2 and water, unlike conventional lignocellulosic methods which require a biomass feedstock. Photofuel's (2015-2020) goal is to engineer microbial cells to directly excrete hydrocarbon and long chain alcohol fuel compounds to the medium from which they can be separated, without the need to harvest biomass. This novel method is expected to improve on conventional solar biofuel production methods in terms of cost, energy efficiency and its ability to be compatible with operation on degraded or desert land. The product fuels are expected to be "drop-in" fuels that can fully or partially replace fossil counterparts without the need for new infrastructure. The novel process is claimed to be at TRL 3, with an ambition to demonstrate up to TRL 4-5.

- The current production method of ethanol involves generating large quantities of ethanol in large-scale centralised plants. This requires high capital investment and large amounts of biomass feedstocks need to be concentrated in a small radius (50km) of the plant for transportation costs to be viable. Due to this, there are only a small number of opportunities for the installation of ethanol plants in Europe. BABET-REAL5 (2016-2020) aims to develop an alternative solution for the production of ethanol by producing competitive ethanol at a smaller industrial scale, enabling the exploitation of a larger number of biomass feedstocks, and hence increasing the number of potential ethanol production plants across Europe. The project will investigate a novel biomass conversion process that is currently developed to TRL 4, with the aim of bringing it up to TRL 5. Business cases will be identified for installations of small-scale demonstration industrial plants in different European and Latin American countries.
- The FLEDGED (2016-2020) project set out to combine a flexible sorption enhanced gasification (SEG) process and a novel sorption enhanced bio-based Dimethyl Ether (DME) synthesis (SEDMES) process to produce DME from biomass efficiently and at low cost. It aims to validate the SEG and SEDMES processes experimentally at TRL 5.
- AMBITION (2016-2019) conducted research into three key areas of biofuel production: biomass pre-treatment, gasification and syngas fermentation. The project developed a number of novel processes (TRL 1-4) for the conversion of biomass into a variety of biofuels.
- Capturing CO_2 from the atmosphere and converting it into a fuel is an attractive idea due to the combined benefit of alternative fuel production and environmental gain from atmospheric CO_2 reduction. HybridSolarFuels (2017-2021) is developing new materials that photochemically convert CO_2 using sunlight into liquid fuels. The project is still ongoing but has so far published 18 scientific papers and has managed to develop photochemical cells for testing.
- The Torero project (2017-2020) aims to demonstrate a concept for producing bioethanol from a waste wood feedstock, which is fully integrated with a large-scale industrial steel mill. In this process, the waste wood is converted to biocoal (via torrefaction), which then replaces conventional fossil-fuel coal in a steel mill blast furnace. The carbon monoxide in the blast furnace exhaust fumes is then microbially fermented to bioethanol. The project is still ongoing; thus far, it has completed the conceptual design of the torrefaction plant, but the plant has yet to be constructed for testing.

7.3.3 Achievements

There are several projects improving on the current state-of-the-art technology based on European funding for alcohol, ether or ester fuels in transport. The results of some these projects are shown below.

BABET-REAL5 developed a methodology for identifying suitable sustainable lignocellulosic biomass feedstocks within France, Germany, Argentina and Uruguay. The methodology considered the risks associated to the removal and competitive uses of the biomasses and the climate change impacts on their sustainable production. The methodology was able successfully identify a sustainable feedstock within each of the regions for use in smaller scale ethanol plants. The project was also able to identify optimal locations within each of the countries for the location of the ethanol plant.

A notable finding from the AMBITION project was that it demonstrated that syngas fermentation is possible on the syngas produced from the gasification of organic solids. Using this process allows for the manufacture of complex molecules in a single step, which opens the opportunity to develop new process chains for biofuel production. The project also found that the yield of butanol from the syngas fermentation could be substantially increased with the addition of CO_2 or hydrogen.

7.3.4 Implications for future research

The novel processes investigated in the reviewed projects are largely at relatively low stages of development (TRL 1-5); considerable further research will be required to bring the alternative production methods up to commercial deployment.

BABET-REAL5 identified a number of optimal locations to trial its smaller scale ethanol plants. To confidently determine whether ethanol can be produced at a cost competitive price at small scales, the plants will need to be constructed and demonstrated.

Photofuel had the aim to produce butanol via a novel biocatalytic production process; however, the cost assessment study found that even in their 'high productivity' scenario, the butanol could not be produced at a competitive price. The study concluded that several upgrades to their proposed plant could be undertaken to achieve profitability; further research would be needed to determine whether the novel plant could be financially viable. Also, the LCA (based on a Norwegian energy mix scenario) determined that the novel process did not offer superior environmental impacts compared to existing biofuel or even fossil fuel production. This puts doubt on whether further research into this novel process is worthwhile.

FLEDGED was able to determine an efficiency range of 38% to 45% (based on Lower Heating Value (LHV)) from its novel biomass to DME process. The report concluded that the biomass to DME efficiency was comparatively low, which is thought to be due to the high methane content in the syngas produced in the fluidised bed gasifier. The conclusion suggests that to improve the DME production, a methane reforming step must be included in the plant. Further research into the inclusion of a methane reforming step would be needed to determine whether higher biomass to DME efficiency could be achieved.

The novel processes investigated in AMBITION had some notable successes; however, the processes were identified to be at the very early stages of development (TRL 1-4); therefore, significant further research is required to bring them to commercial reality.

7.3.5 Implications for future policy development

Alcohols, esters and ethers can offer reductions in carbon emissions relative to fossil fuels and can be blended with fossil fuels (up to certain limits) for use in conventional engines with little modification required. This idea is quite attractive to consumers as it incurs smaller disruption and lower capital costs than switching to other alternative fuel types such as hydrogen.

Many of projects discussed above have been researching production methods of second-generation biofuels (or advanced biofuels) which are manufactured from non-food related biomass. Most biofuels used today are first-generation which are those manufactured from food crops such as sugars and vegetable oils. The sustainability of first-generation biofuels is questionable as they compete on land-use with food crops. The second-generation processes identified in the above projects are still at the early stages of development (TRL 1-5); therefore, further research should be included into any future policy development around biofuels. As identified in Photofuel, the cost of second-generation biofuels is currently too high to be competitive with fossil-fuels; therefore, policy should support research into increasing their cost-effectiveness and/or a subsidy to make them competitive.

Annex 1 lists the projects that were reviewed under this sub-theme in preparing the report.

7.4 Sub-theme 4 – Synthetic paraffinic fuels

This sub-theme covers the research projects addressing SPFs for use in transport. These fuel types are relatively new areas of research, and hence much of the work is around investigating novel production processes and assessing the commercial viability of these fuels. The most promising use for these fuels is in the aviation sector, as they have high energy density.

7.4.1 Overall direction of R&I

Diesel and kerosene are likely to remain as the two major fuels for heavy duty road transport and for aviation due to their superior energy density, which is unmatched by alternatives such as batteries and hydrogen.

Synthetic paraffinic fuels are a new generation of transport fuels made through the Fischer-Tropsch (FT) process from natural gas or biomass, or through hydrotreatment process from vegetable oils (HVO) or animal fats. Synthetic paraffinic fuels are the only alternative fuels which can compete on energy density. These fuels also have the capability of being 'drop-in'; which means that they can be used in conventional fossil fuel engines up to a blend of 100%, without the need for a change of engine components or infrastructure. However, 100% HVO is below the EN590 (diesel) standard for density, and requires a lubricity additive, and has a comparatively much higher cetane number compared to EN590 diesel fuel. Research into this sub-theme is, therefore, well justified and as such, there is considerable funding in this area (€305 m).

Research into the synthetic paraffinic fuel area is still in its early stages, with most projects investigating technologies at low readiness levels (TRL 1-5). The research is largely focused on the production of the fuels; with many projects investigating the use of waste as the feedstock. The concept of turning waste into a high value fuel is an attractive proposition and one that has been heavily publicised. Research into this area is still in its early stages but shows good promise thus far.

SPF for the aviation industry is the most researched end use application, though there is considerable work looking into SPFs as diesel substitute for the heavy-duty transport sector. Many of the projects are attempting to produce the SPF to established quality standards, such as ASTM D7566 (international aviation fuel standard containing synthesised hydrocarbons) and the European standards EN228 and EN590 for diesel and gasoline. This is encouraging, as reaching the standards will enable the commercial uptake of SPF.

There are also projects that are investigating using existing crude oil infrastructure in the SPF production chain. The premise of this work is that by using existing infrastructure, the capital costs of the alternative fuel production will be reduced, and thus the fuel can be made more cost competitive. This is a resourceful idea and one that should be encouraged to accelerate the uptake of synthetic paraffinic fuels.

7.4.2 R&I activities

Table 14 below shows the number of projects and total funding for the different production processes: hydrotreatment from HVO or animal fats, FT and hydrothermal liquefaction (HTL). Many of the projects reviewed in this section were not specific to one process type, but covered multiple production processes. For this reason, the category "Other / multiple types" has the majority of projects and funding assigned to it. No projects were identified that focused purely on the FT process; projects that investigated the FT process also incorporated HVO or more commonly HTL; therefore, these projects were designated as multiple type projects. There was just one HVO specific project, while HTL had six projects. The total value of the funding in this sub-theme is €305 m with the average project value being just under €9 m.

Table 14. Total funding and number of projects researching synthetic paraffinic fuels

Fuel type	Total project value (in € million)	Total EU contribution (in € million)	Number of projects	Average project value (in € million)
HVO	12.4	10.9	1	12.4
HTL	31.2	29.5	6	5.2
Other / multiple types	261.5	209.5	28	10.1
Total	305.1	248.0	35	9.2

*Please note that the multiplication of average project value and number of projects may not equate to the total project value, some projects lacked information on funding and so were excluded from the average calculation. *Source*: Own elaboration.

A selection of research projects in this area is shown below. These projects have been selected as they show good examples of innovation in synthetic paraffinic fuels and have results available to review at time of writing.

— BIO4A (2018-2022) is an ongoing project that aims to produce 200 to 300 thousand tonnes per year of sustainable biojet (HVO/ Hydroprocessed Esters and Fatty Acids -HEFA-) fuel for a new biorefinery in France for use in aviation at commercial scale. BIO4A is demonstrating the production of HEFA from wastes and aiming to move the full value chain from TRL 6 to 7. A research and development (R&D) strategy is being developed for low indirect land use change (ILUC) biofuels that are to be grown in Southern Europe. Three key areas of research include the use of compost, the use of biochar as a Negative Emission Technology and the cultivation of selected varieties of drought resistant oil crops suitable for aviation fuel production, such as Camelina sativa.

- ADVANCEFUEL (2017-2020) aims to facilitate the uptake of advanced liquid biofuels and other liquid renewable fuels (RESfuels) in the transportation sector between 2020 and 2030. It is investigating a wide range of advanced biofuels including methane-based, alcohols, ester and ethers, hydrogen and synthetic paraffinic. It is a multifaceted project that is developing new sets of tools, standards and recommendations for market stakeholders, to remove barriers against the uptake of advanced fuels.
- Food and market waste (FMW) are some of the most abundant unrecycled products which pose waste management issues and negative environmental impacts. FlexJET (2018-2022) is aiming to produce 1 200 tonnes of ASTM-certified biofuel from FMW, which can be used on commercial flights. It is demonstrating the use of American Society for Testing and Materials SABR-TCR technology, which is novel process that combines traditional transesterification (TRANS) and thermo-catalytic reforming (TCR). If successful, the demonstration plant will be upgraded to a commercial scale facility that will be first of its kind with a production capacity of 25 000 tonnes of international certified aviation biofuel.
- TO-SYN-FUEL (2017-2021) is aiming to demonstrate the feasibility of a novel process that will convert organic waste biomass (sewage sludge) into a sustainable biofuel for road transport. Similar to FlexJET, the process used combines TCR, with hydrogen separation through pressure swing adsorption (PSA) and hydrodeoxygenation (HDO), to produce an equivalent gasoline and diesel substitute, and green hydrogen for use in transport.
- 4REFINERY (2017-2021) is investigating biofuel production technologies that can be integrated into existing infrastructures, in the hope to produce biofuels that are cost competitive compared to conventional fossil-fuels. Optimal pathways will be sought for the transformation of bio-liquids from fast pyrolysis and hydrothermal liquefaction (HTL) into advanced biofuels.
- The BioMates project (2016-2021), aims to produce bio-based intermediates (named BioMates) from second generation biomass technologies that can be further upgraded in existing oil refineries for use as fuel. This approach attempts to minimise the use of fossil-fuels (some are used in the final refining step) and minimise capital expense as existing refining infrastructure is used. Non-food biomass feedstocks (such as straw and miscanthus) are converted into a "BioMate" via ablative fast pyrolysis (AFP) and mild catalytic hydroprocessing (mild-MDT) as the main processes.
- Heat-to-Fuel (2017-2021) aims to produce decarbonised diesel and kerosene via an advanced concept which uses both wet and dry biomass feedstocks. Dry biomass and organic waste gasification processes have high amounts of excess heat, which can be conveniently exploited by wet biomass conversion processes. The novel process combines gasification, Fischer-Tropsch, hydrothermal liquefaction (HTL) and Aqueous Phase Reforming (APR). It is hoped that the resulting biofuel will be cost competitive (less than €1 per litre) and have significantly reduced lifecycle emissions.
- CLARA (2018-2022) aims to demonstrate an innovative process called chemical looping gasification (CLG). The process is a novel oxygen-assisted gasification technology through which solid feedstocks are converted into a nitrogen-free synthetic gas, without requiring an energy intensive air separation unit. A FT reactor is then used to convert the synthetic gas into liquid FT-crude. It is hoped that it will be able to produce biofuels at a cost competitive price against conventional fossil equivalents.

7.4.3 Achievements

There are several projects improving on the current state-of-the-art technology based on European funding for synthetic paraffinic fuels in transport. Most projects are still ongoing and have yet to reach conclusion; therefore, the results shown below are interim results that were available at time of writing.

BIO4A has successfully completed its conversion of an old oil refinery into its new biorefinery for the processing of biomass feedstocks. The plant is operational and has the capacity to produce up to 500 000 tonnes of biofuel each year. The biochar tests are also underway; the pilot facilities have produced biochar and have trialled composting it with digestate from biomass feedstock anaerobic digestion plants (co-composting biochar and digestate has the potential to improve fertilising abilities of both components).

The FlexJET project has thus far conducted preliminary research into the conversion potential of food and market waste into a sustainable biofuel. The TCR process has been investigated, which results in three products: biochar (22% by weight), biooil (7%), and permanent gas (54%). The bio-oil higher heating value (HHV) was found to be 36.7 MJ/kg, which is comparable to biodiesel, the produced biochar had a value of 23.6 MJ/kg and the permanent gas showed a value of approximately 17 MJ/Nm^3.

In preparation for construction of its demonstration plant, TO-SYN-FUEL has conducted a mass and energy balance of its novel process. The results showed that for a sewage sludge input of 300kg/hr, the expected yield of biofuel is 30kg/hr (with the remaining products being syngas and biochar). This is a similar result to FlexJET's process which determined that 7% of its products would be biooil.

A techno-economic analysis conducted as part of the 4REFINERY project showed promising potential for the cost competitiveness of the biofuel produced through hydrothermal liquefaction. A numerical model was built using experimental data to establish energy and mass balances for the economic assessment. The analysis was conducted on three scenarios and found that the minimum fuel selling price (MFSP) per litre of gasoline equivalent was in the range of \$0.82 to \$1.14 (at the time of writing, the price in the United Kingdom is approximately \$1.30 per litre of gasoline equivalent).

Crude oil refineries can currently only accept biogenic oils co-feed up to a mix of 10%. An aim of the BioMates study is to investigate methods of increasing this level, so that increased renewable intermediates can replace fossil crude oil. The BioMates study investigated potential fossil-fuel intermediates which may accept a higher biogenic mix. The miscibility of five candidates was investigated. The study was able to identify the two most promising candidates, which were fluid catalytic cracking light cycle oil (FCC LCO) and light vacuum gas oil (LVGO).

Heat-to-Fuel has thus far released several scientific publications; one such study looked into the HTL of a lignin-rich stream from lignocellulosic ethanol production. The experiment investigated the influence of temperature, time and biomass-to-water ratio on product yields, biocrude elemental composition, molecular weight and carbon balance. The resulting biocrude is split between light and heavy fractions; the study was able to determine that highest yields of heavy biocrude were recovered at 300°C and the highest yield for the light fraction occurred at 370°C.

In the CLARA project, the researchers have devised a process model for the entire process chain, stretching from gasification to fuel synthesis and upgrading, to estimate heat and mass balances of the process. The model has allowed the researchers to reach an optimised set of conditions that yield a high process efficiency. Also, initial experiments have found that torrefaction of the raw biomass prior to gasification leads to enhanced feedstock characteristics, facilitating higher gasifier efficiencies and reducing post treatment requirements.

7.4.4 Implications for future research

Research into the synthetic paraffinic fuel area is still in its early stages, with most projects attempting to demonstrate technologies at low readiness levels (TRL 1-5). FlexJET and TO-SYN-FUEL have thus far conducted preliminary research into their waste-to-fuel processes; the next stages for these projects is to build demonstration plants which will prove the concepts identified. If successful, both projects will construct a commercial facility that will be a first of its kind for their respective novel processes.

Many of the results reported by the reviewed projects thus far look promising and SPF has great potential to decarbonise the heavy-duty road transport and aviation sectors where other alternative energy sources do not appear to be viable. Further work should, therefore, focus on demonstrating the concepts to a higher TRL.

Work is underway to investigate the use of existing crude oil infrastructure in the 4REFINERY and BioMates projects. This is an attractive proposition as it reduces capital expenditure and thus increases the chances of SPF being cost competitive against conventional fossil-fuels. The results from 4REFINERY's techno-economic analysis show that it could produce fuel at a cost competitive price, though the price was sensitive to the biocrude yield from the HTL process. Given the high promise of this idea, further work is recommended to validate the results and to investigate optimisation of the HTL process.

Much of the work has focused on the aviation sector, with some research into the heavy-duty road vehicle market. There should be more research into bringing synthetic paraffinic fuel to other transport modes, if economically viable, to explore the potential decarbonisation of each transport mode.

7.4.5 Implications for future policy development

Significant policy support will be required for aviation to fully contribute to the achievement of the 90% reduction in transport emissions by 2050, as envisaged in the European Green Deal. Synthetic paraffinic fuels offer the potential to reach this goal, as they have the high energy density that is required by this industry, whereas other alternative fuels do not. BIO4A and FlexJET are attempting to produce aviation standard SPF from waste feedstocks, with the ultimate ambition of producing it in a commercial scale facility. Waste-to-fuel is an attractive proposition as it could produce an energy dense fuel for aviation, whilst also mitigating waste management issues and the negative environmental impacts of organic waste disposal. If such projects prove successful and the production facilities can be demonstrated at commercial scale, policy should support this.

Similarly to the aviation industry, it is unlikely that battery electric vehicles will be a strong solution to decarbonise heavy-duty road transport, due to the large size and weight of the batteries required for long-distance travel. SPF is, therefore, a promising option for decarbonisation and this is reflected in the research projects reviewed. TO-SYN-FUEL and Heat-to-Fuel are both investigating the production of diesel substitute for road transport, with TO-SYN-FUEL aiming to produce an equivalent gasoline and diesel substitute compliant with EN228 and EN590 European standards. Due to the 'drop-in' potential of some SPFs they could be used in heavy-duty vehicles with little changes to the vehicle components.

Some of the work reviewed shows good promise in terms of the cost competitiveness of the SPF produced (see 4REFINERY), though further policy support will be likely be required to in the early stages of uptake so that it can compete with conventional fossil-fuels.

Some of the projects reviewed expressed concerns specific to policy support, a few of these have been detailed below:

- Bio4A conducted a study into business models for the production of its HEFA fuel; it concluded that the economics of the fuel are challenging. It found that the business case was very sensitive to the amount of policy support available and consequently the case could quickly be shifted from negative to positive if the required incentives were available.
- ADVANCEFUEL conducted a stakeholder engagement study that questioned participants representing industry, research organisations and academia, agriculture and forestry sector experts and end-use sector experts. The aim of the study was to identify the key barriers in the uptake of lignocellulosic feedstock and non-biological origin fuels. A key finding was that the highest barrier for conversion technologies (hydrolysis, gasification, Fischer-Tropsch, etc.) was considered to be the absence of dedicated policy support. The technical challenges in developing these technologies were conversely only considered to be a low to moderate barrier. Another key barrier was identified in the lack of subsidies available to bridge the price gap between renewable and fossil-fuel based fuels. The production costs for renewable fuels are on average 2.5 times those for their fossil-fuel counterparts. Clearly, significant policy support is needed make renewable fuels economically viable.

Annex 1 lists the projects that were reviewed under this sub-theme in preparing the report.

7.5 Sub-theme 5 – Hydrogen and Ammonia

This sub-theme covers the research projects addressing hydrogen and ammonia fuels for use in transport. The concept of hydrogen fuel cell vehicles has existed for many years, though progress in developing affordable vehicles has been slow and research has continued to attempt to overcome some of the problems. The use of ammonia as a fuel is also not new; however, its implementation has been very limited, but it has gained attention in recent years as a potential fuel for the maritime sector. Ammonia is effectively a hydrogen carrier that overcomes some of the difficulties in the storage and transportation of pure hydrogen.

7.5.1 Overall direction of R&I

Hydrogen road vehicle technology is now in the mature stages of development (TRL 6-9) and much of the work focusses on proving the vehicles in real environments. JIVE, H2ME and ZEFER are ongoing large-scale projects that are deploying hundreds of hydrogen vehicles and up to a hundred refuelling stations across multiple member states in Europe. The large-scale nature of these projects is encouraging, as leveraging the benefits of economies of scale will be key in proving the commercial viability of hydrogen transport.

If hydrogen vehicles are to become widespread within the European transport system, there must be necessary refuelling infrastructure in place to support fast and efficient refuelling. As a result, the deployment of refuelling stations has been a key area of research. Many refuelling points have been constructed as part of the projects in this review; however, reports of delays to the deployment process due to regulations have been reported.

There is great potential synergy between hydrogen transport and PtG in a future energy system. The use of large-scale hydrogen electrolysers (hundreds of MW) is, therefore, being explored as a method of grid balancing and of storing excess power.

The use of hydrogen propulsion in the maritime and aviation sectors is less common; however, there is some research being conducted into solutions for both sectors. Real-life trials are due to be conducted of a hydrogen powered ferry and of a hybrid hydrogen fuel cell/internal combustion engine (ICE) aircraft propulsion system. There was just one ammonia fuel project identified, which is going to demonstrate the use of a novel ammonia fuel cell for the propulsion of a ship. The results of the maritime and aviation demonstrations are awaited to determine if hydrogen/ammonia is a viable decarbonisation option for these sectors.

7.5.2 R&I activities

Table 15 below shows the number of projects and total funding for the hydrogen and ammonia sub-theme. This sub-theme is large, with 67 projects and the total project value exceeding €1.2 bn. There was only one ammonia project identified; which had a value of €13 m, the remaining projects and budget were allocated to hydrogen.

Table 15. Total funding and number of projects researching hydrogen and ammonia fuels

Fuel type	Total project value (in € million)	Total EU contribution (in € million)	Number of projects	Average project value (in € million)
Hydrogen	1 275.9	523.5	66	19.7
Ammonia	13.2	10.0	1	13.2
Total	1 289.1	533.5	67	19.5

Source: Own elaboration.

A selection of research projects in this area is discussed below. These projects have been selected as they show good examples of innovation in hydrogen or ammonia fuels and have results available to review at time of writing.

Hydrogen road vehicle technologies have been in development for some time; consequently, the technologies are mature and much research is being conducted into large-scale deployment of the vehicles to test them in real environments.

— JIVE (2017-2022) and its successor JIVE 2 (2018-2023) are both large scale projects that are deploying Fuel Cell (FC) buses across various locations in Europe. Combined, the projects will see the deployment and operation of nearly 300 FC buses in 22 European cities/regions, which is hoped to provide a sound basis for further uptake of these vehicles. The ambition of the projects is to unlock the economies of scale which are required to reduce the costs of fuel cell buses. JIVE and JIVE 2 will also test new hydrogen refuelling stations and implement a comprehensive data monitoring and assessment exercise will capture the relevant evidence to inform next steps for the sector.

- H2ME (2015-2020) and its successor H2ME 2 (2016-2022) are another set of large-scale projects that are deploying fuel cell vehicles and refuelling infrastructure across Europe. The resulting data will allow policymakers, early adopters and the hydrogen mobility industry to validate the readiness of the technology for full commercial roll-out. H2ME brings together Europe's four most ambitious national initiatives on hydrogen mobility (Germany, Scandinavia, France and the UK). The project will expand their developing network of hydrogen refuelling stations and the fleets of fuel cell vehicles (FCEVs) operating on Europe's roads, to expand the activities in each country and to start the creation of a pan-European hydrogen fuelling station network. In total, 200 FC vehicles, 125 fuel cell range extended vans and 29 hydrogen refuelling stations will be deployed. H2ME 2 brings together eight countries and a much larger, more varied array of vehicle types. In total, 1 230 new hydrogen fuelled vehicles and 20 new hydrogen refuelling stations will be deployed.
- ZEFER (2017-2022) aims to explore viable business cases for hydrogen vehicles and refuelling stations via a large-scale deployment project. In total, 180 fuel cell vehicles will be deployed in Paris, Brussels and London; 170 will be operated as a taxi or private hire and the remaining 10 will be used by the police. A large-scale data analysis will be undertaken, and various business cases will be analysed. A targeted dissemination campaign will aim to replicate the business cases across Europe.

In the rail sector, hydrogen fuel cells are also under consideration for lines that are hard, or too expensive, to electrify. To date, there have been no recent projects in TRIMIS focused on the application of fuel cells to trains. However, the FCH2RAIL([48]) consortium has been awarded a project, to start in 2021, to design, develop and test a hydrogen fuel cell powered train. The total project cost is expected to be around €14 m, with €10 m being provided by Horizon 2020 through the FCH-JU. The prototype train is planned to be a hybrid design, which will use normal electric power on lines where it is available and switch to the fuel cell power unit on lines where it is not. The plan is to develop the prototype through to certification test level; a process that is expected to take four years.

Hydrogen fuel cell propulsion is also being investigated in the maritime and aviation sectors where its implementation has been limited thus far.

- Hyseas III (2018-2021) is aiming to bring to market the world's first sea going ferry that will be powered by hydrogen from renewable sources. The project will develop the concept and construct a prototype that will be demonstrated with monitoring of its performance in a real environment. The ship will be operated in the Orkney Islands in Scotland, with the hydrogen largely produced from wind power in the local area.
- HyMethShip (2018-2021) aims to demonstrate the use of methanol as hydrogen carrier aboard ships. The proposed solution reforms methanol to hydrogen, which is then burned in a conventional reciprocating engine that has been upgraded to burn multiple fuel types and specially optimised for hydrogen use. This system will be developed, validated, and demonstrated on shore with a typical engine for marine applications in the range of 2 MW (TRL 6).
- The H2PORTS project (2019-2022) is planning to develop and demonstrate the benefits of using hydrogen fuel cell vehicles within maritime ports, with the aim of reducing emissions from such vehicles. The first prototype to be developed will be a reach stacker, which will be tested in a container terminal at a port, while the second prototype will be a fuel cell powered yard tractor. The project will also develop a mobile hydrogen supply station, which will deliver the fuel for the two prototype vehicles.
- MAHEPA (2017-2021) is investigating two novel low emission propulsion technologies for aviation. Two variants of a low emission, high efficiency, hybrid-electric propulsion architecture will be advanced to TRL 6: the first uses a hydrocarbon fuelled internal combustion engine and an electric generator as primary power source, while in the second a hydrogen fuel cell is used to produce electric power.
- The FLAGSHIPS project (2019-2023) raises the readiness of zero-emission waterborne transport to an entirely new level by demonstrating two commercially operated hydrogen fuel cell vessels. The demo vessels include the world's first commercial cargo transport vessel operating on hydrogen, plying the river Seine in Paris. Commercial operations are set to commence in 2021. The project will reduce the capital cost of marine fuel cell power systems significantly by leveraging knowhow from existing on-shore and marine system integration activities.
- The MARANDA project (2017-2021) develops an emission-free hydrogen fuelled PEMFC based hybrid powertrain system for marine applications. The project includes a validation of the research vessel Aranda

([48]) https://www.railwaypro.com/wp/hydrogen-train-prototype-project-secures-eu-funding/ (accessed on 29 April 2021) in test benches and on board. The research places special emphasis on air filtration and development of hydrogen ejector solutions, for both efficiency and durability reasons.

Just one project is being conducted into the use of ammonia as a fuel; a novel fuel cell is being investigated as the propulsion method for a ship.

— Ammonia (which is effectively a hydrogen carrier) has potential as a fuel in the maritime sector. As a world's first, the ShipFC (2020-2025) project will retrofit an ammonia-powered fuel cell to an offshore vessel to prove and show the case for large-scale zero-emission shipping. An existing vessel (the Eidesvik-owned Viking Energy) is to be retrofitted with a 2MW ammonia-fuelled solid oxide fuel cell, which will be operated for at least 3 000 hours during a one-year period. Socio-technical models and analysis will be performed and a full feasibility study on a series of additional vessels will be conducted.

Power-to-Gas (PtG) is an attractive proposition, as it simultaneously addresses the issues of renewable power intermittency and of providing sustainable fuels for transport and other end uses. The incorporation of large-scale electrolysers into the electricity grid could balance the network whilst also producing useful hydrogen for transport.

— TSO 2020 (2017-2019) is investigating electricity transmission and storage options along the Trans-European Networks for Energy (TEN-E) and TEN-T networks. Part of this study involves the investigation of a large-scale (300MW) hydrogen electrolyser connected to the Dutch electricity grid. The work will demonstrate the technical and commercial viability of power to hydrogen solutions in the Groningen region in the Netherlands, and also, assess the replicability of the solutions in other regions. Among other work, the project will conduct stability analysis of the grid and a CBA of the electrolyser versus an alternative battery system.

7.5.3 Achievements

There are several projects improving on the current state-of-the-art technology based on European funding for hydrogen and ammonia fuels in transport. Most projects are still ongoing and have yet to reach conclusion; therefore, the results shown below are interim results that were available at time of writing.

JIVE thus far made good progress in reducing the capital cost of fuel cell buses, it has reported that seven suppliers are now able to meet the JIVE target price of €650 000 per bus for a standard (non-articulated) vehicle. Germany and the UK have been the first countries begin the procurement of FC buses, with 10 delivered to Cologne, 2 delivered to Wuppertal, 20 orders made for London and 15 orders for Aberdeen. JIVE 2 set a more ambitious target price of €625 000, mixed messages have been received from suppliers as to whether they can meet this price.

H2ME has reported promising results from its large-scale deployment of fuel cell vehicles and hydrogen refuelling stations. To date, 256 fuel cell vehicles and eight refuelling stations have been deployed. In total the vehicles have now driven more than three million km and the refuelling stations have achieved over 95% availability. It has been reported that the fuel cell vehicles have been operated with very similar patterns to petrol/diesel vehicles in terms of trip distance and refuelling. The vehicles have been reliable, durable, shown good performance and there have been zero safety-related incidents. Under the H2ME 2 project, eight refuelling stations and 503 vehicles are in operation; over 25 000 refuelling events have taken place since March 2016. The majority of the fleet operators and drivers have reported positive overall experiences with FCEVs, based on the vehicle performance and refuelling time meeting the operational needs.

To date, 96 of the 180 ZEFER vehicles have been deployed in Paris and London and have accumulated over two million kilometres. It has been reported that the vehicles have performed exceptionally well with deployment partners noting that they operate to the same standard as incumbent diesel vehicles. Work has been conducted to develop an availability app for refuelling stations which is claimed to improve customer experience.

Hydrogen must be produced from zero or low carbon sources for it to be a sustainable fuel; Hyseas III has completed its LCA on the use of its ship powered by hydrogen which is mostly generated by wind power. The study determined that over a 30-year lifespan, an 89% reduction of global warming potential emissions could be achieved when compared to a traditional diesel-electric alternative.

TSO 2020 has conducted a detailed CBA of a 300MW hydrogen electrolyser connected to the electricity grid in the Netherlands, to determine its value to society. The study found that the electrolyser outperformed an equivalent battery system in the key performance indicators (KPI) assessed, which included financial attractiveness and technical integration with renewable power generation. The transport sector was identified as the most promising end use for the hydrogen generated, in order to maximise its revenues. Hydrogen buses, trucks, trains, light-duty vehicles and passenger vehicles were investigated.

HyMethShip has thus far developed a preliminary vessel system layout incorporating all major system components and a battery system that can quickly supply energy to the propulsion system during rapid load increases if the increase in hydrogen pro-duction is delayed. The project has conducted a feasibility study of its novel methanol steam reformer and carbon capture system. It concluded that all of the process steps are feasible with state-of-the-art technology.

MAHEPA has reported that testing of its 300kW ICE and FC-hybrid drive system has shown a high level of technical capability, such that the novel aircraft are due to start their first demonstration flights in 2020. It is claimed that the 120kW fuel cell will be the most powerful fuel cell system ever used to power a flying aircraft.

During the first reporting period of FLAGSHIPS project, definitions for requirements for marine specific fuel cell system were defined. In the two demo vessel cases, work concentrated on the design of the vessels themselves, route studies, ship specifications, design of the hydrogen systems on board and the related systems. This included detailed design of hydrogen processing on-board, all auxiliary systems and safety related issues and systems. Also, work on power-train design and specification was conducted. As a result of all of this work, vessel concepts and specifications were completed.

MARANDA has so far carried out a LCA to assess environmental impacts associated with the use of hydrogen fuel cells in marine applications. A filter and filter monitoring solution was developed for both FC system container and for hydrogen storage container. In the selected FC system container solution all the ventilation air for the fuel cell container is filtered with particle filters. A part of the filtered air is then further purified by chemical filter before it is used by FC system.

7.5.4 Implications for future research

The cost competitiveness of fuel cell vehicles is a key barrier that is limiting their uptake. JIVE, H2ME and ZEFER are all deploying fuel cell vehicles and refuelling stations at a large-scale such that the benefits of economies of scale should start to take effect. A final step in these projects will be to analyse collected data and assess various business cases of the deployments. This next stage of analysis will be a key element, as good business models for hydrogen fuel will increase its chances of reaching commercial reality. In terms of the technical performance of hydrogen vehicles, JIVE, H2ME and ZEFER's real life environment trials have provided some promising results. These projects reported very positive feedback in terms of the performance of the hydrogen vehicles from their users. The vehicle technology has now been demonstrated and so further work should be focused on increasing its commercial viability, rather than on technical development.

Hyseas III and ShipFC will both be testing novel solutions for the maritime sector, the former will be using a hydrogen fuel cell, whereas the latter will be using ammonia. Both of the projects are due to undergo real environment deployment, the results of which will undoubtedly be of great value to the decarbonisation of the maritime sector.

The cost benefit analysis conducted as part of TSO 2020 shows good promise for large-scale hydrogen electrolysers to work with future electricity systems that are dominated by intermittent renewable power. Interestingly, the electrolyser proved to have a greater societal impact than an equivalent battery system. The synergy between large-scale power-to-gas and hydrogen transport could play a pivotal role in the future EU energy system; further work should deploy electrolysers to demonstrate their benefits in a real environment.

The reports from the MAHEPA project indicate that their novel ICE and FC-hybrid drive aircraft system will undergo real flight testing this year. A successful flight demonstration would be a big step for hydrogen in the aviation sector, it is claimed that the 120kW fuel cell will be the most powerful fuel cell system ever used to power a flying aircraft.

As stated in the first deliverables of FLAGSHIPS, the project will create new business opportunities for companies as building of zero-emission vessels and local H_2 supply will emerge as new sectors of growth. The project will also push forward the development of safety approval practices.

7.5.5 Implications for future policy development

JIVE, H2ME and ZEFER will all be investigating business models for hydrogen vehicles and refuelling infrastructure. Whilst the vehicle and refuelling technology is relatively established, it is unlikely that they will prove commercially viable without significant policy support, at least in the short term. H2ME has reported some specific policy recommendations thus far; it has stated that financial incentives for vehicles work best in combination with other benefits for users e.g. priority lane access. Other analysis suggests that grid balancing revenues and electricity price optimisation for electrolysers could lead to a reduction in the price of hydrogen.

H2ME and H2ME 2 noted that there were significant delays to the installation of hydrogen refuelling stations, which was attributed to the effect of regulations. The project reports that there are unclear regulations, codes and standards, and that the administrative process of gaining permits and planning authorisations took over 12 months in many cases. It was noted that H2M Deutschland have been able to reduce the permitting process length from 9 months to 3 months in some cases by improving their administrative procedures. To encourage the deployment of hydrogen infrastructure, the planning processes across the EU should be improved.

The LCA of the Hyseas III project demonstrated that if hydrogen is sourced from low carbon sources (in this case wind power), the lifecycle emissions of transport could be reduced dramatically (89% over 30 years for the ship studied). If electricity had been sourced from an average EU electricity mix, the lifecycle emissions reduction would have been very much smaller, potentially the emissions could have been higher than a conventional diesel-powered counterpart. Policy should, therefore, encourage the production of what is termed 'green' or even 'blue' hydrogen, the former is that produced from renewable sources, whereas the latter is that produced from fossil sources coupled with carbon capture and storage (CCS).

In the MARANDA project new more durable FC systems have been developed with the latest cell components. Optimisation of the hydrogen recirculation, lowering the coolant temperature from 70°C to 60 °C and optimisation of operation strategies will enable longer life-times (> 15 000 hours) so that hydrogen fuel cell use in marine applications becomes possible.

8 Conclusions and recommendations

This report presents a comprehensive analysis of R&I in low-emission alternative energy for transport in Europe. Following the previous report on research and innovation in low-emission alternative energy for transport (Ortega Hortelano et al., 2019), the present report focuses on selected EU funded projects from TRIMIS with end dates from 2019 onwards. The report highlights the most relevant researched technologies and their development phase, as well as the policy context and the market activities in Europe. Some key conclusions are:

— Under the 7th Framework Programme for Research and the Horizon 2020 Framework Programme for Research and Innovation about €2.3 bn has been invested in ALT research projects. Road transport has received more funding than any other transport mode.

— In terms of level of investment, the top technology is *LNG refuelling station*, researched in 25 projects. It is in a high maturity phase and it is directly linked to road transport. The second top technology is *biofuels for road transport*, researched in 31 projects. It is characterised by a lower maturity which means that some time is needed for this technology to be deployed in the market. Finally, the third technology is *alternative aviation fuels* researched in 10 projects. The technology is in lower development phases, between Research and Demonstration/Prototyping/Pilot Production.

— Research on methane based fuels (e.g. CNG, LNG) receives a significant economic support (€944 m) through multiple funded (60) projects. Several projects have demonstrated that methane-based fuels have significant economic potential. However, to gain the full benefits of using CNG as a fuel, from the extraction to the powering of vehicles, research will need to be conducted into carbon-neutral natural gas (or methane) production methods. Although the use of CNG achieves only a limited level of decarbonisation, biomass digestion and power-to-gas technology to produce biomethane (or synthetic methane) have the potential to reduce CO_2 emissions by 100%. Research in this area also analyses how to store and handle these fuels, addressing in this way issues related to methane leakage.

— LPG technologies are fully developed and as such, they are market driven. In fact, there are only seven research projects still ongoing. As an alternative fuel source, LPG and bioLPG has undergone little research, which might be explained by their limited overall environmental advantage over conventional fuels, since they are equally mostly based on fossil energy sources. The majority of the reviewed projects covered a range of alternative fuel types and were not LPG specific. Current research focuses on using LPG in fuel cells for the purpose of auxiliary power. Moreover, some ongoing projects are looking into alternative methods of propane production using renewable sources of CO_2 and electricity.

— Alcohols, esters and ethers come in third place in terms of number of projects (31 projects) and funding received (€241 m). They can reduce carbon emissions and can be blended with fossil fuels (up to certain limits) for use in conventional engines with little modification required. This idea is quite attractive to consumers as it incurs smaller disruption and lower capital costs than switching to other alternative fuel types such as hydrogen. Many of the reviewed projects have been researching production methods of second-generation biofuels (or advanced biofuels) which are manufactured from non-food related biomass. Only one project researched third-generation biofuels' production, which means electrofuels might be scaled up faster than third-generation biofuels. The second-generation processes identified in the reviewed projects are still at the early stages of development (TRL 1-5); therefore, further research should be included into any future policy development around biofuels.

— Research on SPF also benefit from European funding with €305 m through 35 projects. As it is a relatively new area of research, most of the research focus on novel production processes and evaluation of the commercial viability of these fuels. Research into SPF is still in its early stages, so most of the projects investigate technologies at low technology readiness levels (TRL 1-5). Moreover, many projects investigate the potential use of waste as feedstock. Waste-to-fuel is an attractive proposition as it could produce an energy dense fuel for aviation, whilst also mitigating waste management issues and the negative environmental impacts of organic waste disposal. If such projects prove successful and the production facilities can be demonstrated at commercial scale, policy should support this. SPF are mostly investigated in the context of the aviation sector, with some research into the heavy-duty road vehicle market. There should be more research into bringing synthetic paraffinic fuel to other transport modes, if economically viable, to explore the potential decarbonisation of each transport mode.

— Research on hydrogen receives the largest share of total funding exceeding €1.2 bn invested in 67 R&I projects. Hydrogen road vehicle technology is now in the mature stages of development (TRL 6-9) and much of the work focuses on testing the vehicles in real environments. Hydrogen is seen as a good option to decarbonise hard-to-abate sectors, such as road freight transport. The infrastructure for fast and efficient refuelling is necessary for the widespread use of hydrogen vehicles within the European transport system. As a result, the deployment of refuelling stations has been a key area of research. Many refuelling points have been constructed as part of the projects in this review; however, delays to the deployment process due to regulations have been reported. The use of hydrogen propulsion in the maritime and aviation sectors is less common; however, there is some research being conducted into solutions for both sectors. Real-life trials are due to be conducted of a hydrogen powered ferry and of a hybrid hydrogen fuel cell/internal combustion engine (ICE) aircraft propulsion system.

The findings support one important policy consideration for the future. New technologies and changes in the alternative fuels market need some time to materialise. Thus, policies should not consider a radical or sudden change in the market, and therefore, transition periods are critical. It is also noteworthy that there is no silver bullet solution to decarbonisation, and the proper use of the various alternative fuels available will be crucial. Generally speaking, those fuels with the highest economic potential are already on the market (e.g. Methane based fuels and LPG), but they have a limited overall environmental advantage over conventional fuels (petrol and diesel). On the other hand, fuels with a higher potential to decarbonisation are still not commercially viable, and there is not enough infrastructure for their deployment across Europe (e.g. Hydrogen and SPF). . Alternative fuel policies should take into account the current state of low-emission alternative energy for transport. They should evaluate all potential impacts to set realistic targets that ensure the decarbonisation of the transport sector at the highest speed possible to achieve the updated climate target goals.

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List of abbreviations, formulations and definitions

ABERDEEN	Aberdeen City Council
ACARE	Advisory Council for Aviation Research and Innovation in Europe
ACEA	European Automobile Manufacturers Association
AFID	Alternative Fuels Infrastructure Directive
AFP	Ablative fast pyrolysis
AIR LIQUIDE	Air Liquide Advanced Technologies
ALT	Low-emission alternative energy for transport
APR	Aqueous Phase Reforming
APU	Auxiliary power unit
ARCELORMITTAL	Arcelormittal Belgium NV
ASTM	American Society for Testing and Materials
AVL	Anstalt für Verbrennungskraftmaschinen List
BEVs	Battery electric vehicles
CAEP	Committee on Aviation Environmental Protection
CAT	Connected and automated transport
CBA	Cost benefit analysis
CCS	Carbon capture and storage
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CEF	Connecting Europe Facility
CHP	Combined Heat and Power
CIMV	Compagnie Industrielle de la Matière Végétale
CLG	Chemical Looping Gasification
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRF	Centro Ricerche Fiat S.C.p.A.
DAIMLER AG	Daimler AG
DLR	Deutsche Zentrum für Luft- und Raumfahrt e.V.
DME	Dimethyl Ether
EAFO	European Alternative Fuels Observatory
EBR	Electro-bioreactor
EC	European Commission
EEDI	Energy Efficiency Design Index
ELT	Transport electrification
EPA	Environmental Protection Agency
ETS	Emissions trading system
EU	European Union

FAME	Fatty acid methyl esters
FC	Fuel Cell
FCC LCO	Fluid catalytic cracking light cycle oil
FCEVs	Fuel cell vehicles
FCH-JU	Fuel Cells and Hydrogen Joint Undertaking
FMW	Food and market waste
FP	Framework programmes
FP7	7th Framework Programme for research
FRAUNHOFER	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
FT	Fischer-Tropsch
GAIN	US Global Agricultural Information Network
GHG	Greenhouse gas
GTL	Gas to Liquid
H2020	Horizon 2020 Framework Programme for Research and Innovation
HC	Hydrocarbon
HDO	Hydrodeoxygenation
HDVs	Heavy Duty Vehicles
HEFA	Hydroprocessed Esters and Fatty Acids
HHV	Higher Heating Value
HTL	Hydrothermal liquefaction
HVO	Hydrotreated Vegetable Oil
ICAO	International Civil Aviation Organisation
ICE	Internal Combustion Engine
ILUC	Indirect land use change
IMO	International Maritime Organisation
INF	Transport infrastructure
IPs	Innovation Programmes
ITM	ITM Power (Trading) Limited
KPI	Key Performance Indicator
LBSL	London Bus Services Limited
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LVGO	Light Vacuum Gas Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MFSP	Minimum Fuel Selling Price
Mild-MDT	Mild catalytic hydroprocessing
MS	Member State

NEL	Nel Hydrogen AS
NETT	New and emerging technologies and trends
NG	Natural Gas
NO_x	Nitrogen oxides
NTM	Network and traffic management systems
PEM	Proton exchange membrane
PHEVs	Plug-in hybrid electric vehicles
PN	Particle number
PSA	Pressure swing adsorption
PtG	Power to Gas
R&D	Research and Development
R&I	Research and Innovation
RESfuels	Advanced liquid biofuels and other liquid renewable fuels
RVK	Regionalverkehr Köln GmbH
SEDMES	Sorption enhanced bio-based Dimethyl Ether synthesis
SEG	Sorption enhanced gasification
SERA	Single European Railway Area
SI	Spark Ignition
SME	Small Medium Enterprise
SMO	Smart mobility and services
SNG	Synthetic Natural Gas
SPF	Synthetic paraffinic and aromatic fuel
STRIA	Strategic Transport Research and Innovation Agenda
TCR	Thermo-Catalytic Reforming
TEN-E	Trans-European Networks for Energy
TEN-T	Trans-European Transport Networks
TRANS	Traditional transesterification
TRIMIS	Transport Research and Innovation Monitoring and Information System
UK	United Kingdom
US	United States
VDM	Vehicle Design and Manufacturing
VTT	Teknologian tutkimuskeskus VTT Oy
WtW	Well-to-Wheel

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Annexes

Annex 1. Project table

The following table shows all projects that were considered during the development of this report and the sub-theme(s) under which they were considered.

Project acronym	Project name	Project duration	Source of funding	Methane fuels	LPG/BioLPG	Alcohols, Ethers & Esters	Synthetic Paraffinic Fuels	Hydrogen
-	BioLNG EuroNet	2018-2023	CEF	YES				
-	cHAMeleon	2016-2019	Slovenia	YES				
-	H2Benelux	2017-2020	CEF					YES
-	HyBalance	2015-2020	H2020-EU.3.3					YES
-	Nordic Hydrogen Corridor: zero emission transport between the capitals of the Nordic countries with fuel cell vehicles	2017-2020	CEF					YES
-	Policy on eco-friendly transport fuels	2017-2030	National - Netherlands					YES
-	Watertruck+	2014-2019	CEF					YES
-	Zero Emission Valley	2018-2023	CEF					YES
-	A state-of-the art review on the development of CNG infrastructure	2005-2021	-	YES				

	and mapping / digitalisation of the natural gas transmission network in Estonia							
-	Action 2017-EU-TM-0147-W - LNGHIVE2 Vessels Demand: Green and smart links - LNG solutions for smart maritime links in Spanish Core ports	2018-2021	CEF	YES				
-	Biohybrid-Market rollout of sustainable small-scale solution supplying LBG as alternative fuel for heavy-duty transport	2018-2021	CEF	YES				
-	Blue Stations Network	2018-2020	CEF	YES				
-	Construction of a pilot docking station, as a part of an LNG distribution system based on cryogenic tank containers	2017-2020	CEF	YES				
-	Creation of an LNG road haulage market in a smart & quick way	2016-2019	CEF	YES				
-	Demonstration study of infrastructure associated with an innovative LNG traction solution in railway operations	2017-2020	CEF	YES				
-	FueLCNG	2017-2020	CEF	YES				
-	Future transport power sources	2012-2030	-			YES	YES	
-	Green Connect - A public CNG network	2018-2023	CEF	YES				

-	Liquefied BioGas: Fuelling renewable transport in the Visegrad countries	2017-2020	CEF	YES					
-	LNG motion	2016-2020	CEF	YES					
-	LNG Rollout in Central Europe - for a greener transportation sector	2018-2021	CEF	YES					
-	Nordic LNG/CNG - Decarbonisation of the Core Network by deployment of alternative fuel refuelling infrastructure	2018-2021	CEF	YES					
-	Olympic Energy: Tipping the scale towards Bio-CNG for European transport starts in TEN-T Core Urban Node of Paris	2018-2022	CEF	YES					
-	PAN-LNG Project	2015-2019	CEF	YES					
-	PAN-LNG-4-DANUBE	2016-2019	CEF	YES					
-	Policy on eco-friendly transport fuels	2017-2030	-			YES	YES		
-	Seven Europe Network	2018-2021	CEF	YES					
-	Small-scale liquefaction and supply facility for Liquefied Biogas as alternative fuel for the transport sector	2014-2019	CEF	YES					
-	Snam 4 Mobility - retail LNG network development	2018-2023	CEF	YES					

-	Study for a pilot CNG filling station network	2017-2020	CEF	YES				
-	SuperGreen (SG)	2019-2021	CEF	YES				
-	Svealand Public Transport infrastructure roll-out for biogas and electric buses	2018-2023	CEF	YES				
-	Watertruck+	2014-2019	CEF	YES				
-	H2Bus Europe	2018-2023	CEF					YES
2015-EU-TM-0104-S	SiLNGT Small Scale TRANSPORT	2016-2019	-	YES				
2016-MT-SA-0005	Technical Study and Cost-Benefit Analysis for the Development of LNG as a Marine Fuel in Malta	2017-2019	CEF	YES				
2016-PL-SA-0011	The small-scale LNG Reloading Terminal in Gdansk and bunkering services	2017-2019	CEF	YES				
3EMOTION	Environmentally Friendly, Efficient Electric Motion	2015-2019	FP7-JTI					YES
4REFINERY	Scenarios for integration of bio-liquids in existing REFINERY processes	2017-2021	H2020-EU.3.3			YES	YES	
ABC-SALT	Advanced Biomass Catalytic Conversion to Middle Distillates in Molten Salts	2018-2022	H2020-EU.3.3			YES	YES	

ADVANCEFUEL	Facilitating market roll-out of RESfuels in the transport sector to 2030 and beyond	2017-2020	H2020-EU.3.3	YES	YES	YES	YES	YES
ALTERNATE	ASSESSMENT ON ALTERNATIVE AVIATION FUELS DEVELOPMENT	2020-2022	H2020-EU.3.4				YES	
Ambition	Advanced biofuel production with energy system integration	2016-2019	H2020-EU.3.3			YES	YES	
BABET-REAL5	New technology and strategy for a large and sustainable deployment of second generation biofuel in rural areas	2016-2020	H2020-EU.3.3			YES		
BALANCE	Increasing penetration of renewable power, alternative fuels and grid flexibility by cross-vector electrochemical processes	2016-2019	H2020-EU.3.3					YES
BECOOL	Brazil-EU Cooperation for Development of Advanced Lignocellulosic Biofuels	2017-2021	H2020-EU.3.3			YES		
BENEFIC	BENEFIC	2017-2020	CEF	YES				YES
BIG HIT	Building Innovative Green Hydrogen systems in an Isolated Territory: a pilot for Europe	2016-2021	H2020-EU.3.3					YES
BIO2G	Technology for 2G biofuel and biosolvents production verified in a pilot plant	2019-2019	H2020-EU.2.3			YES		
BIO4A	Advanced sustainable BIOfuels for Aviation	2018-2022	H2020-EU.3.3			YES	YES	

BIOLNG4EU	BIOLNG4EU	2017-2020	CEF	YES				
BioMates	Reliable Bio-based Refinery Intermediates	2016-2021	H2020-EU.3.3			YES	YES	
BioRen	Development of competitive, next generation biofuels from municipal solid waste	2018-2022	H2020-EU.3.3			YES		
Blue Baltics	LNG infrastructure facility deployment in the Baltic Sea Region	2016-2019	-	YES				
CAMELOT	UNDERSTANDING CHARGE, MASS AND HEAT TRANSFER IN FUEL CELLS FOR TRANSPORT APPLICATIONS	2020-2022	H2020-EU.3.7					YES
CH2P	Cogeneration of Hydrogen and Power using solid oxide based system fed by methane rich gas	2017-2020	H2020-EU.3.3	YES				YES
CIVITAS ECCENTRIC	Innovative solutions for sustainable mobility of people in suburban city districts and emission free freight logistics in urban centres.	2016-2020	H2020-EU.3.4	YES	YES	YES	YES	
CLARA	Chemical Looping gAsification foR sustainAble production of biofuels	2018-2022	H2020-LC-SC3			YES	YES	
ClimOP	CLIMATE ASSESSMENT OF INNOVATIVE MITIGATION STRATEGIES TOWARDS OPERATIONAL IMPROVEMENTS IN AVIATION	2020-2023	H2020-EU.3.4				YES	
CNG ROMANIA	Initial Market Deployment of a Refuelling Station Network along the Core Network Corridors	2016-2019	CEF	YES				

COHRS	Connecting Hydrogen Refuelling Stations	2015-2019	CEF					YES
COLHD	Commercial vehicles using Optimised Liquid biofuels and HVO Drivetrains	2017-2020	H2020-EU.3.4	YES			YES	
COMSYN	Compact Gasification and Synthesis process for Transport Fuels	2017-2021	H2020-EU.3.3				YES	
CONVERGE	CarbON Valorisation in Energy-efficient Green fuels	2018-2022	H2020-EU.3.3			YES	YES	
CORE LNGas hive	Core Network Corridors and Liquefied Natural Gas	2014-2020	CEF	YES				
COSMHYC	COmbined hybrid Solution of Metal HYdride and mechanical Compressors for decentralised energy storage and refueling stations	2017-2019	H2020-EU.3.4					YES
COSMHYC XL	COmbined hybrid Solution of Metal HYdride and mechanical Compressors for eXtra Large scale hydrogen refuelling stations	2019-2021	H2020-EU.3.4					YES
COZMOS	Efficient CO2 conversion over multisite Zeolite-Metal nanocatalysts to fuels and OlefinS	2019-2023	H2020-EU.3.3		YES	YES	YES	
CRE8	Creating the station of the future	2018-2022	CEF	YES				
CRESCENDO	Critical Raw material ElectrocatalystS replacement ENabling Designed pOst-2020 PEMFC	2018-2021	H2020-EU.3.5					YES

DIGIMAN	DIGItal MAterials CharacterisatioN proof-of-process auto assembly	2017-2019	H2020-EU.3.4					YES
DOLPHIN	Disruptive PEMFC stack with nOvel materials, Processes, arcHitecture and optimized Interfaces	2019-2022	H2020-EU.3.5					YES
DOOR2LNG	Upgrade of the maritime link integrated in the multimodal container transport routes	2016-2019	Finland	YES				
ECO-GATE	European COrridors for natural GAs Transport Efficiency	2017-2019	CEF	YES				YES
eForFuel	Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons	2018-2022	H2020-EU.3.3		YES	YES	YES	
EmX 2025	An R&D base for reduced exhaust emissions in the Norwegian marine transportation sector	2015-2019	Norway	YES				
ENABLEH2	Enabling cryogenic hydrogen based CO2 free air transport (ENABLEH2)	2018-2021	H2020-EU.3.4					YES
ENDURUNS	Development and demonstration of a long-endurance sea surveying autonomous unmanned vehicle with gliding capability powered by hydrogen fuel cell	2018-2022	H2020-EU.3.4					YES
ETIP-B-SABS 2	European Technology and Innovation Platform Bioenergy - Support of Renewable Fuels and Advanced Bioenergy Stakeholders 2	2018-2021	H2020-EU.3.3	YES	YES	YES		

EVERYWH2ERE	Making hydrogen affordable to sustainably operate Everywhere in European cities	2018-2023	H2020-EU.3.3					YES
FASTWATER	FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel: Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up	2020-2024	H2020-EU.3.4			YES		
FCHgo	Fuel Cells HydroGen educatiOnal model for schools	2019-2020	H2020-EU.3.3					YES
Fit-4-AMandA	Future European Fuel Cell Technology: Fit for Automatic Manufacturing and Assembly	2017-2020	H2020-EU.3.4					YES
FLAGSHIPS	Clean waterborne transport in Europe	2019-2022	H2020-EU.3.4					YES
FLEDGED	FLExible Dimethyl ether production from biomass Gasification with sorption-enhancED processes	2016-2020	H2020-EU.3.3			YES	YES	
FlexiFuel-SOFC	Development of a new and highly efficient micro-scale CHP system based on fuel-flexible gasification and a SOFC	2015-2019	H2020-LCE-2014				YES	YES
FlexJET	Sustainable Jet Fuel from Flexible Waste Biomass	2018-2022	H2020-EU.3.3				YES	
FLHYSAFE	Fuel CelL HYdrogen System for AircraFt Emergency operation	2018-2020	H2020-EU.3.4					YES

FReSMe	From residual steel gasses to methanol	2016-2020	H2020-EU.3.3			YES		
FURTHER-FC	Further Understanding Related to Transport limitations at High current density towards future ElectRodes for Fuel Cells	2020-2024	H2020-EU.3.4; H2020-EU.3.5					YES
GAIA	next Generation AutomotIve membrane electrode Assemblies	2019-2021	H2020-EU.3.5					YES
GAINN4MED	GAINN4MED	2017-2020	CEF	YES				
GAINN4MID	GAINN for Mobile Infrastructure Deployment	2017-2020	CEF	YES				
GAINN4MOS	Sustainable LNG Operations for Ports and Shipping - Innovative Pilot Actions	2015-2019	-	YES				
GASVESSEL	Compressed Natural Gas Transport System	2017-2021	H2020-EU.3.4	YES				
Giantleap	Giantleap Improves Automation of Non-polluting Transportation with Lifetime Extension of Automotive PEM fuel cells	2016-2019	H2020-EU.3.4					YES
Go4Synergy in LNG	Go4Synergy in LNG	2016-2019	CEF	YES				
GREAT	Green Region for Electrification and Alternatives fuels for Transport	2015-2019	CEF	YES				
GrowSmarter	GrowSmarter	2015-2019	H2020-SCC-2014				YES	

H2Haul	Hydrogen fuel cell trucks for heavy-duty, zero emission logistics	2019-2024	H2020-EU.3.4						YES
H2ME	Hydrogen Mobility Europe	2015-2020	H2020-EU.3.4						YES
H2ME 2	Hydrogen Mobility Europe 2	2016-2022	H2020-EU.3.4						YES
H2Ports	Implementing Fuel Cells and Hydrogen Technologies in Ports	2019-2022	H2020-EU.3.3						YES
Heat-To-Fuel	Biorefinery combining HTL and FT to convert wet and solid organic, industrial wastes into 2nd generation biofuels with highest efficiency	2017-2021	H2020-EU.3.3					YES	
HEAVEN	High powEr density FC System for Aerial Passenger VEhicle fueled by liquid HydrogeN	2019-2022	H2020-EU.3.4						YES
HEAVENN	Hydrogen Energy Applications for Valley Environments in Northern Netherlands	2020-2025	H2020-EU.3.3						YES
HIGH V.LO-CITY	Cities speeding up the integration of hydrogen buses in public fleets	2012-2019	FP7-JTI						YES
HybridSolarFuels	Efficient Photoelectrochemical Transformation of CO2 to Useful Fuels on Nanostructured Hybrid Electrodes	2017-2021	H2020-EU.1.1				YES	YES	
HYDRIDE4MOBILITY	Hydrogen fuelled utility vehicles and their support systems utilising metal hydrides	2017-2021	H2020-EU.1.3						YES

Hydrogenlogistics	Enabling the Hydrogen Economy	2017-2019	H2020-EU.3.4					YES
HyFlexFuel	Hydrothermal liquefaction: Enhanced performance and feedstock flexibility for efficient biofuel production	2017-2021	H2020-EU.3.3			YES	YES	
HyMethShip	Hydrogen-Methanol Ship propulsion system using on-board pre-combustion carbon capture	2018-2021	H2020-EU.3.4			YES		YES
HySeas III	Realising the world's first sea-going hydrogen-powered RoPax ferry and a business model for European islands	2018-2021	H2020-EU.3.4					YES
HySTOC	Hydrogen Supply and Transportation using liquid Organic Hydrogen Carriers	2018-2021	H2020-EU.3.3					YES
HYTECHCYCLING	New technologies and strategies for fuel cells and hydrogen technologies in the phase of recycling and dismantling	2016-2019	H2020-EU.3.4					YES
INLINE	Design of a flexible, scalable, high quality production line for PEMFC manufacturing	2017-2020	H2020-EU.3.4					YES
INN-BALANCE	INNovative Cost Improvements for BALANCE of Plant Components of Automotive PEMFC Systems	2017-2019	H2020-EU.3.4					YES
INSPIRE	Integration of Novel Stack Components for Performance, Improved Durability and Lower Cost	2016-2019	H2020-EU.3.4					YES
JETSCREEN	JET Fuel SCREENing and Optimization	2017-2020	H2020-EU.3.4				YES	

JIVE	Joint Initiative for hydrogen Vehicles across Europe	2017-2022	H2020-EU.3.4					YES
JIVE 2	Joint Initiative for hydrogen Vehicles across Europe 2	2018-2023	H2020-EU.3.4					YES
KEROGREEN	Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO2, syngas formation and Fischer-Tropsch synthesis	2017-2022	H2020-EU.3.3				YES	
LAST MILE	LAST MILE	2019-2022	CEF					YES
LeanShips	Low Energy And Near to zero emissions Ships	2015-2019	H2020-EU.3.4	YES		YES	YES	
LNG4Trucks	LNG4Trucks	2017-2020	CEF	YES				
LNGAFT	Liquefied natural gas as alternative fuel for transport	2016-2019	CEF	YES				
LNGHIVE2	LNGHIVE2 Infrastructure and Logistics Solutions	2018-2022	CEF	YES				
LONGRUN	Development of efficient and environmental friendly LONG distance powertrain for heavy dUty trucks aNd coaches	2020-2023	H2020-EU.3.4	YES	YES	YES	YES	YES
MacroFuels	Developing the next generation Macro-Algae based biofuels for transportation via advanced bio-refinery processes	2016-2019	H2020-LCE-2015; H2020-EU.3.3	YES		YES		

MAHEPA	Modular Approach to Hybrid Electric Propulsion Architecture	2017-2021	H2020-EU.3.4					YES
MARANDA	Marine application of a new fuel cell powertrain validated in demanding arctic conditions	2017-2021	H2020-EU.3.4					YES
MEHRLIN	Models for Economic Hydrogen Refuelling Infrastructure	2016-2020	CEF					YES
MULTI-E	Multiple Urban and Long-distance Transport Initiatives ? Electric and CNG	2018-2023	CEF	YES				
Nautilus	Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships	2020-2024	H2020-EU.3.4	YES				
NextGenRoadFuels	Sustainable Drop-In Transport fuels from Hydrothermal Liquefaction of Low Value Urban Feedstocks	2018-2022	H2020-EU.3.3				YES	
NYSMART	Novel dual-fuel system for modernisation of air-polluting diesel locomotives to clean and efficient gas operation	2017-2019	H2020-EU.3.4	YES				
ORCA	Optimised Real-world Cost-Competitive Modular Hybrid Architecture for Heavy Duty Vehicles	2016-2020	H2020-EU.3.4	YES				
PEGASUS	PEMFC based on platinum Group metAl free StrUctured cathodeS	2018-2021	H2020-EU.3.5					YES
Photofuel	Biocatalytic solar fuels for sustainable mobility in Europe	2015-2020	H2020-EU.3.3			YES		
PRHYDE	Protocol for heavy duty hydrogen refuelling	2020-2021	H2020-EU.3.4					YES

PROMETHEUS-5	Energy efficient and environmentally friendly multi-fuel power system with CHP capability, for stand-alone applications.	2016-2019	H2020-EU.3.3	YES	YES			
Pulp and Fuel	Pulp and Paper Industry Wastes to Fuel	2018-2022	H2020-EU.3.3				YES	
PURE H2	Hydrogen Purifying Unit and Filling Infrastructure	2018-2021	CEF					YES
REDIFUEL	Robust and Efficient processes and technologies for Drop In renewable FUELs for road transport	2018-2021	H2020-EU.3.3			YES		
REVIVE	Refuse Vehicle Innovation and Validation in Europe	2018-2021	H2020-EU.3.4					YES
REWOFUEL	REsidual soft WOod conversion to high characteristics drop-in bioFUELs	2018-2021	H2020-EU.3.3			YES		
ShipFC	Piloting Multi MW Ammonia Ship Fuel Cells	2020-2025	H2020-EU.3.4					YES
STOREandGO	Innovative large-scale energy STOragE technologies AND Power-to-Gas concepts after Optimisation	2016-2020	H2020-EU.3.3	YES			YES	YES
SUN-to-LIQUID	Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	2016-2019	H2020-EU.3.3				YES	
TAHYA	TAnk HYdrogen Automotive	2018-2020	H2020-EU.3.4					YES
THOR	Thermoplastic Hydrogen tanks Optimised and Recyclable	2019-2021	H2020-EU.3.4					YES

Torero	TORrefying wood with Ethanol as a Renewable Output: large-scale demonstration	2017-2020	H2020-EU.3.3			YES		
TO-SYN-FUEL	The Demonstration of Waste Biomass to Synthetic Fuels and Green Hydrogen	2017-2021	H2020-EU.3.3				YES	YES
TRANSCEND	Technology Review of Alternative and Novel Sources of Clean Energy with Next-generation Drivetrains	2019-2022	H2020-EU.3.4				YES	
TSO 2020	TSO 2020: Electric ?Transmission and Storage Options? along TEN-E and TEN-T corridors for 2020	2017-2019	CEF					YES
VIRTUAL-FCS	VIRTUAL & physical platform for Fuel Cell System development	2020-2022	H2020-EU.3.4					YES
WASTE2ROAD	Biofuels from WASTE TO ROAD transport	2018-2022	H2020-EU.3.3				YES	
ZEFER	Zero Emission Fleet vehicles For European Roll-out	2017-2022	H2020-EU.3.4					YES

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