STUDY

Requested by the TRAN Committee

European Parliament

Assessment of the potential of sustainable fuels in transport

Study

Policy Department for Structural and Cohesion Policies
Directorate-General for Internal Policies
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RESEARCH FOR TRAN COMMITTEE

Assessment of the potential of sustainable fuels in transport

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Abstract

This study provides the European Parliament's Committee on Transport and Tourism (TRAN) with an assessment of the potential of sustainable fuels to decarbonise the transport sector, and help the sector achieve the 2050 decarbonisation goals. It assesses their potential for use in maritime, aviation and road transport, considering their technology readiness, feedstock availability, sustainability of supply, resource and energy efficiency, and the most appropriate match-making between fuels and applications.

This document was requested by the European Parliament's Committee on Transport and Tourism.

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LIST OF ABBREVIATIONS

AFIR	Alternative Fuels Infrastructure Regulation
ATJ	Alcohol-to-jet fuel
BECCS	Bioenergy with carbon capture and storage
BEV	Battery electric vehicle
BtL	Biomass-to-liquids
CAN	Climate Action Network
CAPEX	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon capture, utilisation and storage
CCS	Carbon capture and storage
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSRD	Corporate Sustainability Reporting Directive
DAC	Direct air capture
EC	European Commission
EEA	European Economic Area
EEB	European Environmental Bureau
EEDI	Energy Efficiency Design Index
EJ	Exajoule (1 x10^{18} joules)
ERSV	Electric road system vehicle
ETC	European Topic Centre
ETD	Energy Taxation Directive
ETS	Emissions Trading System
EU	European Union
EV	Electric vehicle
FAME	Fatty acid methyl esters
FCEV	Fuel cell electric vehicle
FSD	Financial Stability Board

FT	Fischer-Tropsch
GHG	Greenhouse gas
H_2	Hydrogen
HDV	Heavy-duty vehicle
HEFA	Hydroprocessed esters and fatty acids
HVO	Hydrotreated vegetable oil
ICAO	International Civil Aviation Organisation
ICMA	International Capital Market Association
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCF	Low-carbon fuel
LCFS	Low Carbon Fuel Standard
LDV	Light-duty vehicle
Lge	Litre of gasoline equivalent
LNG	Liquefied natural gas
LPO	Loan Programs Office
MeOH	Methanol
Mtoe	Million tonnes of oil equivalent
N_2	Nitrogen
N_2O	Nitrous oxide
NFRD	Non-Financial Reporting Directive
NGO	Non-governmental organisation
NH_3	Ammonia
O_2	Oxygen
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
OPEC	Organisation of the Petroleum Exporting Countries
PAC	Paris Agreement compatible
PBtL	Power and biomass-to-liquids
PHEV	Plug-in hybrid electric vehicle

PV	Photovoltaic
RCF	Recycled carbon fuel
RD&I	Research, development and innovation
RED	Renewable Energy Directive
RES	Renewable energy sources
RFNBO	Renewable fuel of non-biological origin
RRF	Recovery and Resilience Facility
SAF	Sustainable aviation fuels
SMEs	Small and medium-sized enterprises
SMR	Steam methane reforming
TCO	Total cost of ownership
TCFD	Task Force on Climate-Related Financial Disclosures
TEN-T	Trans-European Transport Network
TRAN	European Parliament Committee on Transport and Tourism
TRL	Technology readiness level
UCO	Used cooking oil

GLOSSARY OF TERMS

Bioeconomy	*The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, microorganisms and derived biomass, including organic waste), their functions and principles*[1].
Bioenergy	Biomass used in the production of energy[2].
Biomass	The biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste[3].
Drop-in fuel	Fuels that can directly be used on board existing vehicles (aircraft, ships, cars, trucks, etc.).
e-ammonia	Ammonia produced with renewable hydrogen.
e-methanol	Methanol produced with renewable hydrogen.
Hard-to-abate sector	Any sector for which the options to decarbonise are not straightforward due to a lack of appropriate technology or lack of competitiveness, such as aviation and shipping.
Point source emissions	Emissions issued by singe identifiable point sources, such as smokestacks from large factory installations.
PBtL	Power & biomass-to-liquids are fuels obtained from biomass (e.g. residual forestry waste or by-products) and hydrogen derived from renewable electricity.
PtL, e-liquids or liquid derivatives	Power-to-Liquids or liquid derivatives are all hydrogen-based derivatives produced via Fischer-Tropsch synthesis[4] or from methanol. They comprise e-kerosene, e-diesel and e-gasoline.
Renewable hydrogen	Hydrogen produced via electrolysis using renewable (mainly wind and photovoltaic, or hydropower)-based electricity.
Renewable hydrogen derivatives	Comprises all products and fuels produced with renewable hydrogen including e-ammonia, e-methanol, e-liquids (also called liquid derivatives), e-gases.

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[1] (European Commission, June 2022).

[2] (European Environment Agency, 2001).

[3] (European Environment Agency, n.d.).

[4] The Fischer-Tropsch process is a catalytic chemical reaction in which carbon monoxide (CO) and hydrogen (H2) in the syngas are converted into hydrocarbons of various molecular weights, see also (National Energy Technology Laboratory, 2017).

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EXECUTIVE SUMMARY

Key findings

- Sustainable fuels will be suitable for different transport modes and transport applications, depending on their technical specifications, their sustainability characteristics including **feedstock availability**, their **cost-competitiveness** and their **technology readiness**.
- Given the global limitation of resources, the shift to sustainable fuels should be first driven by a significant increase in **energy efficiency**.
- **Liquid and gaseous sustainable fuels** should be primarily dedicated to transport sub-sectors that cannot be easily electrified, i.e. aviation, shipping, and – possibly – part of heavy-duty road transport. **Direct electrification** from renewable sources is considered as a key option to decarbonise road transport and short-haul shipping. This is not exempt from challenges, e.g. sourcing of raw materials and battery end-of-life treatment.
- **Biofuels** are cheaper than renewable e-liquids, but they face availability limitations exacerbated by competing demand in the bioeconomy and sustainability constraints with respect to land use.
- **Renewable e-liquids** could be among the most relevant options by 2050 if the carbon they use is sustainably sourced, thanks to the fact that they do not require changes to infrastructure or powertrains. Challenges remain with the high reliance on large-scale renewable electricity production, low energy efficiency, high production costs, and low technology readiness of some of their enabling technologies (such as direct air capture).
- **Renewable hydrogen** could technically be a viable fuel for heavy-duty road, short-range aircraft and shipping. Important challenges remain with the low energy density, costs required for infrastructure development and high-risk profiles of related investments.
- **E-ammonia and e-methanol** are cheaper than other e-liquids and are good candidates for maritime. The development of infrastructure needed for their transport, storage and distribution is cheaper than for hydrogen, but still subject to investment risks. Challenges remain with e-ammonia's safety issues and sourcing of renewable carbon for e-methanol.
- **Recycled Carbon Fuels** (RCFs) may contribute to GHG emission abatement in the near term. However, carbon sourcing from processes that still lead to net CO_2 increases will become a limiting factor for RCFs, along with competition from carbon capture.
- **Supporting infrastructure** needed for sustainable fuel take-up is fuel-specific. It requires reinforcing the electricity system, developing a hydrogen network, and adapting the existing oil and liquid infrastructure to accommodate a higher share of biofuels.
- **Existing policies and the set of policy proposals in 'Fit for 55'** tackle most of the barriers to accelerate the shift to sustainable fuels, the deployment of the required infrastructure and the changes in vehicle powertrain technologies.
- The EU's policy to support sustainable fuels shall seek to further **enhance technological development, foster industrial transformation, and strengthen re-distributional measures without compromising sustainability**.

The global context for sustainable fuels in transport

Sustainable fuels, combined with reductions in energy demand, can **significantly reduce GHG emissions whilst not jeopardising other sustainability requirements** regarding biodiversity, water resources, air quality, land use, and material sourcing. The study focuses mainly on the following sustainable fuels: **biofuels** (from oleochemical, biochemical and thermochemical pathways),

renewable fuels of non-biological origin (RFNBO, including renewable hydrogen, and different e-fuels), **recycled carbon fuels** (RCFs), **fossil and nuclear-based hydrogen,** pursuant to the Taxonomy Regulation. A key alternative to liquid or gaseous transport fuels is **direct electrification**. This is not assessed in detail in this research, but it is still included, given its relevance as a key option for the transition to clean energy and sustainable mobility, especially for road, rail and short-distance shipping, and the implications that it has on the determination of the overall boundary of demand for other fuels.

This study assesses the potential of sustainable fuels to decarbonise the transport sector in the EU and analyses the viability of sustainable fuels and energy vectors for transport against multiple factors: sustainability, scalability, energy efficiency, energy density, feedstock and material availability, cost, technology, market readiness and safety.

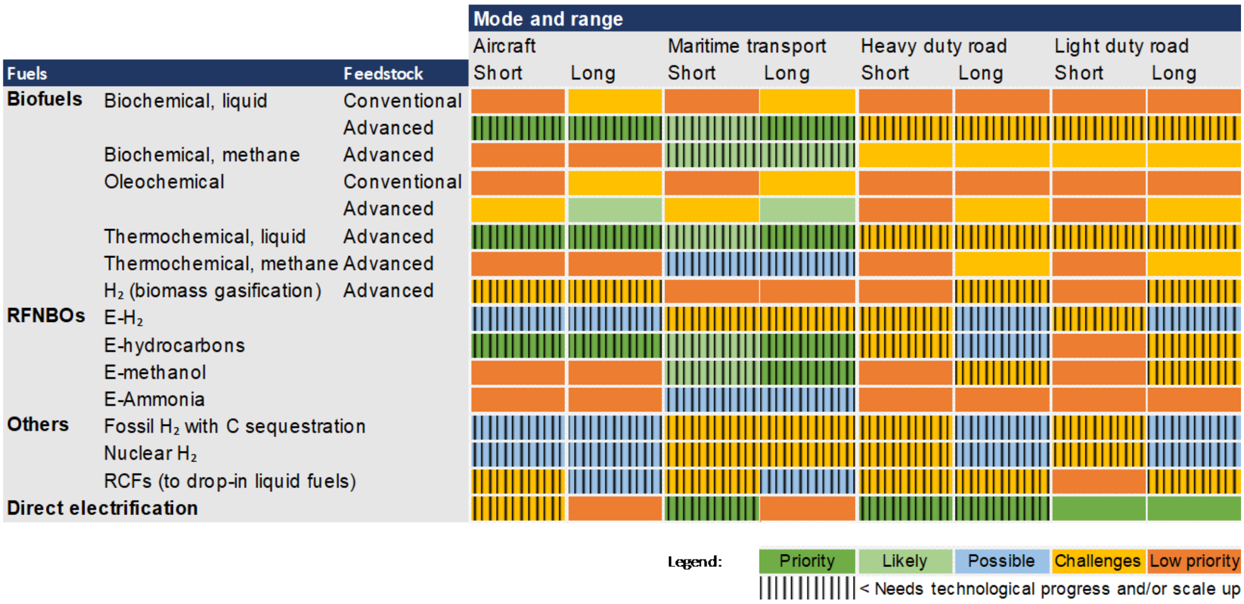
Sustainable fuels and decarbonisation in the different transport modes

Most of the transport decarbonisation scenarios examined in this study that are compatible with the Paris Agreement **combine technical energy efficiency improvements and reduced demand for motorised activity with fuel shifts.** As well as reducing GHG emissions, they target decreased pollution, noise and congestion levels, and increased safety.

Decreasing fuel consumption is crucial to afford a long-term supply, given the resource constraints to sustainably produce all fuels. Direct electrification generally plays a large role in the energy efficiency gains of the transport sector, **especially in the road sector**.

The table below illustrates the qualitative evaluation of all fuels and their link with the main transport end-use applications. It is based on the assessments presented along this study, providing insights on which fuel is best suited for which application.

Table ES1 - Match making between fuels and transport modes – Summary of all factors



			Mode and range							
			Aircraft		Maritime transport		Heavy duty road		Light duty road	
Fuels		**Feedstock**	Short	Long	Short	Long	Short	Long	Short	Long
Biofuels	Biochemical, liquid	Conventional	Low priority	Challenges	Low priority	Challenges	Low priority	Low priority	Low priority	Low priority
		Advanced	Priority |||||	Priority |||||	Likely |||||	Priority |||||	Challenges |||||	Challenges |||||	Challenges |||||	Challenges |||||
	Biochemical, methane	Advanced	Low priority	Low priority	Likely |||||	Likely |||||	Challenges	Challenges	Challenges	Challenges
	Oleochemical	Conventional	Low priority	Challenges	Low priority	Challenges	Low priority	Low priority	Low priority	Low priority
		Advanced	Challenges	Likely	Challenges	Likely	Low priority	Challenges	Low priority	Challenges
	Thermochemical, liquid	Advanced	Priority |||||	Priority |||||	Likely |||||	Priority |||||	Challenges |||||	Challenges |||||	Challenges |||||	Challenges |||||
	Thermochemical, methane	Advanced	Low priority	Low priority	Possible |||||	Possible |||||	Low priority	Challenges	Low priority	Challenges
	H_2 (biomass gasification)	Advanced	Challenges |||||	Challenges |||||	Low priority	Low priority	Low priority	Challenges |||||	Low priority	Challenges |||||
RFNBOs	E-H_2		Possible |||||	Possible |||||	Challenges |||||	Challenges |||||	Challenges |||||	Possible |||||	Challenges |||||	Possible |||||
	E-hydrocarbons		Priority |||||	Priority |||||	Likely |||||	Priority |||||	Challenges |||||	Possible |||||	Low priority	Challenges |||||
	E-methanol		Low priority	Low priority	Likely |||||	Priority |||||	Low priority	Challenges |||||	Low priority	Challenges |||||
	E-Ammonia		Low priority	Low priority	Possible |||||	Possible |||||	Low priority	Low priority	Low priority	Low priority
Others	Fossil H_2 with C sequestration		Possible |||||	Possible |||||	Challenges |||||	Challenges |||||	Challenges |||||	Possible |||||	Challenges |||||	Possible |||||
	Nuclear H_2		Possible |||||	Possible |||||	Challenges |||||	Challenges |||||	Challenges |||||	Possible |||||	Challenges |||||	Possible |||||
	RCFs (to drop-in liquid fuels)		Challenges |||||	Possible |||||	Challenges |||||	Possible |||||	Challenges |||||	Challenges |||||	Low priority	Challenges |||||
Direct electrification			Challenges |||||	Low priority	Priority |||||	Low priority	Priority |||||	Priority |||||	Priority	Priority

Legend: Priority Likely Possible Challenges Low priority

||||||||||| < Needs technological progress and/or scale up

Source: author elaboration developed for this analysis.

Investment needs and financial implications

Despite a projected reduction in absolute energy demand in the transport sector by 2050 in the EU in a Paris Agreement-compliant scenario, **annual expenditures in energy production for the transport**

sector could amount to around the same amount as in 2022 by that time. By 2050, these **expenditures are expected to cover e-liquids, electricity, biofuels and hydrogen production**. They account for higher costs of sustainable fuels compared to fossil fuels, even though improvement in technology and learning curves will reduce their costs towards 2050.

Investments in **renewable electricity generation are one of the most important underlying elements** in this transition, both for direct electrification and the production of RFNBOs.

Additional **investments in infrastructure deployment and adaptation, as well as investments in vehicles and new powertrains**, are inevitable, regardless of the mix of alternative solutions deployed. These expenditures can be minimised or optimised with smart choices, e.g. sharing infrastructure with other energy end-uses.

It is expected that large-scale infrastructure and alternative powertrain investments associated with the use of **hydrogen** as a fuel would be far higher than the reuse and repurpose of existing assets for biofuels and e-liquids or the reinforcement of the existing electricity network for direct electrification. **Hydrogen valleys and clusters,** centred on industry, will play a crucial role for renewable hydrogen. These can minimise infrastructure costs while leveraging lower production costs compared to e-fuels. Synergies with maritime transport in port cities are likely to be among the most relevant in transport.

Capital, primarily for technology improvements and infrastructure development, needs to be **mobilised in a timely manner by all stakeholders** both from the public and private sectors. Sustainable fuel production scale-up and the adaptation and deployment of associated infrastructure should go hand-in-hand, with decisions being taken on the match-making between fuels and their applications.

Policy priorities

The Fit for 55 policy proposals are among the most comprehensive ever developed globally. They have the potential to take the EU one step further to **accelerating real-world technology deployment**.

It is recommended that in their final adoption, the level of ambition be at least maintained, if not increased.

This analysis results in several policy recommendations to address remaining gaps and weaknesses:

- Exploring further the recommended pathways for developing and deploying sustainable fuels and matching the different end-use applications.
- Increasing the share of RFNBOs in 2050 for the maritime and aviation sectors, and having large pleasure/luxury boats and private jets spearhead the efforts.
- Ensuring that hydrogen and RFNBOs or RCFs needing large amounts of electricity for their production are subject to additionality requirements when production is scaled up.
- Establishing clear pricing signals via the Emissions Trading System (ETS) and the Energy Taxation Directive (ETD) to remove biases in the fiscal treatment applied to fossil fuels subject to low tax rates, for both domestic and international aviation and maritime transport.
- Complementing carbon pricing with mechanisms supporting innovation and re-distributional measures (to address energy poverty).
- Mobilising research, design and innovation (RD&I) spending on key enabling technologies for a transition of transport to sustainable energy and fuels (e.g. batteries, water electrolysis, Direct Air Capture, electrochemical reduction of CO_2).

- Supporting pilot and demonstration projects to speed up identification of the most suitable sustainable fuels for specific applications, (e.g. methanol, ammonia or e-hydrocarbons for long-distance shipping).
- RD&I agendas should remain open to a possible phase-in of hydrogen use in heavy-duty road, or even in maritime and aviation.

1. INTRODUCTION

1.1. Background to the study

This report presents the results of the research study commissioned by the European Parliament Committee on Transport and Tourism (TRAN) on the "Assessment of the potential of sustainable fuels in transport".

The aim of the study was to assess the potential of sustainable fuels, in particular biofuels, to decarbonise the transport sector and help the sector achieve the Green Deal's GHG emissions reduction targets by 2030 and 2050 and the 90% reduction in transport emissions by 2050. The research assessed the potential of sustainable fuels in transport, in particular in the following transport modes: aviation, maritime and road transport.

Some attention is given here to measures to reduce GHG emissions by 2030 (e.g. the 'Fit for 55' proposals) and these were also covered in an earlier Rapid Response Report (Trinomics, 2022). However, the main focus of this report is on the 2050 time horizon and the energy mix across transport sectors needed to achieve net-zero emissions by that date.

The transport sector is responsible for 24% of global direct energy-related CO_2 emissions (International Energy Agency, 2022), around 1% more when also accounting for emissions on a well-to-wheel basis, and even more when taking into account vehicle manufacturing and infrastructure construction. According to data preceding the Covid-19 pandemic, this share is 27% in the European Union if international aviation and maritime transport (bunkers) are included (22% if they are excluded) (European Environment Agency, 2020). The transport sector also remains directly dependent on oil for 91% of its energy end-use (International Energy Agency, 2022).

1.2. Approach and methodology

The study was based on a combination of desk review and stakeholder engagement. This enabled using the latest available research and analysis from the literature as well as input from the most relevant stakeholders who provided their on-the-ground expert views and perceptions of the possibilities and challenges ahead for sustainable transport.

The **literature** reviewed for this report included academic papers, industry papers and studies, and position papers produced by advocacy groups and NGOs. To avoid out-of-date information, research focused on evidence published since 2016. Literature focused on EU countries was prioritised, except for a review of best practices in third countries.

To gather complementary, on-the-ground information by engaging external experts and stakeholders, a **workshop** was held in July 2022 with participants from international organisations, businesses and NGOs. Presentations on key topics were made, including an initial draft of the fuels versus application matrix, followed by a discussion with participants to collect different points of view.

1.3. Overview of the study

Solutions for transport decarbonisation should ideally balance cost, energy, resource availability and resource efficiency. In transport, the identification of optimal solutions varies by mode, vehicle, and mission/usage profile of the vehicles. It also varies by geography, given the difference in availability of primary materials such as biomass and/or minerals, and availability of energy (e.g. because of differences in terms of endowment in solar and/or wind energy to produce electricity).

Solutions need to account for risks related to disruptive changes to existing assets. It is better for economic competitiveness and social stability if existing assets can continue to be used cost-effectively. At the same time, a sole focus on the protection of existing assets could hamper development, growth and export opportunities, leading to other forms of negative impacts misaligned with the growth and resilience objectives of the overarching EU policy.

This study gave priority to the options contemplated in the list of fuels in the recast of the Renewable Energy Directive (RED) and the proposal to update it, as included in the 'Fit for 55' package. These include (European Commission, 2018; European Commission, 2021):

i. **Biofuels** from 'conventional', and 'advanced and waste-based biofuels' (i.e. biofuels that are produced from advanced and waste feedstocks: Part A and Part B of the RED Annex IX), including oleochemical, biochemical and thermochemical pathways;
ii. **Renewable fuels of non-biological origin** (RFNBOs), i.e. liquid and gaseous fuels whose energy content is derived from renewable sources other than biomass, e.g. renewable-based hydrogen and its derivatives; and
iii. **Recycled carbon fuels** (RCFs), i.e. liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin, are not suitable for material recovery, or are produced as an unavoidable and unintentional consequence of industrial production.

The report is structured as follows:

- Chapter 2 reviews the characteristics of these three categories of sustainable transport fuels: biofuels, renewable fuels of non-biological origin, recycled carbon fuels, along with other fossil-based fuels;
- Chapter 3 reviews four groups of scenarios from the literature that have the long-term goal of reaching the 1.5°C Paris Agreement commitment. It reflects on the viability of different sustainable fuels for each transport mode;
- Chapter 4 presents which fuels are the most appropriate for the different transport modes and applications (e.g. long vs short haul). It provides an overview and assessment of the potential of existing and most promising technologies to develop the use of sustainable fuels in each mode;
- Chapter 5 discusses finance and investment needs based on cost assessments, resource availability, energy demand projections, technology learning and fossil energy price scenarios. It analyses the financial investments needed to develop and promote the use of sustainable fuels in aviation, maritime and road transport in the EU;
- Chapter 6 assesses whether the existing EU regulatory framework is conducive to developing and using the existing and most promising sustainable fuels, and considers the barriers to the uptake of the fuels;
- Chapter 7 proposes a set of clear and practicable policy recommendations for EU policymakers on what could support the development and use of sustainable fuels to contribute to European Green Deal Objectives.

2. OVERVIEW OF THE DIFFERENT TRANSPORT FUELS

Key findings

- Direct electrification from renewable electricity has the best energy performance and sustainability score compared to the other fuels. It should be promoted whenever technically feasible, while considering the potential constraints on raw materials for batteries.
- **Biofuels** are cheaper than renewable e-liquids, but face availability limitations exacerbated by competing demand in the bioeconomy and sustainability constraints with respect to land use. It will be important to clearly define what can make them viable and to supplement them with other sustainable fuels. Food- and feedstock-based biofuels have a lower sustainability performance than advanced bio-based fuels.
- **Renewable hydrogen** (synthesised from electrolysis and direct CO_2 air capture) is cheaper and more energy efficient to produce than other RFNBOs. However, it faces significant technical challenges to be transported, stored, distributed and used as a transportation fuel.
- **Renewable e-liquids** have fewer issues with sustainability constraints compared with biofuels, but they are subject to cost, technology readiness, and energy efficiency challenges. They need to be produced with very low life-cycle emissions in the long term and with expensive direct capture of carbon from the air. The prospects for cost reductions and good sustainability performance make e-liquids a promising option to decarbonise aviation and maritime transport in 2050. Power and biomass-to-liquid fuels are e-liquids that use by-product CO_2 emissions from biofuel synthesis as a source of carbon, which is one of the opportunities to overcome the challenges of direct air capture.
- **Renewable e-methanol and e-ammonia** have lower production costs than e-liquids and lower investment risks for the development of new fuel distribution infrastructures, in comparison with hydrogen. Challenges remain with e-ammonia safety issues and sourcing of renewable carbon for e-methanol.
- **Recycled Carbon Fuels** may contribute to significant GHG emission abatement in the near term, but in most transport modes, they are only bound to lead to partial long-term decarbonisation.

2.1. Introduction

This chapter gives a summary of the characteristics of sustainable fuels, including a short description, the identification of the main applications for their use, along with a set of criteria that define their sustainability. These criteria include life-cycle GHG emissions, land use and land use change risks, energy efficiency, primary energy needs and water requirements. The analysis also includes information on costs, supply availability, infrastructure needs and concludes with considerations on the scalability of all of these fuel options.

Fuels covered include:

- Biofuels, including oleochemical, biochemical and thermochemical pathways;
- Renewable fuels of non-biological origin (RFNBO): hydrogen, synthetic hydrocarbons, including liquid and gaseous e-fuels, and e-ammonia[5]. RFNBOs are also compared to fossil fuel-based hydrogen;
- Recycled carbon fuels (RCFs).

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[5] Options using nuclear rather than renewable electricity for their production are also briefly discussed in the RFNBOs section.

Direct electrification is not the focus of this study, but the role and scale of transport electrification are touched upon, given the large impact it may have on the role of liquid and gaseous sustainable fuels. Additional details underpinning this analysis are provided in Annex A (Annexes A.1.1 to A.8.7), including the main applications for their use, life-cycle GHG emissions, land use and land use change risks, energy efficiency and primary energy needs, water requirements, information on costs, supply availability, infrastructure needs, and scalability of all these fuel options.

2.2. Biofuels

Biofuels can be fully or partially blended with petroleum-based fuels using, to a certain extent, existing fuel distribution infrastructure. Biofuels can be produced through three main pathways - biochemical, oleochemical/lipid and thermochemical production pathways. The following sections summarise these three options.

Biochemical pathways include the production of ethanol and alcohol-to-jet fuels from sugar bearing crops (namely sugar cane), crops producing grains that yield starch, lignocellulosic crops and waste materials. They include conventional conversion processes for the conversion of sugars and starches, and advanced processes for the conversion of lignocellulosic and waste products.

Oleochemical and lipid pathways include converting oil-bearing crops and waste products such as soybean and used cooking oil to fatty acid methyl esters (FAME biodiesel) or treating them with hydrogen to obtain high quality fuels that can be blended with diesel (hydrotreated vegetable oil, HVO) or jet fuel (hydroprocessed esters and fatty acids (HEFA)). These are considered diesel-like fuels.

Thermochemical pathways include the production of gasoline-, diesel-, or jet-like fuels from lignocellulosic crops and waste materials through chemical conversions reliant on high-temperature processes.

2.2.1. Biochemical pathways

Short description (technology, market readiness)

Biofuel production through biochemical conversion processes[6] primarily relates to the fermentation of sugars into short-chain alcohols such as ethanol for conventional or 'first generation' biofuel production. Sugars are usually from sugar crops (e.g. sugar cane) or derived from starches (e.g. from corn). Advanced processes, namely enzymatic hydrolysis, expand the scope of short-chain alcohol production to lignocellulosic biomass as a primary feedstock. This is also considered an advanced biofuel, as it is not competing directly for land use with food, but its sustainability profile still depends on the way its primary feedstock (woody biomass) is collected.

The feedstock used can be summarised as follows.

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[6] Pathways are a broader concept than processes and can include different processes and feedstocks.

Table 2-1 Feedstock for biochemical pathways

Feedstock	Type	Pathway or Process
Sugar cane	Conventional or first generation	Processing of feedstock for removal of sugar, followed by fermentation
Corn starches, cereals	Conventional or first generation	Cleaning and milling of feedstock, enzymatic conversion of starch into sugar, followed by fermentation
Lignocellulosic (e.g. forestry and agricultural residues, or energy crops)	Advanced feedstock	Pre-treatment and enzymatic hydrolysis, followed by fermentation

Ethanol is a key output of biochemical biofuel production pathways. It can take a hydrous or an anhydrous form. The hydrous form contains water and can only be used in vehicles specifically adapted to it. Such vehicles are called flex-fuel vehicles, and they still require a substantive share (more than 20% by volume) of anhydrous ethanol to allow blending ethanol with gasoline, to avoid water separation in the fuel tank. Hydrous ethanol is currently only used in Brazil, where it is produced from sugar cane, and where anhydrous ethanol (also mainly from sugar cane) is also produced at scale (Horta Nogueira et al., 2020, OECD/FAO, 2021). Anhydrous ethanol is also produced in the United States, mainly from corn, and in Europe, largely from food and feed crops, mainly cereals and sugar beet (OECD/FAO, 2021)[7]. More advanced technologies based on cellulosic feedstock, such as crop residues, dedicated energy crops, or wood, do not make up large shares of total biofuel production (OECD/FAO, 2021).

Biomethane is also a possible output of other biochemical pathways for the production of biofuels. The key biochemical process leading to biogas production is anaerobic digestion, where microorganisms break down biogenic material in the absence of oxygen, forming methane and other gases. However, biomethane in transport is hampered by competing demand in sectors where it shall replace fossil methane and other challenges (Trinomics, 2022). This is especially the case in the near term, following the war in Ukraine. For these reasons, biomethane is only discussed further as a biochemical biofuel in Annex A[8].

Characteristics summary

The main product from biochemical pathways is bioethanol. This can be upgraded into alcohol-to-jet fuel, suitable for the aviation sector. Currently, the main application[9] for bioethanol is as gasoline blend in light road vehicles. Above a certain blending rate (10% by volume) or for independent use, it requires engine adaptations (flex fuel vehicles). Alcohol to jet fuels are suitable as drop-in substitutes of petroleum-based jet kerosene in aviation.

The life-cycle GHG emissions of ethanol and alcohol to jet fuels can vary greatly, depending on the feedstock and the location. In general, biochemical processes have lower life-cycle emissions of GHG than fossil-based benchmarks. Across biochemical pathways, corn-based biofuels have significantly

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[7] Ethanol can also be used as a feedstock to make ethyl tertiary butyl ether (ETBE), a fuel additive used in gasoline.

[8] See Annexes A.1.1, A.1.2, A.1.3, A.1.6, A.1.7, A.1.8.

[9] For further information on applications of biofuels from biochemical pathways, see Annex A.1.1.

higher life-cycle GHG emissions than sugar cane ethanol and advanced biochemical pathways based on lignocellulosic feedstock. Process improvements such as the sourcing of heat from low-carbon electricity can reduce life-cycle GHG emissions. Indirect land use change emissions are generally estimated to be lower for lignocellulosic pathways if they rely on residues or energy crops grown in land areas that are not rich in soil carbon. They are significant, though, if energy crops compete directly for high quality land with conventional crops, as this can induce the displacement of land with high carbon stocks.

All biochemical pathways leading to ethanol are also characterised by higher primary energy needs per MJ of fuel with respect to the 1.1 to 1.3 MJ/MJ range of fossil benchmarks, once the energy content of the feedstocks is also accounted (ANL, 2022a and ANL, 2022b). Costs are primarily dependent on the cost of feedstock and on the cost of the technical conversion process. The costs are generally similar to oleochemical pathways (see Section 2.1.2) for conventional processes, and higher for advanced processes which have lower technology readiness, which is one of the factors that limits production at scale.

There is a possibility of using existing gasoline infrastructure to a certain extent, with likely upgrades needed to accommodate the physical characteristics of bioethanol, such as water affinity and solvent behaviour. Infrastructure costs are bound to increase as the blending rates increase, leading to deeper equipment replacement or upgrade requirements (including of vehicles or engines) in cases of 100% bioethanol use (no blend). The need for new or repurposed infrastructure should also consider the need to minimise the risks of asset stranding, which is far from irrelevant if life-cycle emissions of the fuels cannot be brought to very low levels.

Policy action has led to the historic growth in bioethanol production and use. Sustainability issues related to life-cycle GHG emissions, land use change, water requirements, and impacts on food prices are occurring with large-scale production, especially with food and feed-based pathways converting starch into fuels. Their production to date has been shown to induce a complex set of market dynamics such as increases in food prices, cropland expansion that induces deforestation, increases in fertiliser use, and water quality degradation. Combined with challenges from a looming food crisis following the invasion of Ukraine, this limits the scope for their rapid expansion, especially in the near term. The future scale-up of bioethanol production is to be primarily based on advanced feedstock, accompanied by more stringent sustainability requirements. Opening up the possibility of food- and feed-based pathways to be part of a sustainable scale-up of these fuels requires profound advances in policy, technology, and agricultural practices. Power and biomass-to-liquids (PBtL) are fuels made from biomass and hydrogen derived from renewable electricity. PBtL fuels are an option to improve sustainability, as they allow the increase of biofuel yields per unit of land used.

Table 2-2 Technology, market and sustainability analysis summary: biofuels via biochemical pathways (own elaboration, based on in-depth analysis developed in Annex A)

Feedstock	**Corn Starches, Cereals**	**Sugar Cane**	**Lignocellulosic (e.g. Forestry and Agricultural Residues, or Energy Crops)**
Life-cycle GHG emissions (Annex A.1.2)	🟥	🟨	🟩
Land use and land use change risk (Annex A.1.3)	🟥	🟥	🟨
Primary energy needs (energy efficiency of production) (Annex A.1.4)	🟩	🟨	🟥
Water requirements (Annex A.1.5)	🟥	🟩	🟩
Cost (Annex A.1.6)	🟨	🟨	🟥
Infrastructure requirements (for 100% use) (Annex A.1.7)	🟨	🟨	🟨
Infrastructure (for use as blend) (Annex A.1.7)	🟩	🟩	🟩
Scalability (Annex A.1.8)	🟥	🟥	🟨

Legend: Green - high score for the sustainability area (low-risk/impact). Red - low score for the sustainability area (high-risk/impact). Yellow - intermediate. Comparison is across fuels.

Notes: for sugar cane, the energy efficiency of production (in yellow) can be improved (i.e. primary energy needs can be reduced) with process improvements, especially if using bagasse for cellulosic production and switching to solar energy for heat. For all feedstocks, water requirements are dependent on region-specific rainfall levels.

2.2.2. Oleochemical and lipid pathways

Short description (technology, market readiness)

Biofuel production through oleochemical and lipid pathways converts lipid feedstocks such as vegetable oils, animal fat, or used cooking oil into fuels that have characteristics similar to diesel products through processes of transesterification or hydrogenation.

Transesterification is a chemical process that reacts oil or fat with methanol and leads to a compound, fatty acid methyl ester (**FAME biodiesel**), that can be used in compression ignition engines. It does not have the same specifications as petroleum diesel (IEA, 2004), and it is therefore most commonly used as a low-volume blend. This is typically 7% in Europe due to regulatory requirements (ePURE, 2020), or up to 20% in the United States (US DOE, n.d.). Pure FAME biodiesel is typically used as a blend-stock to produce lower blends and is rarely used as a transport fuel (US DOE, n.d.).

Hydrogenation (or hydrotreatment) is a chemical process involving molecular hydrogen that enables the production of paraffinic fuels, fully compatible with diesel and jet fuel, and possibly also compatible with fuels used in maritime transport. Production is often integrated into refining facilities due to the availability of hydrogen on site and can be applied to feedstocks such as vegetable oil, fat, or waste oils[10]. **The end-product, hydroprocessed esters and fatty acids (HEFA), is currently the main drop-in sustainable fuel in aviation** (IEA Bioenergy, 2019). **This is similar to hydrotreated vegetable oil (HVO), often referred to as "renewable diesel",** which can also be used as a drop-in fuel for diesel, and is co-produced with HEFA[11].

Characteristics summary

Both processes are technologically mature and can make use of all the above-mentioned feedstock.

These products are best suited for vehicle categories that are largely reliant on diesel fuels: heavy-duty road vehicles, aircraft and ships. The products are also technically suitable for diesel cars.

The feedstock-to-fuel processing energy requirements are generally low across all oleochemical pathways. Oleochemical biofuels allow a reduction in life-cycle GHG emissions in comparison with the fossil equivalent, without however offering the potential for a zero- or near-zero-emission solution. Land use requirements for oleochemical pathways based on crops are the result of the combined effect of biomass yields and process conversion. Due to high land use requirements, emissions due to indirect land use change can be very significant for oleochemical biofuels, especially in cases where expansion of cropland leads to deforestation (as occurred in countries like Indonesia for the production of palm oil).

The costs of biofuel production through oleochemical and lipid pathways are primarily dependent on the cost of feedstock. Given the technology maturity, there are little prospects for significant cost reductions in the future. Competitiveness with fossil-based alternatives can be achieved with efficient waste oils supply chains, or in cases where fossil fuel prices increase.

With FAME, there is the possibility to use existing diesel infrastructure to a certain extent, but due to its physical characteristics, infrastructure upgrades are likely needed. In the case of 100% FAME use (no blend), full infrastructure replacement may be necessary. For HVO/HEFA, there is full compatibility with existing petroleum diesel and jet fuel infrastructure and engines. However, HEFA is currently approved only for 50% or 10% blends. The need for new or repurposed infrastructure should consider the need to minimise the risks of asset stranding. Also, in this case, this is far from irrelevant if life-cycle emissions of the fuels cannot be brought to very low levels.

Growth in biodiesel and renewable diesel production has historically been driven by policy action. Sustainability issues are primarily linked to direct and indirect land use change. The supply of waste feedstock (namely used cooking oil) is inherently limited and constrained by waste stream volumes.

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[10] Suitable feedstocks include fats, oils, and greases from oilseed crops or algae (Holladay, Abdullah and Heyne, 2020).

[11] For further information on applications of biofuels from oleochemical and lipid pathways, see Annex A.2.1.

Table 2-3 Technology, market and sustainability analysis summary: biofuels via oleochemical and lipid pathways (own elaboration, based on in-depth analysis developed in Annex A)

Feedstock	Conventional (Virgin Vegetable Oils)	Advanced (Waste and By-Products)
Life-cycle GHG emissions (Annex A.2.2)	🟥	🟩
Land use and land use change risk (Annex A.2.3)	🟥	🟥
Primary energy needs (energy efficiency of production) (Annex A.2.4)	🟩	🟩
Water requirements (Annex A.2.5)	🟨	🟩
Cost (Annex A.2.6)	🟨	🟨
Infrastructure requirements (for 100% use) (Annex A.2.7)	🟨	🟨
Infrastructure (for use as blend) (Annex A.2.7)	🟩	🟩
Scalability (Annex A.2.8)	🟥	🟥

Legend: Green - high score for the sustainability area (low-risk/impact). Red - low score for the sustainability area (high-risk/impact). Yellow - intermediate. The comparison is across feedstocks.

Notes: for land-use and land-use change, all feedstock is at risk of inducing land use change, especially if production occurs at large scale, and even if risks are somewhat lower for waste products. Large-scale palm oil production in particular has seen very detrimental low indirect land-use change effects on life-cycle emissions.

2.2.3. Thermochemical pathways

Short description (technology, market readiness)

Thermochemical pathways largely consist of the conversion of lignocellulosic feedstock to bio-based intermediates, followed by their conversion into fuels. The suitability of these fuels for various applications is discussed in Annex A.3.1. Feedstocks include wood, energy crops, solid waste containing biogenic material, and residues from agriculture and forestry.

Three main conversion families characterise these thermochemical pathways: pyrolysis[12], hydro-thermal liquefaction, and gasification. The product is liquid (bio-oil/biocrude[13]) for the first two pathways, and synthetic gases (syngas) for the third. Both bio-oil and syngas need further processing

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[12] This is the thermal decomposition of materials at elevated temperatures in an inert atmosphere.

[13] Bio-oil is a dark brown liquid with a similar physical appearance to crude oil but is chemically distinct. It has a lower hydrogen/carbon (H/C) ratio and contains a significant fraction of oxygen. These properties give it low chemical stability and a lower energy density (less than 50%) than crude oil. Bio-oils also contain water, with concentrations that vary depending on the moisture content of the biomass feedstock and the production process. Bio-oils are obtained as the result of the thermal decomposition of biomass (via pyrolysis or hydrothermal liquefaction) through exposure at temperatures ranging between 200 and 500°C, eventually combined with catalytic cracking with the aim to reduce oxygen content.

to yield fuels suitable for transport vehicles. These processes typically require the addition of hydrogen[14].

Processes converting biomass through thermochemical pathways into fuels, especially in processes involving syngas, are generally called "biomass-to-liquids" (BtL).

Thermochemical pathways offer the possibility of widening the range of biomass feedstocks that refineries and other biofuel plants can use to produce fuels beyond lipids, but they are currently still at a low technology readiness level (IEA Bioenergy, 2019). The broader spectrum of primary biomass is an important advantage. It can produce better fuel yields per hectare and have a good capacity to abate life-cycle GHG emissions, but it also comes with higher energy requirements for feedstock conversion. Therefore, it is generally accompanied by higher conversion costs.

Biomethane (also referred to as renewable natural gas) can also be produced as a result of thermochemical processes, consisting of thermal gasification of solid biomass followed by methanation and cleaning (IEA, 2020). However, as mentioned in the case of biochemical pathways (Section 2.1.1), the case of biomethane in transport is hampered by competing demands in sectors intended to replace fossil methane, not including transport, and other challenges. Therefore, biomethane is only further discussed as a biochemical biofuel in Annexes A.1.1 to A.1.3 and A.1.6 to A.1.8.

Characteristics summary

The main products from thermochemical pathways are:

- Bio-oil/biocrude (from pyrolysis or hydro-thermal liquefaction processes).
- Syngas (from gasification process).

Both are not yet produced at scale. The products need to be further processed into gasoline/diesel-like fuels, requiring the addition of hydrogen. The overall process is referred to as biomass-to-liquids (BtL). The feedstock are, for example, lignocellulosic products from wood, energy crops, municipal solid waste, agricultural and forestry residues.

After being processed, the fuels produced are technically suitable as drop-in fuels for a wide range of modes of transport: light-duty and heavy-duty road vehicles, aviation and maritime transport.

Thermochemical pathways are characterised by lower GHG emissions per MJ compared with petroleum-based fuels. However, they also have higher primary energy requirements per MJ of fuel (and therefore lower energy efficiency) and a greater reliance on biomass resources than starch-based biochemical biofuels or oleochemical pathways. Indirect land-use change effects are inherently low for waste-based pathways, while they depend on biomass yields, conversion efficiency, biomass input requirements, and substitution effects with alternative land uses for energy crops. Broadly, estimates for GHG emissions, energy requirement per MJ of fuel, and land-use change impacts for thermochemical biofuel pathways are similar to those developed for lignocellulosic and advanced biochemical biofuels.

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[14] Bio-oils require renewable or low-carbon hydrogen to be upgraded to transport fuels. The upgrading process can be integrated into refining facilities that can also have access to biomass feedstocks. Using renewable or low-carbon hydrogen can also ensure that the life-cycle GHG emissions of the fuels are low. In the case of syngas, the conversion into hydrocarbons takes place via a process known as Fischer-Tropsch (FT) synthesis. This has commercial applications globally in very large plants using fossil fuels (coal, natural gas) as primary feedstocks, but the scale suitable for biomass needs to be much smaller.

Their cost structure for thermochemical biofuels is characterised by high capital costs, with room for improvement through technology developments and scale. The high capital costs make the final fuel price less sensitive to feedstock prices, compared to other biofuels.

Biofuels from thermochemical pathways are fully compatible with existing petroleum, diesel, and jet fuel infrastructure and engines. This is similar to HVO/HEFA produced through oleochemical and lipid pathways (see Section 2.1.2). However, thermochemical pathways require more significant changes along the upstream value chain in the production, collection, and processing of the feedstock in comparison with petroleum fuels.

The use of advanced feedstock gives thermochemical pathways a better sustainability profile than conventional biofuel pathways, provided that the feedstock is waste- or residue-based. However, feedstock supply approaches need to be carefully considered to ensure that scalability and sustainability are compatible. This would entail, for example, avoiding options leading to the removal of soil carbon stocks and ensuring virtuous agricultural practices.

Table 2-4 Technology, market and sustainability analysis summary: biofuels via thermochemical pathways (own elaboration, based on in-depth analysis developed in Annex A)

Feedstock	Conventional (Ligncocellulosic Biomass)	Advanced (Waste and By-Products)
Life-cycle GHG emissions (Annex A.3.2)	🟩	🟩
Land use and land use change risk (Annex A.3.3)	🟨	🟩
Primary energy needs (energy efficiency of production) (Annex A.3.2)	🟥	🟥
Water requirements (Annex A.3.4)	🟨	🟩
Cost (Annex A.3.5)	🟥	🟥
Infrastructure requirements (for 100% use) (Annex A.3.6)	🟨	🟨
Infrastructure requirements (for use as blend) (Annex A.3.6)	🟩	🟩
Scalability (Annex A.3.7)	🟥	🟨

Legend: Green - high score for the sustainability area (low-risk/impact). Red - low score for the sustainability area (high-risk/impact). Yellow - intermediate. The comparison is across fuels.

Notes: The life-cycle emissions of advanced (waste-based) feedstocks is highly dependent on the nature of the waste. The green shading refers to solid feedstocks with high shares of biogenic material.
Advanced (residue-based) feedstocks and/or biofuels produced from the pyrolysis process have relatively low water requirements (green), while other feedstocks and processes have intermediate water requirements (yellow).

2.3. Renewable fuels of non-biological origin (RFNBOs)

Renewable Fuels of Non-Biological Origin (RFNBOs) comprise hydrogen produced via electrolysis with renewable electricity, and all products and fuels derived from it, as long as other chemical elements that they contain (e.g. carbon, oxygen, nitrogen) are also not from biological origin.

The RFNBO categories covered here are:

- Molecular hydrogen (H_2, gaseous or liquid form) – the term is usually shortened into "hydrogen";
- E-hydrocarbons, including:
    - E-liquids:
        - Non-alcoholic liquid e-hydrocarbons such as **e-kerosene, e-diesel, e- gasoline,** primarily composed of hydrocarbon molecules C_nH_{2n+2} of different lengths determined by the number "n";
        - **E-methanol** (CH_3OH), and;
    - **E-methane** (e-CH_4) which is gaseous under ambient temperature and pressure conditions;
- **E-ammonia** (NH_3).

RFNBOs are chemically similar to their fossil counterparts.

2.3.1. Renewable hydrogen

Short description (technology, market readiness)

Hydrogen is a fuel of growing interest as it can be derived from a variety of primary energy sources and is an important chemical molecule already used in the production of fuels. Hydrogen is already produced at-scale for a range of industrial uses, mainly using fossil fuels, either by steam methane reforming (76%) or coal reforming (23%) (IEA, 2019).

In line with the Hydrogen Strategy for a climate-neutral Europe (COM/2020/301 final), "**renewable hydrogen**" (one of the RFNBO options) refers to hydrogen produced through the electrolysis of water, where the electrolyser is powered by renewable electricity.

While renewable hydrogen is the main focus of this section, comparative indications on other pathways thatproduce hydrogen are available in the annexes relevant to renewable hydrogen production[15], in particular in Annex A.4.2. These include conventional fossil-based hydrogen (from methane reforming), hydrogen derived from nuclear electricity, hydrogen derived from non-renewable grid electricity, and hydrogen derived from biomass. Fossil-based hydrogen pathways, including processes with lower life-cycle GHG emissions than conventional fossil-based hydrogen, are further discussed in Section 2.4.1.

Characteristics summary

In transport, hydrogen may be used directly as a fuel via an internal combustion engine or a fuel cell[16]. The combustion or its use in a fuel cell does not produce direct emissions of CO_2. It may also have a role in other sustainable fuel production for transport as an intermediate component in producing e-

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[15] Annexes A.4.1 to A.4.7.

[16] Hydrogen internal combustion engines and hydrogen fuel cells | Cummins Inc.

liquid/gaseous fuels (see Sections 2.3.2 on e-hydrocarbons and 2.3.3 on e-ammonia). Further details regarding its applications are available in Annex A.4.1.

Production pathways are crucial to assess life-cycle GHG emissions of hydrogen. Renewable hydrogen has a significant capacity to cut life-cycle GHG emissions with respect to conventional fossil-based hydrogen production pathways and hydrogen from electrolysis using grid electricity. Life-cycle GHG emissions for renewable hydrogen are also comparable with hydrogen from nuclear electricity and from biomass. Per MJ of fuel produced, land use requirements for renewable hydrogen production are far lower than for any crop-based biofuel (by a factor of 80 to 200, with details depending on crops and conversion efficiencies (KiM, 2022). Renewable hydrogen also comes with high primary energy requirements, comparable to those of fossil hydrogen and hydrogen from nuclear electricity (if this is accounted for as primary energy without thermal losses), lower than for hydrogen from biomass, and far lower than in cases where electricity is from the grid. **Because of the significant energy losses that occur during hydrogen transport, storage, and end-use, failing to rely on low-carbon forms of primary energy would quickly render hydrogen production counter-productive in terms of GHG emission reduction.**

The water requirements for renewable hydrogen production are 10 times higher than for petroleum fuels (gasoline and diesel fuel), and comparable with biofuel production from waste feedstocks (biochemical and thermochemical pathways). They are higher than for rainfed biofuel production and roughly a factor 10 smaller than for corn-based biofuels production in North America (which is reliant on significant irrigation requirements).

Production costs are primarily dependent on the cost of electrolysers and the availability of cheap renewable energy. Unit costs go down with the scale-up of production facilities and in regions with particularly high solar and wind electricity potential. Hydrogen liquefaction always increases costs. Significant costs also arise from imports, and for transport and distribution infrastructure via trucks or pipelines.

Renewable hydrogen needs dedicated supply infrastructure with a wide network if there is to be broad use in individual end-uses (e.g. personal vehicles, trucks). There is a trade-off between the proximity of production facilities to end-use locations, which leads to savings in infrastructure deployment costs, versus centralised, large-scale production facilities, which reduce production unit costs thanks to economies of scale but require extensive infrastructure for distribution to end-use locations.

Hydrogen as an RFNBO has a significant potential for scalability due to the large quantities of water available on the planet (including seawater) and the lack of competition for biomass resources. Its need for renewable electricity may however constrain its scale-up, in particular regarding other alternatives for transport such as direct electrification, for which renewable electricity generation may be used much more efficiently.

Table 2-5 Technology, market and sustainability analysis summary: renewable hydrogen from electrolysis (own elaboration, based on in-depth analysis developed in Annex A)

Fuel Product	Renewable Hydrogen
Life-cycle GHG emissions (Annex A.4.2)	🟩
Land use and land use change risk (Annex A.4.3)	🟩

Fuel Product	Renewable Hydrogen
Primary energy needs (energy efficiency of production) (Annex A.4.2)	🟨
Water requirements (Annex A.4.3)	🟩
Cost (production) (Annex A.4.5)	🟨
Cost (including infrastructure) (Annex A.4.5 and annex A.4.6)	🟥
Infrastructure (Annex A.4.6)	🟥
Scalability (Annex A.4.7)	🟨

Legend: Green - high score for the sustainability area (low-risk/impact). Red - low score for the sustainability area (high-risk/impact). Yellow - intermediate.

Notes: This table focuses on hydrogen as a RFNBO, i.e. produced via electrolysis from renewable electricity. In the case of hydrogen produced via electrolysis with non-zero-carbon electricity, its life-cycle GHG emissions would not be coloured in green.

Land use requirements are significantly lower for renewable hydrogen than for hydrogen from biomass. They are also primarily dependent on land use requirements for renewable power generation. Primary energy needs are comparable to hydrogen from fossil methane reforming and nuclear hydrogen, but only in cases where nuclear electricity, rather than heat, is considered a primary form of energy.

Water requirements, coloured in green, are comparable with current hydrogen production from fossil energy via steam methane reforming.

Production costs are not the only cost component to be considered for hydrogen use in transport since hydrogen (especially if produced in centralised facilities) needs to be stored and delivered to stations and vehicles. Adding these infrastructure costs significantly increases the cost of hydrogen delivered, unless there can be economies of scale from high hydrogen demand across different end-uses, especially in hydrogen industrial clusters. This is an unlikely development, given the greater competitiveness of direct electrification, not only in road transport but also in buildings and part of the industrial end-uses.

2.3.2. Renewable e-hydrocarbons (e-methane and liquid e-fuels including e-methanol)

Short description (technology, market readiness)

A range of synthetic hydrocarbon fuels and alcohols (including methanol) can be produced from the chemical combination of hydrogen and carbon. To fall within the scope of the fuels defined in the Renewable Energy Directive as renewable fuels of non-biological origin (RFNBO) (European Commission, 2018), they need to match the RFNBO definition. These are liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass. For further information about the main applications of these fuels, see Annex A.5.1.

The chemical processes for the synthesis of liquid e-hydrocarbons from hydrogen and carbon include methanation (to produce methane), methanol synthesis (to produce methanol) and the Fischer-Tropsch process (to produce e-fuels), as illustrated by Figure 2-1. All processes require hydrogen, which must be renewable to meet the RFNBO definition, and a source of carbon, typically integrated in a carbon monoxide building block. As carbon monoxide is not readily available, it needs to be produced from primary feedstocks, typically carbon dioxide (CO_2), through thermochemical or other conversions, including electrochemical reduction[17].

A Delegated Regulation proposed by the European Commission on the methodology for assessing GHG emissions savings from RFNBOs and recycled carbon fuels (RCFs, discussed in Section 2.3.2) used in transport (European Commission, 2023) suggests that, in principle, only carbon from the atmosphere collected via direct air capture (DAC) should be eligible for the synthesis of hydrocarbons as RFNBOs (European Commission, 2023). The same proposal indicates that credits should not be granted for capturing CO_2 which has already been accounted for under other provisions of law. This, in principle, excludes emissions from fuel combustion falling within the scope of the EU ETS and other regulated sectors.

Nevertheless, the Delegated Regulation proposal states that, in the near term, the origin of carbon used for the production of RFNBOs and RCFs is not relevant for determining emission savings of such fuels. This is due to the large number of concentrated sources of carbon, including in the form of gaseous CO_2. Due to lower energy requirements for the use of concentrated sources of CO_2, the proposal argues that their near-term capture is not expected to hinder the progress of decarbonisation. Pragmatically, the proposal suggests that capturing emissions from non-sustainable sources of carbon (such as fossil fuel combustion) should only be considered as avoiding emissions until 2040. This means that concentrated point source emissions of CO_2 covered by the EU ETS (and therefore including from fossil-based power generation) could fall within the scope of viable sources of carbon for RFNBOs until that date.

This temporary inclusion of concentrated point source recognises that GHG emission abatement can, at best, be halved between industrial facilities and fuels, which means point source emissions would not deliver emission cuts aligned with the 70% reduction included in the definition of sustainability requirements for RFNBOs and RCFs according to the recast of the Renewable Energy Directive (European Commission, 2018). The temporary inclusion also recognises the benefit of relying on concentrated sources that are still very abundant in the near term, enabling production of RFNBOs and RCFs at lower costs. This choice is comparable to the use of a multiplying factor for emerging technologies that could offer sizable long-term contributions to emissions reductions when the source of carbon is switched to DAC. Risks related to the choice to allow for point sources may arise from limitations for the optimal deployment of DAC in the same locations of the point sources (due to the need for a switch). However, analyses available today show that these are limited in Europe (Sendi et al., 2022).

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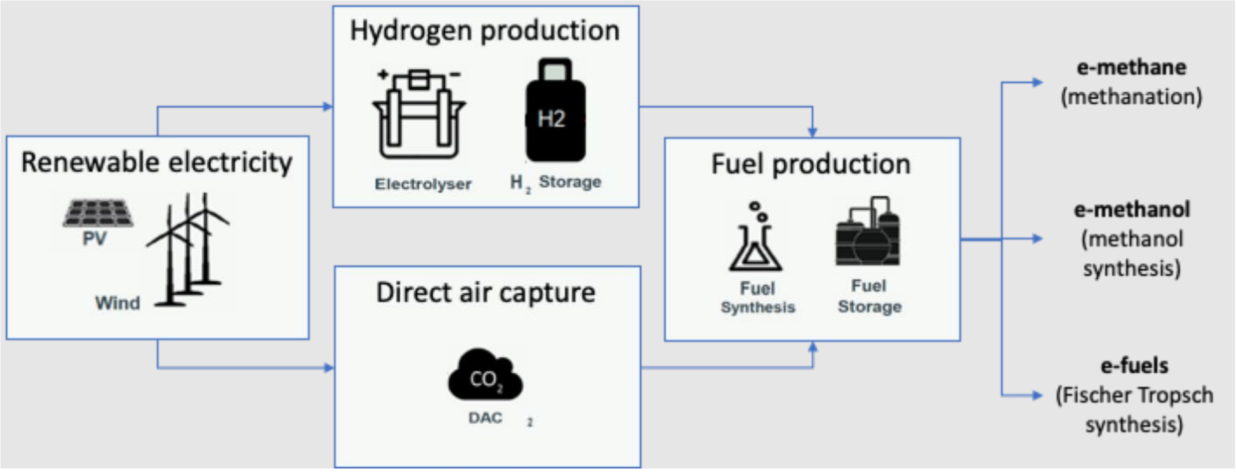
[17] CO_2 conversion to CO can be performed through biological, thermochemical, photochemical, and electrochemical means (Jouny et al., 2018). Electrochemical conversion of CO_2 can lead also to other hydrocarbons, with several advantages, including greater energy efficiency (and with prospects for greater cost effectiveness), but it is also at a low technology readiness level than other approaches, still requiring many advances for commercial use (Park et al., 2021, Jouny et al., 2018).

Figure 2-1 Simplified scheme of processes for the synthesis of renewable e-hydrocarbons



Source: developed for this analysis combining information from FVV (2022) and EnTEC (2022).

Characteristics summary

Depending on the exact product, e-hydrocarbons can technically be a substitute to all typical forms of petroleum fuels (e.g. gasoline, diesel, jet fuel) and be used in all transport sectors by vehicles with a combustion engine. Methanol is under particular consideration as a maritime fuel.

The life-cycle GHG emissions of other synthetic hydrocarbons largely depends on the way the hydrogen (H) and carbon monoxide (CO) needed for their synthesis are obtained. **Similar to the case of recycled carbon fuels (RCFs) and hydrogen, failing to rely on low-carbon forms of primary energy would quickly make e-hydrocarbon production counter-productive from a GHG emission abatement perspective.** This is due to the important primary energy needs to synthesise them compared to the production of fossil hydrocarbons and, beyond an initial transitional phase, to the need for circularity with respect to direct emissions generated from the combustion of the fuels[18].

Water requirements for renewable e-hydrocarbons are well below those for irrigated crops in biofuel production.

E-hydrocarbon costs are primarily dependent on the cost of hydrogen production via electrolysis and on the cost of DAC. Underpinning this is the cost and scale of renewable electricity generation.

Liquid RFNBO hydrocarbons can be produced to be drop-in fuels, requiring no infrastructure or powertrain adaptations, which is their major advantage. However, they have greater losses in energy efficiency for production, compared to hydrogen as an RFNBO. E-methanol, which would be used primarily in the maritime sector, would require infrastructure investments only in ships and ports, while e-methane requires a major overhaul of infrastructure and powertrains if it is to be used widely in the transport sector.

E-hydrocarbons have among the highest potential for scalability of all sustainable fuels, due to the large available quantities of primary resources to synthesise them (water and air) and no competition for biomass resources. Nevertheless, DAC requires extremely large volumes of air to be processed (influencing land use requirements of DAC installations) and of renewable electricity per unit of fuel

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[18] Further challenges derive from losses occurring for the conversion of fuels into useful energy, especially in cases that compete with direct electrification (and therefore for inland transport modes).

delivered. This adds to the amount of renewable electricity needed for renewable hydrogen production and an overall lower energy efficiency than hydrogen production, due to the additional step of combining hydrogen with carbon. Therefore, the speed and scale of renewable electricity deployment and the need to reduce costs of hydrogen production and other processes to reach better economic competitiveness will be the main constraining factors for e-hydrocarbons' effective and rapid scale-up. Scale mismatches between DAC and very capital-intensive plants like those needed for Fischer-Tropsch synthesis may also add challenges to the opportunities to cut long-term costs and achieve large-scale production.

Table 2-6 Technology, market and sustainability analysis summary: renewable e-hydrocarbons (own elaboration, based on in-depth analysis developed in Annex A)

Fuel Product	E-Hydrocarbons	E-Methanol	E-Methane
Life-cycle GHG emissions (Annex A.5.2)	🟩	🟩	🟩
Land use and land use change risk (Annex A.5.3)	🟩	🟩	🟩
Primary energy needs (energy efficiency of production) (Annex A.5.4)	🟥	🟨	🟥
Water requirements (Annex A.5.5)	🟩	🟩	🟩
Cost (production) (Annex A.5.6)	🟥	🟨	🟨
Cost (including infrastructure) (Annex A.5.6 and A.5.7)	🟥	🟥	🟥
Infrastructure (Annex A.5.7)	🟩	🟨	🟥
Scalability (Annex A.5.8)	🟨	🟨	🟨

Legend: Green – high score for the sustainability area (low-risk/impact). Red – low score for the sustainability area (high-risk/impact). Yellow – intermediate.

Notes: This table treats e-hydrocarbons as an RFNBO, i.e. produced via electrolysis from renewable electricity and DAC. In the case that e-hydrocarbons were produced via electrolysis and DAC with non-zero-carbon electricity, their life-cycle GHG emissions would not be coloured in green.

Land use requirements are significantly lower than fuels requiring cropland, but are likely to be higher than for renewable hydrogen (Section 2.2.1) due to the very significant quantities of air to be processed for DAC (expanding land requirements).

The energy efficiency of production, coloured in red, is lower than for renewable hydrogen (due to additional processes to combine hydrogen and carbon).

Water requirements, coloured in yellow, are comparable to renewable hydrogen and well below those biofuels that are not naturally supplied by rainwater (such as sugar cane).

Costs are currently high, but they can fall significantly with increased development and scaling up of enabling technologies, in particular electrolysers, DAC, electrochemical CO_2 reduction and fuel synthesis. Using point source CO_2 as a temporary measure can help reduce near-term costs.

Infrastructure costs are low for drop-in hydrocarbon fuels, and higher for fuels that are not currently largely adopted in the transport energy mix, like methanol and methane. Increased demand can have important implications for cost reductions, allowing to share the fixed costs of infrastructure construction across larger volumes of fuel.

Scalability is affected by the volumes of air that need to be processed via DAC and, most importantly, by the need for large amounts of low-cost, and low-carbon electricity.

2.3.3. Renewable e-ammonia

Short description (technology, market readiness)

Ammonia (NH_3) is a compound of hydrogen and nitrogen. The most common method to produce ammonia is the Haber-Bosch process, in which nitrogen (N_2) is combined with hydrogen (H_2) in the presence of a catalyst. Ammonia is a crucial chemical product for the production of nitrogen-fixing fertilisers (IEA, 2019), which is currently its main use. Currently, 72% of the global production of ammonia uses hydrogen produced from steam methane reforming of natural gas and 22% uses coal, mostly in China (ITF, 2020). These production processes rely on fossil fuels, which make it a carbon-intensive product.

When ammonia is produced from renewable hydrogen (see Section 2.3.1) and nitrogen obtained by air separation, it is referred to as renewable e-ammonia.

Ammonia is relatively easy to liquefy (e.g. -33°C at atmospheric pressure) and has a high volumetric energy density (Elbaz et al., 2022, IEA, 2019). Ammonia is toxic, flammable, corrosive, and a risk to human and animal life in case of leakage or accident. If ammonia from a pressurised storage tank is released above the waterline into the air, it will produce a dense, toxic cloud. If released from a refrigerated storage tank at atmospheric pressure, ammonia will form a gas lighter than air that is quickly dispersed in the atmosphere. If spilled at sea, its reaction with water forms ammonium hydroxide (Kass et al., 2021). Leaks and accidents will typically have a local effect, and in water, it could contribute to eutrophication[19]. With pressurised tanks, major shipborne releases can have dire consequences for the ship crew and any nearby population.

However, ammonia has been extensively used commercially for decades. It can be detected at concentrations lower than those that can cause lasting health issues and has established industry best practices for safety (IRENA, 2022, IEA, 2019). Operational standards and regulations are being developed to ensure that the use of ammonia as a fuel meets existing safety codes. The main difference with current uses is that, if used as a fuel in a wide array of ships that are not otherwise specialised in carrying ammonia (see discussion on applications in Annex A.6.1), it would entail building safe ammonia carrying capabilities on all those ships, along with propulsion systems processing it as a fuel, also requiring trained personnel. Further regulatory developments need to minimise harmful emissions of nitrous oxide that arise in production, transport and combustion of ammonia (Cames at al., 2022).

Characteristics summary

Renewable e-ammonia is mostly considered for use as a sustainable fuel for shipping, being easier to liquefy than other options such as renewable hydrogen or renewable e-methane. Prospects for use in other modes are limited by its toxicity and safety risks, requiring it to be handled by trained professionals.

The cost of renewable e-ammonia is primarily dependent on the cost of hydrogen production via electrolysis from renewable electricity. It is however significantly cheaper than renewable e–methanol

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[19] A process of pollution that occurs when a lake or stream becomes over-rich in plant nutrients; as a consequence, it becomes overgrown in algae and other aquatic plants. The plants die and decompose. While decomposing, the plants rob the water of oxygen, and the lake, river or stream becomes lifeless. Nitrate fertilisers that drain from the fields, nutrients from animal wastes, and human sewage are the primary causes of eutrophication, EEA website.

(which is also currently widely discussed as a potential sustainable fuel for shipping), due to the ease of recovering nitrogen from the air, in comparison with carbon.

Although renewable e-ammonia could potentially take advantage of existing ammonia infrastructure, this is very under-developed in comparison with the scale of potential needs in a scenario that sees wide adoption of ammonia as a shipping fuel. This means there is a need for infrastructure investments, including in replacing or adapting ship engines.

Renewable e-ammonia has among the highest potential for scalability of all sustainable fuels, due to the large available quantities of primary resources to synthesise it: water and nitrogen (constitutive of about 80% of the air). Key scalability challenges for its use as a fuel relate to safety and toxicity hazards, limiting it to a potentially viable option only in shipping. The speed and scale of renewable electricity deployment, and challenges with public acceptance, will also be a constraining factor to its effective scale-up.

Table 2-7 Technology, market and sustainability analysis summary: renewable e-ammonia (own elaboration, based on in-depth analysis developed in Annex A)

Fuel Product	E-Ammonia
Life-cycle GHG emissions (Annex A.6.2)	🟩
Land use and land use change risk (Annex A.6.3)	🟩
Primary energy needs (energy efficiency of production) (Annex A.6.4)	🟨
Water requirements	🟩
Cost (production) (Annex A.6.5)	🟨
Cost (including infrastructure) (Annex A.6.5 and A.6.6)	🟥
Infrastructure (Annex A.6.6)	🟥
Scalability (Annex A.6.7)	🟨

Legend: Green - high score for the sustainability area (low-risk/impact). Red - low score for the sustainability area (high-risk/impact). Yellow - intermediate.

Notes: This table treats e-ammonia as an RFNBO, i.e. produced via electrolysis from renewable electricity and DAC. In case e-ammonia was produced via electrolysis and DAC with non-zero-carbon electricity, its life-cycle GHG emissions would not be coloured green.
Land use requirements are significantly lower than for fuels requiring cropland.
Water requirements, coloured in green, are comparable to those of renewable e-hydrocarbons (see Section 2.2.2).
Costs are currently high, but they can fall significantly with increased development and scaling up of enabling technologies, in particular electrolysers.
Infrastructure costs are high, especially in the near term, for fuels that are not currently largely adopted in the transport energy mix. The infrastructure cost and technical viability challenge for ammonia is similar to methanol, and likely lower than in the case of methane or hydrogen. Increased demand can have important implications for cost reductions, allowing sharing of the fixed costs of infrastructure construction across larger volumes of fuel.
Scalability is affected by the need for large amounts of low-cost and low-carbon electricity.

2.4. Others (fossil-based)

The other pathways considered include: nuclear and fossil-based hydrogen with carbon capture and storage (CCS); recycled-carbon-fuels (e.g. fuels produced from the capture of CO_2 from industrial smokestacks, combined with hydrogen); and hydrocarbon fuels with emissions offset by carbon removal and storage (e.g. via DAC + CCS).

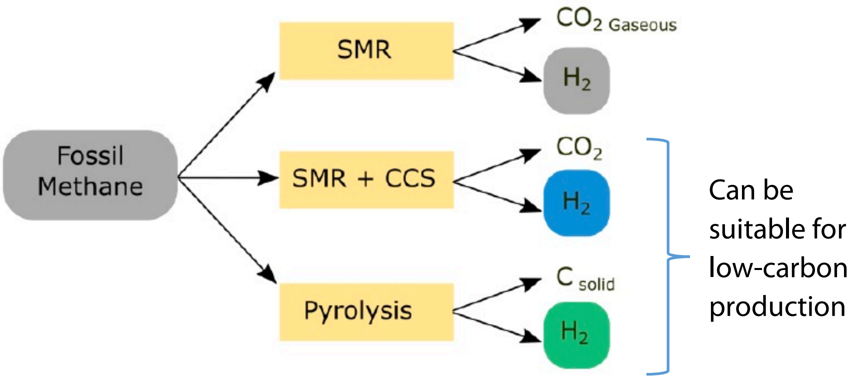
This section focuses on fossil-based hydrogen and RCFs. Nuclear hydrogen is briefly discussed as a comparative low-carbon option in the renewable hydrogen section (2.3.1). Hydrocarbons, whose emissions are offset by carbon removal and storage, are considered a comparative (and competing) option to sustainable fuels in Chapter 4.

2.4.1. Fossil-based hydrogen

Short description (technology, market readiness)

Figure 2-2 summarises the three main pathways for the production of hydrogen from fossil energy. This includes the **two main pathways that can be suitable for low-carbon production** (the focus of this section), i.e. hydrogen from methane reforming with carbon capture and storage, and hydrogen from methane pyrolysis.

Figure 2-2 Schematic figure on the production of hydrogen from fossil energy



Note: SMR = steam, methane reforming; CCS = carbon capture and storage.

Source: adapted from ITF, 2020.

Summary and sustainability analysis

Fossil-based hydrogen could enable the widening of the scope of the primary feedstocks used for hydrogen production if paired with effective carbon capture technologies, renewable energy (needed to enable effective carbon capture), and strict rules regarding methane emissions. It therefore serves the same applications as the ones described for renewable hydrogen in Section 2.3.1 and in Annex A.7.1.

For the same reasons, fossil-based hydrogen with carbon capture could, if done in a way that has a strong focus on CO_2 emission abatement (see discussion on sustainability aspects of fossil-based hydrogen production in Annexes A.7.2 to A.7.5), reduce the amount of primary renewable energy and help manage asset-stranding risks for fossil energy in a deep decarbonisation context (UK CCC, 2020)[20,21].

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[20] This UK CCC report recommends a "blue hydrogen bridge" as a useful tool for achieving net-zero emissions. The findings from this study are also discussed in CarbonBrief (2021). Other expert and/or stakeholder statements going in the same direction are available on RechargeNews (2022) and CNBC (2021).

[21] See also Annexes A.7.7 and A.7.8 for supply and infrastructure, and for scalability considerations for fossil-based low-carbon hydrogen.

To be economically competitive, fossil-based hydrogen with carbon capture would require low fossil energy prices (see Annex A.7.6). In the absence of this condition, the likelihood to be outcompeted by renewable or nuclear hydrogen would increase significantly.

The development of fossil energy prices and a strict regulatory framework will therefore be crucial determinants to enable these technologies to be part of the energy mix in a decarbonising context.

2.4.2. Recycled carbon fuels

Short description (technology, market readiness)

Recycled carbon fuels are defined in the 2018 recast of the European Renewable Energy Directive as liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin. They are further defined as not being suitable for material recovery or from waste processing gas and exhaust gas of non-renewable origin, which are produced as an unavoidable and unintentional consequence of the production process in industrial installations (European Commission, 2018). Its applications are discussed in Annex A.8.1. A typical example of RCF is a fuel made from fossil-derived wastes (e.g. non-recyclable plastic waste or industrial waste gases) that would otherwise be landfilled or incinerated (DfT, 2022). Another example of feedstock are steel mill waste gases, typically containing carbon monoxide (DfT, 2022, ARTFuels, n.d.).

RCFs are produced by means of thermochemical conversion technologies such as gasification, pyrolysis and liquefaction (ARTFuels, n.d.) and subsequent synthesis into fuels, generally following the combination of carbon monoxide and hydrogen into hydrocarbons.

Summary and sustainability analysis

There are challenges in achieving meaningful GHG emission reductions in comparison to other treatments of waste streams (including competition from carbon capture and storage), limited availability of waste streams, and a need to shift to DAC and other carbon sources allowing net atmospheric removals to lead to low life-cycle emissions. Hence, RCFs will likely play a temporary role to enable GHG emission reductions in transport (see discussion on RCFs’ sustainability, costs, infrastructure requirements and scalability in Annexes A.8.2 to A.8.7). In a context requiring deep emission reductions, a recent analysis developed in the United Kingdom indicates that RCFs are likely to remain marginal (DfT, 2022).

3. CRITICAL REVIEW OF SUSTAINABLE FUEL PROSPECTS IN TRANSPORT

Key findings

- In the long-term decarbonisation scenarios 1.5TECH & 1.5LIFE for the EU Long Term Strategy and the CAN Europe/EEB 2050 PAC scenario, transport decarbonisation is driven by 1) a significant **increase in energy efficiency** through vehicle efficiency improvements, at least some **reduction in motorised activity**, and **direct electrification**; 2) the **penetration of sustainable fuels** such as renewable electricity, biofuels, and RFNBOs.
- All **aviation decarbonisation** scenarios considered show only **limited increases in overall energy demand** and a **significant shift to sustainable fuels**. Most of the scenarios propose a balanced mix of biofuels and RFNBOs, while CAN Europe presumes most of the fuels to be liquid RFNBOs as well as a more significant decrease in activity.
- Projections for the **maritime sector** are characterised by a **diversification of fuels and powertrains** by 2050, including a small level of direct electrification and a mix of hydrogen, bio-LNG, liquid biofuels, diesel-like RFNBOs, methanol, and ammonia, even though the majority of these fuels cannot be used on-board current ships.
- **Direct electrification plays a central role in the decarbonisation of road transport.** This frees up sustainable feedstock needed for other applications, including for shipping and aviation. Road transport electrification is already occurring with light-duty vehicle, and can be used for heavy-duty vehicles, although they face challenges regarding battery size requirements, distances covered and charging times.

The aim of this chapter is to review contrasting scenarios and pathways from the literature to reflect on the drivers for the deployment of all sustainable fuels, to confirm the viability of different sustainable fuels, or to potentially provide another point of view that will need to be critically analysed.

3.1. Prospects for final energy demand of sustainable fuels

This section reviews projections for energy demand and supply for the transport sector for four groups of major scenarios which are either European or global in scope. The scenarios are reviewed for how energy demand in the heavy-duty road, aviation and maritime sectors will be met by electrification and sustainable fuels by 2050. These scenarios are all compatible with the Paris Agreement, i.e. they would reduce emissions by 2050 so that global warming is limited to 1.5°C above pre-industrial levels.

Scenario Group 1 is the 1.5TECH and 1.5LIFE scenarios developed to support the EU 2050 Long Term Strategy reducing GHG emissions in accordance with the Paris Agreement (European Commission, 2018). These scenarios reflect differing levels of technology deployment, circular economy implementation, and consumer choices. Transport decarbonisation in Europe is driven by significant energy efficiency improvements and mainly by the contributions of e-liquids, biofuels, hydrogen and direct electrification.

Scenario Group 2 includes global mitigation pathways that keep the global temperature increase to below 1.5°C (IPCC, 2018). These pathways are part of a larger set reviewed by the IPCC that describe integrated, quantitative evolutions of all emissions over the 21st century associated with global energy and land use and the world economy. For the average of the pathways considered here, 25% of the final global transport energy consumption is electrified in 2050, while biofuels constitute around an eighth of global transport final energy consumption.

Scenario Group 3 is the Paris Agreement Compatible (PAC) scenario elaborated by the Climate Action Network (CAN) Europe with the European Environmental Bureau (EEB) (CAN Europe/EEB, 2020). In this scenario, energy efficiency is the main driver. All private cars, some of the road freight fleet, and a small share of shipping and aviation will be directly electrified by 2040. While renewable hydrogen and its derivatives (ammonia, e-liquids) will constitute most of the supply in the three latter sub-sectors, second-generation biofuels are only temporarily being used in aviation.

Scenario Group 4 contains three different scenarios, reflecting HIGH, MEDIUM and LOW uptake of low carbon fuels (LCF), that were developed by Concawe, a research group of European fuel manufacturers (Concawe, 2021). These scenarios provide an indication of the number of refining plants and the cumulative investment required by 2050. In the HIGH Scenario, LCF can provide a substantial proportion of the energy demand for passenger vehicles in 2050 compared to full electrification, while about 70% of fossil fuels in aviation and maritime are replaced by biofuels and e-fuels. Lignocellulosic-based fuels are assumed to be ready for deployment in 2025 with a direct ramp up, while higher bio-blends are foreseen in gasoline and fuels from renewable electricity scale up from early 2025.

More information on the general context, main assumptions and results in terms of final energy demand for each scenario group are provided in Annex B.

While sustainable fuels were addressed in the short term in a previous EU Rapid Response Report (Trinomics, 2022), this report focuses on the longer-term 2050 time horizon. The scenarios and pathways considered here were generally developed prior to the Covid-19 pandemic. More recent work, such as for the ‘Fit for 55’ proposals (European Commission, 2021) and the recast of the Renewable Energy Directive (European Commission, 2021), are available but are focused on the shorter-term 2030 time horizon. Ongoing work for the RePowerEU Plan (the EU’s response to the global energy market disruption) (European Commission, 2022) also focuses on 2030. It is showing that estimates of energy demand for different sustainable fuels in 2030, in particular for RFNBOs, are currently evolving due to the current Russia crisis. However, while the exact pace of change and targets that can be achieved by 2030 is uncertain, estimates for sustainable fuels demand in 2050, as considered below, are not expected to change substantially if net-zero GHG emissions by that date are to be achieved. Therefore, even with a faster pace of transport sector decarbonisation, the assessments made here are not influenced by the use of a shorter-term scenario, as the most significant changes, including to infrastructure, would come from 2030 onwards.

3.2. The role of demand reduction and electrification

The role and quantities of sustainable liquid and gaseous fuels for transport, to achieve the objective of a decarbonised and sustainable transport sector by 2050, will depend closely on the role of electrification and the overall motorised mobility demand trend of the sector.

3.2.1. Motorised transport energy demand has to reduce for a sustainable energy future

Despite a continuous increase of passenger and freight transport activity and emissions over the past decades at the global level (the reduction caused by the Covid-19 pandemic aside) (IEA, 2021), most, if not all transport decarbonisation scenarios combine vehicle energy efficiency improvements and technology shifts with a reduction in motorised activity demand, at least on a per capita or per GDP unit basis.

Systemic improvements that optimise available transport capacity and reduce travel distances are necessary for the transition towards greater sustainability. These improvements are needed to reduce

GHG emissions, and to also create more liveable cities thanks to decreased pollution, noise and congestion levels. Due to energy efficiency advantages, they align also with energy security requirements. Systemic improvements, such as those characterising compact cities, can also increase non-motorised mobility such as walking and cycling, and lead to improved transport safety.

Taking these considerations into account, all of the Paris Agreement-compliant decarbonisation scenarios listed in Section 3.1 and reviewed in Annex B present a strong decrease in transport energy use in 2050 in comparison with current levels (Table 3-1). Total projected final energy demand from the transport sector in 2050 varies for the scenarios that are European in scope, despite always being significantly lower than the baseline. Differences arise when comparing the primary energy demand associated with final energy use since scenarios do not rely on the same energy carriers, and the energy efficiency of the production of different energy carriers is also subject to major variations. The end-use technology mix also varies across scenarios, especially with respect to electrification. Similarly, the primary energy mix needed in each scenario is subject to important variations such as between proportions of biofuels and RFNBOs.

All of the European scenarios yield a significant reduction in energy demand, with a median reduction of around 45% over 35 years. At the global scale, the median pathway in the IPPC 1.5C global scenarios yield a more modest reduction of 16% over 40 years. This reflects stronger increases of key drivers like population and GDP at the global scale (if compared with the EU alone), as well as differences in technology and structure across different global regions.

The Concawe scenarios have the highest energy usage in 2050 at 209 million tonnes of oil equivalent (Mtoe) – equivalent to 8.8 exajoules (EJ). The lowest is the CAN Europe PAC scenario at 1900 Terawatt-hours (TWh), equivalent to 163 Mtoe or 6.8 EJ. The EU Commission's 1.5LIFE scenario and the CAN Europe's PAC scenario include strong demand reductions due to lifestyle changes, adding to energy efficiency improvements. Furthermore, all of these scenarios include a significant share of direct transport electrification. Since electric vehicles are 2 to 4 times more energy efficient per km than internal combustion engines (T&E, 2017, US DoE, 2022), direct transport electrification also significantly contributes to decreasing overall transport energy demand by 2050.

Table 3-1 Transport energy demand trends of the Paris Agreement-compatible scenarios presented in Section 3.1

Scenario		Baseline Energy Demand	2050 Energy Demand	Trend
Scenario scope: EU27+UK				
EU 2050 long-term strategy	1.5TECH	360 Mtoe/ 15 EJ (2015)	200 Mtoe/8.4 EJ	-44% in 35 years
	1.5LIFE		185 Mtoe/7.7 EJ	-49% in 35 years
CAN Europe	PAC	3 600 TWh/ 13 EJ (2015)	1 900 TWh/ 6.8 EJ	-47% in 35 years
Concawe	HIGH LCF demand*	366 Mtoe/ 15.3 EJ (2015)	209 Mtoe/8.8 EJ	-43% in 33 years
Scenario scope: Global				
IPCC	1.5DS-L pathways	95 EJ (2010)	80 EJ	-16% in 40 years

* Total transport energy demand in 2050 is only available for the Concawe HIGH scenario

Sources: author's assessment based on European Commission, 2018 ; IPCC, 2018 ; CAN Europe/EEB 2020 ; Concawe, 2021

3.2.2. The demand for sustainable transport fuels will largely depend on the rate of direct transport electrification

Over the past decade, transport electrification has been increasingly highlighted among experts, policymakers and stakeholders as a decarbonisation option for at least a significant subset of transport activity. This is due to a combination of technical, market and societal reasons:

- The absence of tailpipe emissions from electric vehicles;
- The rapidly decreasing cost of lithium-ion batteries, boosted by the boom of consumer electronics and the early electric vehicle market (IEA, 2018, Figure 5.1), and expectations for cost cuts to remain in place despite increases in material costs (Benchmark Minerals Intelligence, 2021, BNEF, 2022);
- A competitive total cost of ownership vs internal combustion engines for light-duty vehicles (BEUC, 2021), and increasing prospects for competitiveness for other vehicle types and services mainly on the road, especially with continued reductions in battery costs;
- The high energy efficiency of electric vehicles, in comparison to internal combustion engines (T&E, 2017; US DoE, 2022);
- Lower current or projected life-cycle GHG emissions in comparison to internal combustion engines in all parts of the world (Knoboch et al., 2020);
- The potential and real prospects for electricity mixes to further decarbonise and eventually become zero-carbon (EEA, 2022).

In the Paris Agreement-compliant scenarios presented in Section 3.1, except Concawe's HIGH scenario, direct electrification plays a very significant role in the transition of the transport sector, with between roughly one-quarter and two-thirds[22] of the transport sector being electrified in final energy terms (Table 3-2). The rest is covered by sustainable liquid and gaseous fuels, including hydrogen, other RFNBOs, and biofuels, with a remaining share of fossil fuel use. Only the HIGH scenario of Concawe presumes a significant long-term presence of liquid and gaseous fuels in all transport segments, with a direct electrification rate not exceeding 10%.

Most scenarios presented in Section 3.1 point to a total amount of sustainable fuels in transport that are not electricity, of roughly 2-5 EJ by 2050 (EU 1.5TECH and 1.5LIFE scenarios[23], CAN Europe's PAC scenario and Concawe's LOW and MEDIUM LCF scenarios). The most pessimistic scenario for transport electrification, Concawe's HIGH scenario, suggest a final use of low-carbon fuels in transport of up to 7 EJ.

Box 1 illustrates that RFNBOs require more renewable electricity generation than direct transport electrification.

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[22] Around one-quarter: EU 1.5TECH scenario, EU 1.5LIFE scenario, IPCC 1.5DS-L pathways; around two-thirds: CAN Europe PAC scenario.

[23] These include, in addition to 4-5 EJ of alternative liquid or gaseous, around 1 EJ of remaining fossil fuel consumption.

Box 1 RFNBOs require more electricity than direct electrification

The synthesis of hydrogen and RFNBOs from electricity is less efficient than direct electrification (*), and the conversion of these fuels into motive power aboard vehicles (i.e. the drive train efficiency) incurs losses that are much larger than in battery electric vehicles. For 1 unit of electric energy produced:

- 0.95 units can be available for direct end-use (after transport, storage, and distribution) and 0.7 units can directly be used as motive power by a battery electric vehicle (accounting for losses on-board the vehicle).
- Only 0.2 units of energy in the form of hydrogen from electrolysis can be used as motive power by a fuel cell electric vehicle (accounting for losses during the production and transportation of the fuel and on-board the vehicle).
- Only 0.1 units of energy from liquid synthetic fuel, also obtained from electrolysis, can be used as motive power by an internal combustion engine vehicle (accounting for losses during the production and transportation of the fuel and on-board the vehicle).

(*) Because of a first conversion from electricity to hydrogen in the case of hydrogen synthesis and a second conversion from hydrogen to a liquid fuel (hydrocarbon or ammonia) in the case of liquid fuel synthesis.

Sources: IRENA, 2022 ; Bicer et al., 2016 ; Transport & Environment, 2017.

Table 3-2 Transport electrification trends of the Paris Agreement-compatible scenarios presented in Section 3.1

Scenario	Energy Demand	2050 Direct Electricity Use	2050, Liquid and Gaseous Fuels	Summary, 2050
		Scope: EU27+UK		
EU 2050 long-term strategy **1.5TECH and 1.5LIFE scenarios**	Transport (all)	▪ 25-30% is electrified, 50 Mtoe (~2 EJ)	▪ 100-125 Mtoe (~4-5 EJ) Sustainable fuels ▪ 25 Mtoe (~1 EJ) fossil fuels	▪ Total share of direct electrification for all transport modes: 25-30% ▪ 2 EJ direct electrification ▪ 5-6 EJ liquid and gaseous fuels, of which: ~1 EJ fossil fuels
	Heavy-goods vehicles	5-10% of heavy-goods vehicles are electrified[24]		
	Maritime		▪ 51 Mtoe (~2 EJ) (international)	
	Aviation	Very marginal direct electrification of aviation (1-2 Mtoe/~0.05 EJ)	▪ 50-58 Mtoe (~2 EJ)	
CAN Europe **PAC scenario**	Transport (all)	Around two-thirds of final energy consumption is electrified, 1300 TWh (~4.7 EJ)	▪ 600 TWh (~2.2 EJ) ▪ Renewable hydrogen: 250 TWh (~0.9 EJ) ▪ E-liquids : 370 TWh (~1.3 EJ)	▪ Total share of direct electrification for all transport: ~70% ▪ 4.7 EJ direct electrification

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[24] Direct electrification (fuel cell and hybrid vehicles excluded).

Scenario	Energy Demand	2050 Direct Electricity Use	2050, Liquid and Gaseous Fuels	Summary, 2050
			▪ E-ammonia: 86 TWh (~0.3 EJ) ▪ Biofuels: marginal to none (~0 EJ) ▪ Fossil fuels: marginal to none (~0 EJ)	▪ 2.5 EJ liquid and gaseous fuels, of which: 0 EJ fossil fuels
	Light-duty vehicles	Fully electrified private car fleet (achieved by 2040)		
	Heavy-goods vehicles	Road freight covered primarily by electrification		
	Maritime	Electrified shipping for short-distance and part of mid (intra-EU) distance	Ammonia: 86 TWh (~0.3 EJ)	
	Aviation	Progressive development of electric aircraft post-2040, displacing biofuel use	RFNBOs: 370 TWh (~1.3 EJ)	

Concawe - HIGH	Transport (all)	~10% of final energy consumption is electrified: 18 Mtoe (~0.75 EJ)
		Passenger car segment not fully electrified
			LCF in all transport segments.	▪ Total share of direct electrification for all transport: ~10%
				▪ 1 EJ direct electrification
				▪ 8 EJ liquid and gaseous fuels, of which:
				  ▪ 1.3 EJ fossil fuels
				  ▪ ~7 EJ LCFs

	Road		▪ 90 Mtoe (~4 EJ) LCFs ▪ No fossil fuels left by 2050	
	Maritime and aviation		▪ 70 Mtoe (~3 EJ) LCFs (70% of liquid fuel demand) ▪ 30 Mtoe (~1.3 EJ) remaining fossil fuels (30% of liquid fuel demand)	
Concawe – MEDIUM	Transport (all)	Full electrification of light-duty passenger vehicles	LCF in heavy-duty vehicles, aviation and maritime	In heavy-duty vehicles, aviation and maritime: 107 Mtoe (~5 EJ) LCFs
Concawe – LOW	Transport (all)	Full electrification of road vehicles	LCF in aviation and maritime only	In aviation and maritime: 67 Mtoe (~3 EJ) LCFs
Scope: Global				
IPCC **1.5DS-L pathways**	Transport (all)	- 25% of final energy consumption is electrified, ~20 EJ	▪ Biofuels: ~10 EJ	Total share of direct electrification for all transport: 25% (~20 EJ)

Sources: author's assessment based on European Commission, 2018, IPCC, 2018, CAN Europe/EEB, 2020, Concawe, 2021.

3.2.3. “Hard-to-abate” modes of transport

As shown by all scenarios considered in Section 3.1, liquid and gaseous sustainable fuels are primarily dedicated to subsets of transport that cannot be easily electrified: the so-called “hard-to-abate” transport modes. These are primarily the heaviest and longest distance modes, for which current technology battery costs and key properties (in particular energy density) mean that electrification cannot be cost competitive.

Due to the scale of the energy transition, cost-effectiveness is important for assessing which fuels are suitable for which modes. Sustainable biofuels, hydrogen and its derivatives are better suited for sectors where direct electrification is not feasible, more expensive and less effective in enhancing energy efficiency, starting with aviation and shipping (MIMS, 2022 and Armaroli et al., 2022).

As mentioned in the section on hydrogen (Section 2.3.1), energy efficiency, energy diversification and increased reliance on renewable electricity will enable lower energy costs. These factors will also have positive consequences for economic development and the just transition, reducing risks of social instability.

As a result, the maritime and aviation sectors would be those most reliant on liquid and/or gaseous sustainable fuels in a decarbonised future, with few alternative options. Some services could nonetheless be electrified, as a small part of activity would still be taking place on smaller and shorter-distance aircraft or ships.

For road-based modes, the question of a high reliance on liquid and gaseous fuels in a sustainable future, versus direct electrification, remains more open and has not yet fully reached consensus for heavy-duty long-haul trucks. Light-duty vehicles (passenger cars and vans), on the contrary, are usually not considered as “hard-to-abate” and become largely electrified in all scenarios, except in Concawe’s HIGH scenario.

These aspects, as well as further discussion on the types of sustainable fuels to meet each hard-to-abate sector’s demand, are further developed in the next sections.

3.3. Scenarios for specific transport modes

3.3.1. Sustainable fuel demand in aviation: a 2050 sustainable fuel mix based on drop-in fuels

Decarbonising the aviation sector will require a combination of measures to enhance energy efficiency and shift its energy mix to sustainable options. Reducing the energy needed to fly requires reductions of aircraft weight, improved thermodynamic efficiency of propulsion and enhanced aerodynamics, complementing operational improvements. Making sure that the aviation fuel mix is sustainable requires energy options with low GHG emissions on a life-cycle basis, low impacts on direct and indirect land-use change, high energy efficiency in fuel making, and large-scale availability.

In all the decarbonisation scenarios presented in Section 3.1 that focus on Europe, for aviation there are limited increases in overall energy demand and significant changes in the fuel types used. Similar results, focused on energy efficiency enhancements and a transition in the fuel mix, are also reflected in work done by the International Civil Aviation Organisation (ICAO) (ICAO, 2022). Energy demand is projected to increase through economic and population growth, but these will largely be offset by significant energy efficiency improvements through both operational and technical aircraft enhancements. This combination results in estimates of energy demand across the EU by 2050 that remain similar to the pre-Covid values (and close to 2-2.5 EJ[25]) for all decarbonisation scenarios reviewed in Section 3.1.

In its most ambitious sustainable fuels penetration scenario (IS3),[26] ICAO (ICAO, 2022) sees a global 2050 aviation fuel mix (in tonnes) composed of around 40% of biofuels, 56% of liquid "drop-in" RFNBOs (together classified as "sustainable aviation fuels") and a relatively marginal share of liquefied hydrogen (4%)[27, 28]. This scenario sees a complete phase-out of fuels directly derived from fossil hydrocarbons.

The direct electrification of road transport helps to ensure sustainable liquid and gaseous fuels – which are subject to a number of availability constraints – are available to the aviation sector, where they are most needed.

ICAO's IS3 scenario includes small amounts of liquefied hydrogen in the energy mix before 2050. This implies that technological progress and cost reductions could be opening up the option of new hydrogen-powered aircraft before 2050, however with a significant expansion of the use of hydrogen aviation technologies occurring only after 2050. This accounts for delays in widespread adoption due to slow fleet turnover, along with significant changes to airport and energy infrastructure. There will be challenges to ensure costs associated with distributing relatively small volumes of hydrogen. This also reflects that hydrogen is more likely to be a suitable option for short-haul flights (as also discussed by the International Transport Forum (ITF) in ITF, 2021), even if a role in long-haul applications may not be ruled out (WEF, 2022).

Strong shifts towards low carbon sustainable fuels in aviation are also identified in the European Commission's scenarios 1.5TECH and 1.5LIFE and in the CAN/EEB PAC scenario. The latter presumes 85% of the energy demand for aviation will be met with RFNBOs and 15% with liquid biofuels. Proportions of the aviation energy demand vary between the 1.5TECH and 1.5LIFE scenarios: for liquid biofuels these are 25% and 45%, respectively, and for e-liquids these are 33% and 13%, respectively. The Commission's scenarios consider aviation as the sector with the highest residual share of fossil fuels: around 40% by 2050 in these scenarios. For aviation, the Concawe scenarios are based on the Commission's scenarios.

These results are broadly coherent with the indications emerging from other aviation sector-specific studies e.g. Milieu Consulting and Ricardo (2022). The "Decarbonising air transport" report of the ITF (ITF, 2021) clearly identifies energy efficiency improvements and a switch to drop-in fuels as the most likely developments. These fuels include advanced biofuels, including PBtL, and "drop-in" RFNBOs. It flags important technical challenges for hydrogen and acknowledges that direct air capture to offset emissions from hydrocarbon extraction could well be cheaper than RFNBOs (ITF, 2021).

The Mission Possible Aviation Transition Strategy (MPP, 2022) is also focused on sustainable aviation fuels production, including both biofuels and RFNBOs. In addition, it has a more optimistic assessment for hydrogen and electric aircraft by 2050, with a contribution to the sector's CO_2 emissions reductions of between 10% and 25%, depending on the pathway. In that study, the vast majority (92-96%) of

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[25] 2 396 000 TJ = 2.4 EJ (2 400 PJ) of aviation kerosene in 2017 according to the EEA (2019).

[26] The other two ICAO scenarios still rely on a certain share of conventional jet fuel and "low-carbon aviation fuels", which continue the current trend of fossil fuels reliance and for which serious sustainability concerns have been raised, hence the choice of the most ambitious ICAO scenario for this analogy.

[27] Figure 0.1 in ICAO (2022). RFNBOs and liquefied hydrogen continue growing significantly after 2050. The share of hydrogen represents the demand of jet fuel displaced by hydrogen demand.

[28] These shares account for hydrogen in terms of displaced jet fuel demand. Assuming an energy density for SAF similar to jet kerosene (as they are chemically similar) and the energy density of liquefied hydrogen being 2.7 times that of jet kerosene (Greenbaum, 2012 and Fung, 2005), the fuel mix implies that, in terms of mass, the hydrogen share would be close to 1.5% of the total.

capital investments to achieve net-zero in the aviation sector is dedicated to fuel production, split about equally between sustainable aviation fuels production and renewable electricity generation to produce RFNBOs.

The transition to sustainable fuels is likely to be progressive. The production of RFNBOs has a low technology readiness, and the current focus of biofuel production is on conventional pathways. Conventional biofuels that are already mass-produced and used in the road transport sector include options (in particular HVO) that have the potential to be shifted with priority towards HEFA (which is used in aviation)[29]. Crucial requirements to ensure sustainability are both the avoidance of land use and land use change effects and increased reliance on renewable hydrogen as input for the process. Waste-based aviation fuels need to complement this development, while shifting to advanced biofuel production pathways[30]. Low carbon hydrogen can help enhance the processes, ensuring higher biofuel yields from carbon available from waste streams. RFNBOs mean an increased reliance on renewable energy overall, increased availability of renewable hydrogen and a progressive integration of other carbon streams (from industry, via RCFs, and through direct air capture (DAC)).

Additional GHG emissions abatement may be derived from carbon capture and storage technologies, as long as the carbon feedstock is also extracted from the atmosphere[31]. If this is not the case, technologies like DAC and carbon capture and storage (CCS) may also need to be targeted to offset residual positive emissions from hydrocarbon extraction (ITF, 2021).

Due to the significant need for RFNBOs, which have low technology readiness today, achieving sustainability in aviation requires significant capital investments to develop, deploy, and scale up technologies. In particular, for low-carbon hydrogen, DAC and the integration of renewable hydrogen with biogenic carbon in PBtL.

3.3.2. Sustainable fuel demand in maritime transport: multiple fuels and technologies in contention

Projections for the maritime sector are characterised by a diversification of fuels and powertrains by 2050 (Table 3-3). The sustainable fuel mix and ship/engine types across scenarios and within a single scenario can be as diverse as including direct electrification, hydrogen, bio-LNG, liquid biofuels, diesel-like RFNBOs, methanol, and ammonia. The issue is that the majority of these fuels cannot be used on-board current ships. Electricity, hydrogen, bio-LNG to some extent, methanol, and ammonia are not “drop-in” fuels and they would be able to penetrate the maritime sector only with new-built ships or retrofits.

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[29] There is currently limited planned additional biofuel production capacity for Fatty Acid Methyl Ester (FAME) and bioethanol in Europe. However, a significant increase in production capacity (a doubling by 2025 from 2021 levels) for hydrotreated vegetable oil (HVO), which is suitable as a sustainable aviation fuel, is foreseen by the industry (T&E, 2021).

[30] From 2020 to 2030, about 65% of the additional capacity for HVO proposed by 2025 would be met primarily by advanced feedstocks (including animal fats and UCO) (T&E, 2021).

[31] If the cost of sequestering carbon, extracting fossil fuels, and refining is less than the cost of producing sustainable biofuels, RFNBOs, or RCFs, the combination of negative emissions and fossil hydrocarbon extraction could be economically competitive with e-fuels or PBtL. Barriers faced by this approach are similar to those faced by biofuels and e-fuels and mainly relate to pressures on land use for biogenic carbon production, high primary energy requirements, and air processing requirements for DAC. Additional barriers relate to the geopolitical challenges associated with a continued reliance on fossil energy.

Table 3-3 Fuel mix in final energy demand for the maritime sector by 2050, by scenario

Scenario	Oil	Gas	Electricity	Hydrogen	Liquid Biofuels	E-liquids
EU 2050 long-term strategy - 1.5LIFEMar*		X (Nat. gas & e-gas)			X	X
POLES-JRC 2C*	X	X		X	X	
CAN Europe, PAC			X	X		X (Ammonia)
CONCAWE - HIGH	X				X (Advanced)	X
IEA ETP 2020 SDS**	X			X	X	X (Ammonia)

Sources: author's assessment based on scenarios discussed in EC, 2018 (Figures 54 and 55); IEA, 2020; scenarios described in Section 3.1 and Annex B.

Notes: *EU international maritime; **global international shipping; SDS = Sustainable Development Scenario. Only fuels reaching at least 5% of the total energy demand in the considered scenario are shown.

Across the scenarios shown in Table 3-3, there are important variations between fuel types that would require different ship powertrains and associated infrastructure. Such diversity may have the advantage of associating each type of shipping activity with the best-suited fuel, and ship, depending on range, size, weight, and type of goods carried. On the other hand, this places a significant question mark on the certainty of the pathway to decarbonise shipping. With multiple fuels and powertrain types, economies of scale in deploying a certain technology are not as easily reached, and various parallel, potentially redundant, infrastructures may be developed. Therefore, close attention should be paid to making scalable and future-proof investments for shipping, considering the deployment of sustainable fuels and technologies across various shipping segments as well as across other transport modes and energy end-use sectors. This will enable opportunities to mutualise and scale-up production capacity and infrastructure, and to reach significant cost reductions.

Direct electrification in shipping refers to the electric motor associated with batteries carried on board the ship. It is usually considered for a small share of shipping, for short-distance or ferry services, close enough to population hubs to make recharging infrastructure possible. The combination of the small share of ships eligible for direct electrification, their limited energy needs (compared to long-distance, heavy-shipping), and the high energy efficiency of direct electrification leads to a very marginal share of electricity in the final energy demand mix of shipping scenarios. That said, the electrification of at-port activities of ships, called cold-ironing, has already been adopted in Nordic countries and it is increasingly considered elsewhere, including as a requirement in the recent 'Fit for 55' European policy proposals, discussed in Section 6.2.1. Air quality is a key driver in this since electricity can be easily obtained from the land, avoiding the issue of electricity storage on-board the ship, while significantly improving the air quality of ports and their vicinity.

Bio-LNG or e-LNG (LNG as RFNBO) may be seen as a solution for shifting existing fossil LNG-powered ships, usually LNG tankers, to a sustainable fuel. However, prospects for a significant adoption of this decarbonisation approach are limited for several reasons. Few ships are currently capable of running on natural gas and biogas supply is geographically constrained and often not available next to ports. Biogas is subject to competing uses next to the areas of production and as a complement to methane of fossil origin in the natural gas network. Moreover, biogas is unlikely to be available on such a large scale to justify a widespread transition of ships to LNG powertrains (MIMS, 2022, Armaroli et al., 2022, ICCT, 2022). LNG powertrains have low potential to penetrate other transport sectors (see Trinomics, 2022), so there are rather low prospects for a significant scale-up of infrastructure for such uses, especially in a context of the gas supply crisis Europe has been undergoing since 2022.

Some of the scenarios reviewed for this study consider **hydrogen** as a relevant fuel for the future of the maritime sector. In particular, hydrogen in fuel cells is one of the options considered for medium-distance shipping in the CAN PAC scenario (see Section 3.1). Elsewhere, hydrogen accounts for 15% of the maritime energy mix in the IEA ETP 2020 Sustainable Development Scenario (IEA, 2020). A positive assessment of hydrogen and ammonia as potential zero-carbon bunker fuels also identifies green hydrogen, along with green ammonia, as the most promising zero-carbon bunker fuels within the maritime industry at present (Englert et al., 2021). This is due to the advantageous balance of favourable features relating to their life-cycle GHG emissions, broader environmental factors, scalability, economics, and technical and safety implications. It should be noted that ships running on methanol are currently in service, that orders for further methanol-powered ships have been placed (Maersk, 2022, Splash247, 2022), and that investment decisions on low-carbon methanol production have been taken (Ørsted, 2022). Ammonia powertrains are not yet commercially available, but work is ongoing to develop them. For example, MAN Energy Solutions has developed a timeline to deliver commercially viable ammonia-burning engines by 2024 (Global Maritime Forum, 2022).

However, other sector-specific analyses indicate that there are various different views on the use of hydrogen in maritime transport. Liquid fuels are more practical on board of ships than hydrogen, which has a low volumetric density and presents safety risks. Liquid sustainable fuels have a greater potential to use existing infrastructure than hydrogen. The sector-specific study “A strategy for the Transition of Zero-Emission Shipping” (UMAS, 2021) points out that “the industry remains sceptical about pure hydrogen pathways for deep-sea shipping, and barriers to other options (possibly related to sustainability risks) would likely need to be raised for hydrogen fuel to be considered feasible”. Similar conclusions suggesting a limited uptake of hydrogen vs liquid e-hydrocarbons and e-ammonia in shipping due to lower technology readiness and greater technical challenges, also arise from a very recent assessment by one of the main ship classification societies (DNV, 2022).

Liquid RFNBOs have many advantages, including lower infrastructure costs, lower energy requirements for storage and greater compatibility with existing facilities. However, these need to be balanced with the fact that producing a RFNBO other than hydrogen incurs more energy conversion losses and, apart from ammonia, requires sources of renewable carbon. For these reasons, uncertainties remain over fuel choice.

The coexistence of hydrogen ships with ships running on biofuel/RFNBOs also risks requiring two parallel distribution infrastructures. The relatively small scale at which hydrogen is likely to be used in the road transport sector as well as in other end-use sectors may affect its deployment in the maritime sector. In general, local hydrogen production or import/export facilities close to ports may justify the use of hydrogen as a fuel in ships that have a regular journey through such ports. However, volumes of hydrogen used in these circumstances would likely be limited, with challenges to achieve unit cost reductions for the deployment of the fuel distribution and storage infrastructure.

Redundancy and scalability risks may also arise for RFNBOs if multiple types are to coexist in the shipping sector. While engine adaptations or retrofits and dual fuel designs may mean ships can switch from one to the other as these fuels become more widely available, the infrastructures needed for the distribution of ammonia and methanol, as well as on-board storage tanks, are very different.

The choice between biofuels and RFNBOs also depends on the scalability/sustainability/availability of feedstock for biofuels and of renewable electricity for RFNBOs. Similar to the aviation sector, multiple options could coexist and complement each other over time, with biofuels deploying in the short-to-medium term (with advanced biofuels rapidly displacing any conventional ones) and RFNBOs covering an additional share of decarbonisation when the technologies reach the market. For drop-in RFNBOs, e-methanol and e-ammonia, one advantage is that they all rely on the same building block: renewable hydrogen. This makes increases in hydrogen production capacity relevant in any case.

If the vast majority of shipping activity in 2050 was to rely on sustainable liquid fuels (for the aforementioned reasons), the fuel mix would be split between biofuels and liquid RFNBOs. The European Commission 1.5LIFEMar scenario suggests that liquid biofuels could cover about 1 EJ of 2050 maritime demand. If the rest was to be covered by liquid RFNBOs, its demand in the maritime sector would amount to around 1 EJ as well[32].

A final energy demand of 2 EJ in the EU maritime sector by 2050 will require very ambitious operational and technological efficiency measures. These will need to be achieved in parallel with the deployment of sustainable fuels.

3.3.3. Sustainable fuel demand in road: important prospects for alternative powertrains and large-scale electrification

Today, road transport accounts for the vast majority of energy use in transport[33]. This means that the future choice of energy in road transport will be a key determinant of the scale of deployment of the different energy options across the other modes.

Due to considerations of energy efficiency and costs, an extremely wide range of scenarios by a variety of organisations point to a central role for electrification in the path to road transport decarbonisation by 2050. Using electricity in road transport vehicles enables better affordability and greater energy efficiency, making it more likely that the quantities of liquid and gaseous fuels necessary to decarbonise the economy can be sustainably produced.

All scenarios presented in Section 3.1 that focus on Europe point towards a surge in demand for electricity in road transport. Those with higher electrification rates also point to lower overall energy needs. Table 3-2 shows that estimates for European final energy needs for road transport in 2050 are close to 3 EJ of the final energy demand (out of 7 EJ across all transport) for scenarios with a high share of electric vehicles (e.g. the CAN Europe PAC scenario). Scenarios with lower shares of EVs (e.g. the Concawe HIGH scenario) see road transport energy needs increase to 5 EJ (and 9 EJ overall)[34], due to the better energy efficiency of EVs compared to other vehicle technologies[35]. Increased primary energy needs would also lead to significant increases in costs, with detrimental macroeconomic effects on economic growth and strong increases in the pressure exerted to ensure that sustainable amounts of fuels can actually be produced.

Light-duty vehicles, including passenger cars and vans, are among those that have already experienced significant shifts towards electrification. There has been substantial progress achieved over the past

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[32] If RFNBOs were to be scaled up faster and biofuels were more constrained than in the 1.5LIFEMar by feedstock availability and sustainability concerns, the volume of RFNBOs in the sector could be higher than 1EJ by 2050.

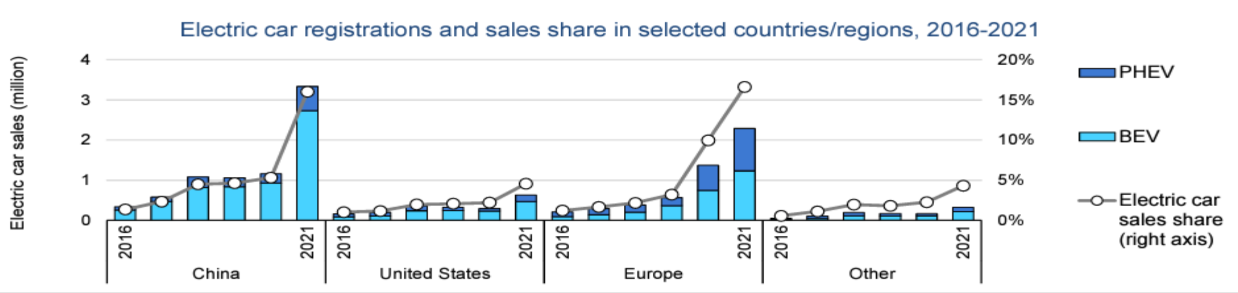
[33] Assumption based on the global share of road vehicles CO_2 emissions in the total of transport CO_2 emissions in 2020 (78%) (IEA, 2021).

[34] Complementary demand (4-5 EJ) is assigned primarily to aviation and maritime (see Sections 3.3.1 and 3.3.2).

[35] See also Section 3.2.1 and Box 1.

few years: in Europe, electric car sales reached 2.3 million in 2021, – 17% of the market share[36]. The market is also dynamically growing in other world regions (Figure 3-1).

Figure 3-1 Electric car registrations and sales share in selected countries/regions, 2016-2021



Source: Global EV Outlook 2022, IEA (2022). All rights reserved.

Notes: BEV = Battery Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle.

Due to the scale of the change, transitioning remaining light-duty vehicles to alternative powertrains, primarily electric, is far from negligible. Substantial investments are required, along with major evolutions in the automotive industry and its supply chains, including for sustainable battery materials. However, the clear possibilities of a cost-effective transition to electric vehicles, especially if compared with other technologies, and reinforced by the existence of a widespread electricity distribution and charging network, will remain key drivers for investments in this direction.

The relevance of a transition to electric vehicles is reinforced by the scale of the change already achieved today, by important synergies with parallel developments towards digitalisation and connectivity, and, most importantly, by the combination of both opportunities for job creation for early movers and risks of job losses for late movers.

The change is so significant that effects are expected to be felt more broadly across society, with impacts on jobs, skillsets and industrial competitiveness, requiring proper anticipation and handling by governments. Unsurprisingly, rewards for early movers (and risks for later movers), commensurate to the scale of change, have already prompted major action by several public administrations, stimulating a rush of supportive policies from Asia to North America.

In energy terms, considering that passenger light-duty vehicles represent around two-thirds of current road transport energy demand[37], a shift towards electrification of light-duty vehicles, in 2050, would account for roughly 1.5 EJ[38].

Heavy-duty vehicles can also benefit from a transition towards direct electrification, also with net benefits on overall energy demand, although they face larger challenges regarding battery size required, distances covered and charging times.

Since the average journey for road freight transport (per tonne of load transported) in the European Union is around 140 km, and 40% of European road freight transport activity (in tonne-kilometres) takes place on distances shorter than 300 km (Eurostat, 2022)[39], a significant portion of heavy-duty vehicle

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[36] This is in a context of a declining car market overall (-25% in 2021 vs 2019).

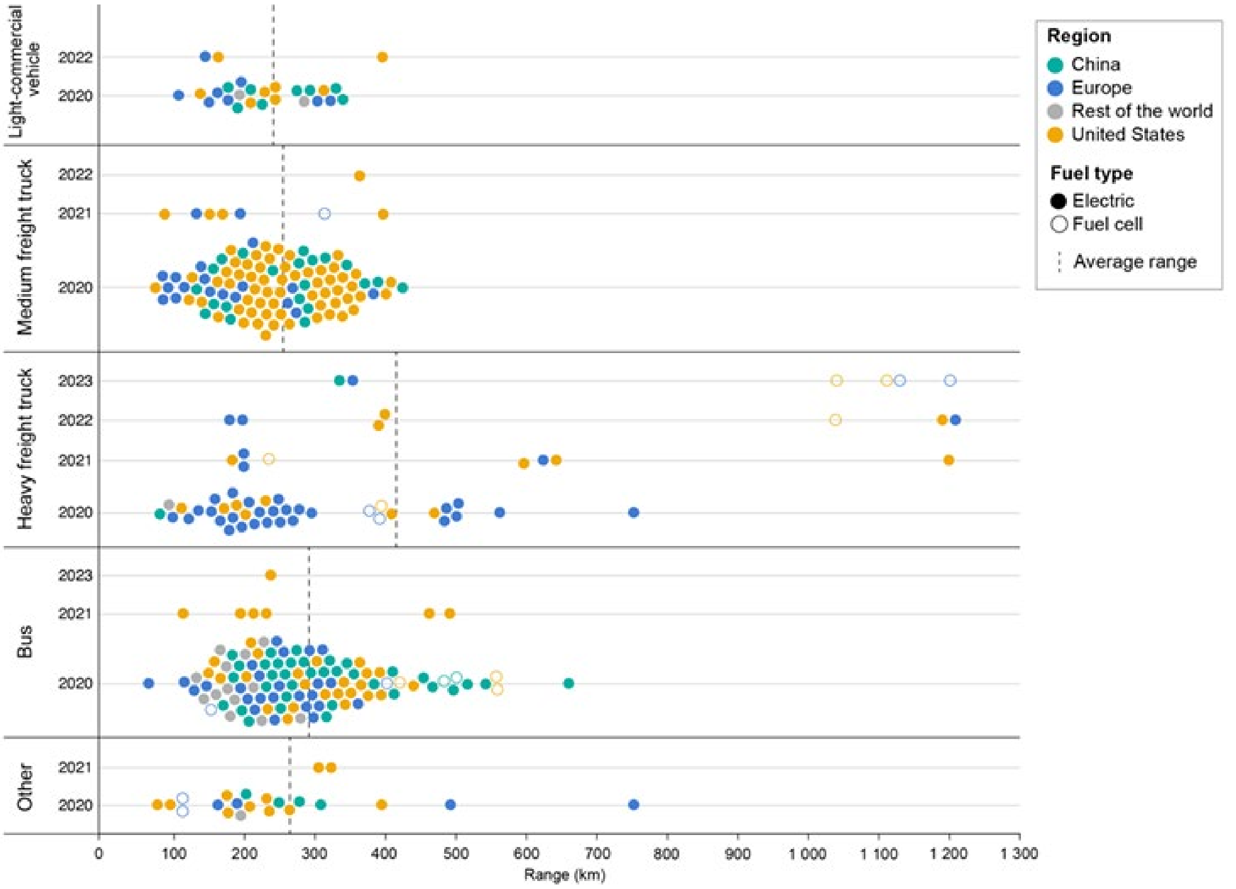
[37] Assumption based on the global share of light-duty vehicles CO_2 emissions in the total of light-duty vehicle, bus and minibus, and heavy trucks CO_2 emissions in 2020 (60%) (IEA, 2021).

[38] Based on a total energy demand for road transport of 2.5 EJ by 2050, representative of a very energy efficient sector thanks to the combination of large-scale electrification and demand-side measures.

[39] Data for the year 2021.

activity has a realistic potential to electrify. Better cost effectiveness against alternatives, as flagged by major industrial players in the field (Gründler and Kammel, 2021) and by a number of researchers (IEA, 2018, Plötz, 2022, Ainalis et al., 2020, ITF, 2022), shows that this is a viable option. Further confirmations are visible in the models of zero-emission heavy-duty vehicles currently offered and announced by the industry, covering ranges of several hundred kilometres. Among those powertrains, electric ones[40] are far more numerous than fuel cell ones, with nearly no fuel cell models amongst the lighter segments (light-commercial vehicles and medium-freight trucks) and very few in the heavier ones (Figure 3-2).

Figure 3-2 Current and announced zero-emission heavy-duty vehicle models by segment, release year and powertrain in major markets, 2020-2023



Source: Global EV Outlook 2021, IEA (2021). All rights reserved.

Fuel cell and full electric solutions may also be among most cost-competitive solutions if charging/refuelling infrastructure can be effectively brought to a fairly high rate of utilisation[41], when compared to hybrid solutions still relying on liquid fuels, whether fossil or sustainable (IEA, 2020). This is shown in Figure 3-3. There are however large risks of costs increments for users in case of a general underutilisation of charging and/or refuelling infrastructure, pointing to the importance of deploying solutions strategically. As battery costs are proportional to their size/capacity, using batteries with less than the 700 km range considered in Figure 3-2 would also significantly help decrease the capital costs, and thus the total cost of ownership, of battery electric trucks.

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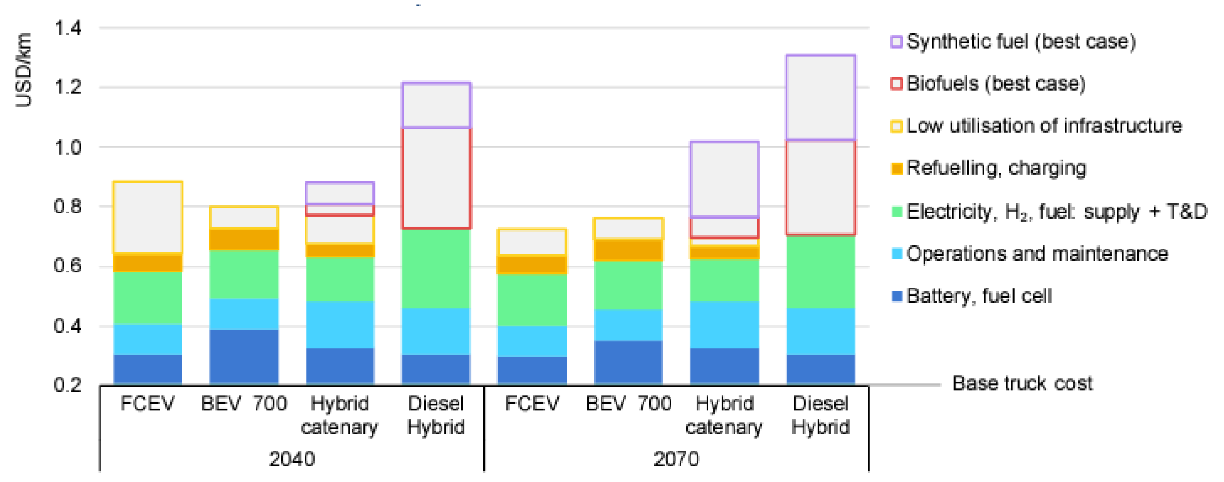
[40] Full battery electric and plug-in hybrid electric.

[41] With fossil fuel prices on an upward trajectory (driven e.g. by taxes based on local pollutants and CO_2 emissions).

Figure 3-3 Total cost of ownership of heavy-duty trucks by low-carbon fuel in the IEA Sustainable Development Scenario, 2040 and 2070

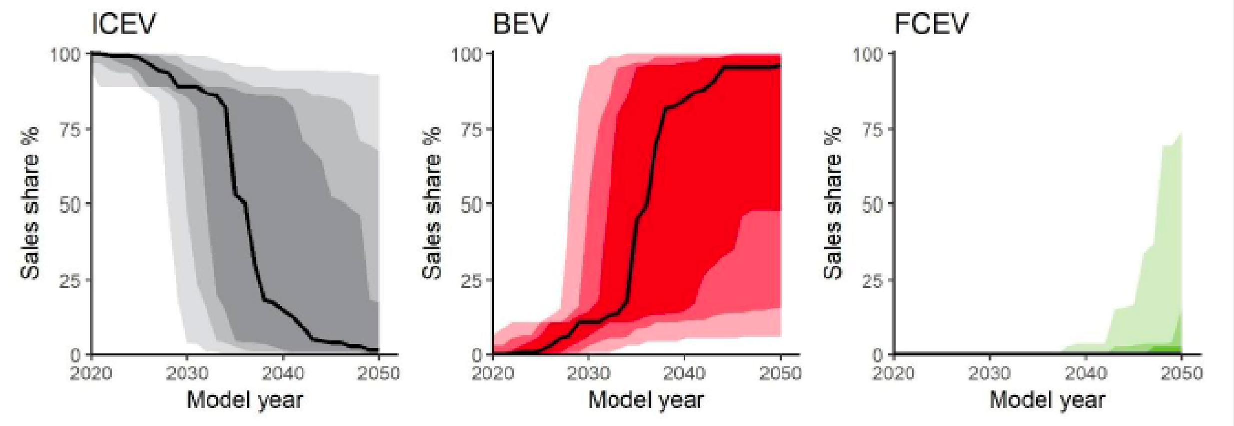


Source: Energy Technology Perspectives 2020, IEA (2020). All rights reserved.

Note: The assessment is not region-specific.

Recent research, focused on Europe and investigating the financial viability of battery electric vehicles (BEVs), electric road system vehicles (ERSVs) and fuel cell electric vehicles (FCEVs), clearly shows that hydrogen FCEVs are less cost-competitive than the other two zero-emission technologies (ITF, 2022 and Figure 3-4). This analysis points to the fact that FCEVs might play a niche role in the future fleet of heavy-duty road vehicles, corroborating other analyses coming to similar conclusions (such as Plötz, 2022, Gründler and Kammel, 2021, MIMS, 2022, Armaroli et al., 2022, Traton, 2022 and ITF, 2021). These analyses raise important doubts about whether large-scale hydrogen refuelling infrastructure would be sufficiently utilised and call into question whether policies should necessarily remain technology neutral. The mass-market adoption of hydrogen as a fuel for trucks would require large amounts of expenditure (on hydrogen transport, storage and distribution infrastructure for transport applications) compared to focusing on low-regret investments, such as the reinforcement of the electricity network[42].

Figure 3-4 Potential sales shares of lowest total-cost-of-ownership technology accounting for uncertainty (excluding ERSVs and focusing on Europe)



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[42] Similar concerns have been flagged for the use of hydrogen in buildings, where it would likely be outcompeted by heat pumps. See, for example, IPCC, 2022, IEA, 2021, Uerckerdt at al., 2021, Flis and Deutsch, 2021, ICCT, 2021, amongst others.

Source: ITF (2022).

The “Expected Adoption scenario” of the “Making zero-emissions trucking possible” report also suggests a near-full penetration of battery electric trucks in the urban and regional segments by 2050 (MPP, 2022). This is due to the estimated differences in when total cost of ownership (TCO) parity for battery electric trucks and hydrogen electric trucks[43] versus trucks running on internal combustion engines for Europe will occur[44]. This is associated with a very marginal penetration of hydrogen electric trucks by 2050 (< 1% sales share). In the long-haul segment, hydrogen electric trucks represent 35% of the sales share in 2050, with the rest being covered by battery electric trucks, which penetrate the segment massively between 2030 and 2040. In the "Expected Adoption scenario”, Europe is the region with the highest penetration of alternative powertrains in the trucks sector, and the region with the highest electrification rate of trucks. This translates into 8.4 million battery electric trucks across Europe by 2050, and half a million hydrogen electric trucks, displacing almost fully any internal combustion engine truck.

Assuming a near-full transition of the road transport sector by 2050 to alternative powertrains with an energy demand split of roughly 10% hydrogen (likely optimistic, based on the considerations above) in the long-distance segment of heavy-duty vehicles and 90% electricity for most other vehicles, the heavy-duty road sector would need around 0.1-0.2 EJ of hydrogen and close to 1 EJ of electricity in 2050[45]. Scenarios with complementary demand for sustainable fuels such as sustainably produced biofuels and RFNBOs would most likely see first a displacement of hydrogen, rather than electricity, due to more attractive total cost of ownership profiles for electric trucks and buses (MIMS, 2022, Armaroli et al., 2022, ITF, 2022).

As in the case of light-duty road vehicles, the main constraints that could limit electrification in heavy-duty vehicles may relate with material demand, at least in the bridging phase towards large scale adoption (ITF, 2021), and also because of sustainability-related constraints, requiring careful consideration for the promotion of best practices (IEA, 2019, IEA, 2021 and Armaroli et al., 2022).

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[43] Fitted with a fuel cell electric powertrain.

[44] Around 2025 in the urban and regional segments, and in 2033 in the long-haul segment, for battery electric trucks. Hydrogen electric trucks will be available from 2035/40 onwards in all segments.

[45] Based on a total energy demand for road transport of 2.5 EJ by 2050, representative of a very energy efficient sector thanks to the combination of large-scale electrification and demand-side measures.

4. WHICH FUEL FOR WHICH TRANSPORT MODE

Key findings

- **Different sustainable fuels will be suitable for different transport modes and transport applications** depending on the technical specifications of the fuel, the sustainability characteristics, feedstock availability, cost-competitiveness and technology readiness.
- **Direct electrification from renewable energy** is the most suitable option for the decarbonisation of **road transport and short haul shipping**. However, the low energy density of the batteries compromises its use beyond short and possibly medium haul.
- **Liquid and gaseous sustainable fuels** should be primarily dedicated to transport sub-sectors that cannot be easily electrified, i.e. the **heaviest and longest distance modes**. This would apply mainly to aviation and maritime, and it may in part apply to heavy-duty, long-haul road transport vehicles.
- **Renewable e-liquids** are interesting options to decarbonise modes by 2050 that cannot shift towards direct use of electricity, such as aviation and shipping.
- Heavy-duty road, short-range aircraft and shipping might be candidates for **renewable hydrogen**, but significant technical challenges remain. In road transport, many hydrogen applications are likely to be outcompeted by direct electrification.
- **E-ammonia and e-methanol** are competitive candidates for **maritime fuels**, although their adoption remains uncertain. Safety issues are a barrier for ammonia, and the sourcing of carbon remains a challenge for methanol.

The overview developed in Chapter 2 outlines what are the different options suitable as sustainable transport fuels, offering insights on their alignment on sustainability.

The critical review in Chapter 3 identifies key characteristics of the transport activity, energy demand and sustainable fuel demand in the EU, with a focus on the 2050 timeframe. The analysis developed in Chapter 3 also outlines what are the likely magnitudes of demand for different transport fuels. The assessment draws on different scenarios related to transport and energy developments in the EU. It also looks at analytical inputs that are specific to different transport modes drawn from key references in energy, decarbonisation and sustainability analyses.

This Chapter builds on the overview in Chapter 2 and the critical review in Chapter 3 to identify which sustainable fuel could be the best fit for which mode of transport. For this, we consider the technical feasibility, safety constraints, availability, sustainability criteria, cost competitiveness and technology readiness.

The modes of transport taken into account include aviation, maritime transport, heavy-duty road, and light-duty road. All of them are divided into two sub-categories: short- and long-distance.

The fuel categories considered include liquid and gaseous biofuels, RFNBOs, direct electrification and other options, as described in Chapter 2.

RFNBOs include renewable hydrogen, e-hydrocarbons, e-methanol and e-ammonia. Hydrogen from biomass gasification using advanced feedstock is also considered. Other fuels considered include fossil hydrogen with carbon sequestration, RCFs, and hydrogen produced using nuclear power, although these are not developed in depth.

Fossil hydrocarbons whose emissions are offset by carbon removal and storage technologies are discussed as possible options, even if not included in the summary tables.

Finally, PBtL fuels are integrated into the considerations developed for biofuels, taking into account the significant reductions in land use demand that they enable.

4.1. Technical feasibility and safety constraints

The first factor to be assessed concerns the technical feasibility, including safety aspects. This includes the situations where low technology readiness means that fuels do not pass safety standards. Table 4-1 illustrates the resulting assessment and, in particular, it points to areas where technical challenges tend to exclude some options.

Key examples include:

- The case of gaseous fuels in aviation, where technology readiness is very low, despite ongoing efforts to increase levels of technology readiness (especially for hydrogen). For hydrogen aircraft, commercial adoption is being considered over short ranges, but it is still a speculative prospect (ITF, 2021, ICAO, 2022 and ICCT, 2022)[46]. Methane is not generally considered as a possible aviation fuel.
- The case of ammonia has prospects limited to maritime applications, mainly due to its toxicity. However, even in maritime transport, it faces challenges due to the need to develop technical specifications and handle risks that are more significant in comparison with methanol (Kaas, 2021).
- The specific difficulties faced by hydrogen in long distance aviation and shipping, mainly due to its poor volumetric energy density. This adds to the technical difficulties to keep it in a liquid state at extremely low temperatures. However, there is research into the circumstances capable to give this option a greater technical feasibility in shipping (ICCT, 2020, ICCT, 2020b and ICCT, 2022).
- Similar challenges arise for electrification in long-distance shipping and aviation due to the low energy density and low specific energy of batteries.

Observations for other fuels are mainly related to the varying experiences with their production volumes and real-world experience to date. In particular:

- Even if technically feasible and commercially available, methane is far less frequently used in road transport than liquid fuels due to infrastructure-related challenges.
- Drop-in liquid fuels face lower technical barriers than ethanol, even if the latter is used at high blend level in Brazil.
- Hydrogen fuel cell vehicles are technologically ready, but far from being as widespread as combustion vehicles or battery electric vehicles.
- Battery electric vehicles face fewer technical challenges on short trips than on long distances, due to the higher likelihood of requiring higher power charging on longer distances, with possible drawbacks on battery durability.

Even though it has been based on an accurate desk review and literature evidence, Table 4-1 remains the appreciation of the authors and should only support decision makers by providing the broad picture in one visual.

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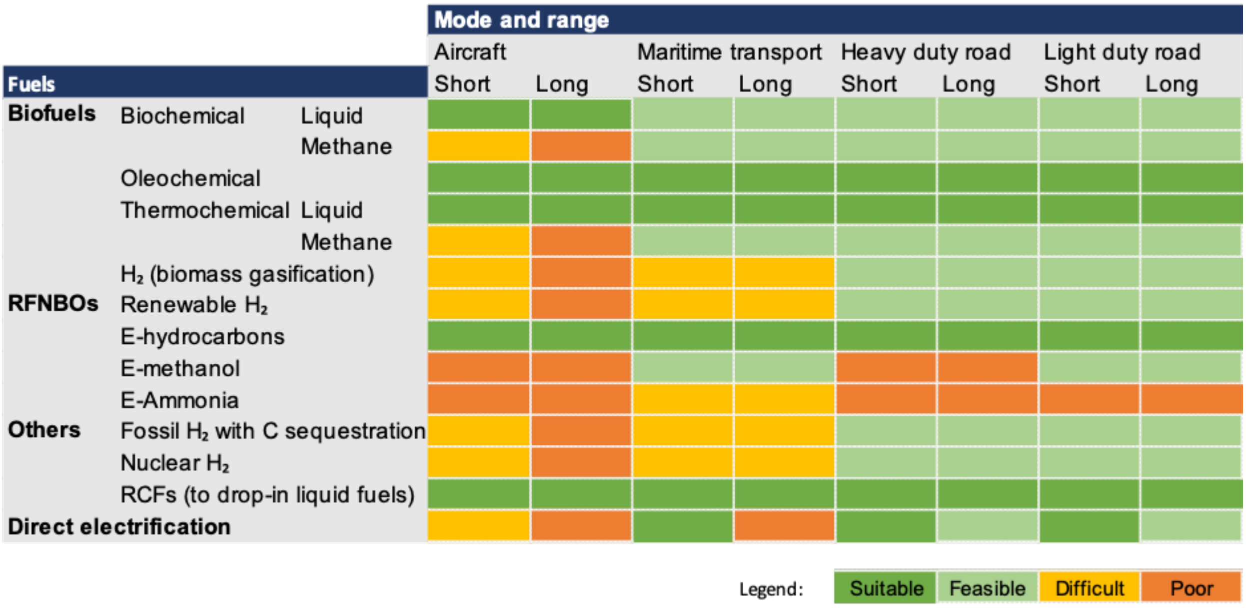
[46] This adds to uncertainties regarding the use of hydrogen as a fuel, when taking into consideration non-CO_2 climate forcing effects of water emissions at high altitude (NLR, 2022).

Table 4-1 Match-making between fuels and end-use applications - Technical feasibility



Fuels			Aircraft Short	Aircraft Long	Maritime transport Short	Maritime transport Long	Heavy duty road Short	Heavy duty road Long	Light duty road Short	Light duty road Long
Biofuels	Biochemical	Liquid	Suitable	Suitable	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
		Methane	Difficult	Poor	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
	Oleochemical		Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable
	Thermochemical	Liquid	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable
		Methane	Difficult	Poor	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
	H_2 (biomass gasification)		Difficult	Poor	Difficult	Difficult	Feasible	Feasible	Feasible	Feasible
RFNBOs	Renewable H_2		Difficult	Poor	Difficult	Difficult	Feasible	Feasible	Feasible	Feasible
	E-hydrocarbons		Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable
	E-methanol		Poor	Poor	Feasible	Feasible	Poor	Poor	Feasible	Feasible
	E-Ammonia		Poor	Poor	Difficult	Difficult	Poor	Poor	Poor	Poor
Others	Fossil H_2 with C sequestration		Difficult	Poor	Difficult	Difficult	Feasible	Feasible	Feasible	Feasible
	Nuclear H_2		Difficult	Poor	Difficult	Difficult	Feasible	Feasible	Feasible	Feasible
	RCFs (to drop-in liquid fuels)		Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable
Direct electrification			Difficult	Poor	Suitable	Poor	Suitable	Feasible	Suitable	Feasible

Legend: Suitable Feasible Difficult Poor

Source: author elaboration developed for this analysis.

4.2. Availability and sustainability criteria

The second factor to be assessed concerns the fuel availability and its alignment with sustainability requirements, particularly regarding:

- Life-cycle GHG emissions, including indirect land use change effects.
- Production efficiency, covering energy, material/resource efficiency and water requirements.

Assessing the overall sustainability impacts for a fuel is a complex task. It is not easy to compile the different sustainability parameters into a single indicator. Additionally, different analysts with the most expertise in each field performed specific analysis of different sustainability criteria.

Table 4-2 attempts to make this holistic assessment, based on the views of the authors of this work. It also tries to consider important trade-offs[47] and attempts to summarise, in one place, the considerations developed in Chapter 2 with greater granularity[48]. The assessment takes into account a progressive scale, ranging from poor performance in case of significant limiting factors to good performance in case of a few limitations, good sustainability alignment, and the potential to see improvements in the future.

Key indications developed in Chapter 2 include:

- Better performance of fuels from low-carbon electricity if compared with biomass as a primary resource, due to lower land use change pressures.
- Within biomass-based pathways, worse performance for options reliant on food and feed as feedstock, where availability remains limited[49].

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[47] The improvement of one factor may negatively impact another one (e.g. higher biofuel yield per hectare may be detrimental to pollutant emissions due to higher use of fertilisers), which stresses the importance of carrying out a careful assessment from a holistic point of view.

[48] In the choice of fuels based on sustainability criteria, expected volumes matter and may impact the overall sustainability of the solution (e.g. local production and use can remain more controllable and manageable than a massive production unit leading to deploying monoculture, or massive forest harvesting).

[49] Even if there are some exceptions (e.g. oil cover crops and oil trees on marginal land), scaling up is likely to be limited.

- Limitations for RCFs due to small volumes of renewable carbon available with these pathways, and the lock-in effect from fossil fuel.
- Limitations for pathways based on offsets from carbon removal and storage due to the poor performance to date of carbon capture and storage as a technology to deliver net emission savings.
- Lower limitations for renewable electricity directly feeding battery vehicles due to higher energy efficiency (in land transport). However, there are challenges related to the need to develop, at scale, supply chains of critical materials, linked with possible supply bottlenecks and other geopolitical issues, mainly related to the economic implications of changes in the relevance of different global commodities (IRENA, 2019, IEA, 2021, CSIS, 2021 and Bordoff O'Sullivan, 2022).

Table 4-2 Fuels and feedstock – Availability and sustainability constraints

		Source/Feedstock				
		Conventional	Advanced			
Fuels		Food- & Feed-based	Non-Food- & Feed-based	Waste-based	Electricity	Other
Biofuels	Biochemical	🟧	🟨	🟨		
	Oleochemical	🟧	🟨	🟨		
	Thermochemical	▨	🟨	🟨		
	H_2 (biomass gasification)	▨	🟨	🟨		
RFNBOs	Renewable H				🟩	
	E-hydrocarbons				🟩	
	E-methanol				🟩	
	E-Ammonia				🟩	
Others	Fossil H_2 with C sequestration					🟩
	Nuclear H					🟩
	RCFs			🟨		
Low-carbon electricity					🟩	

Legend:			
	🟩 Limited constraints	🟨 Constraints	🟧 Strong constraints
	Not matching	▨ Unlikely	

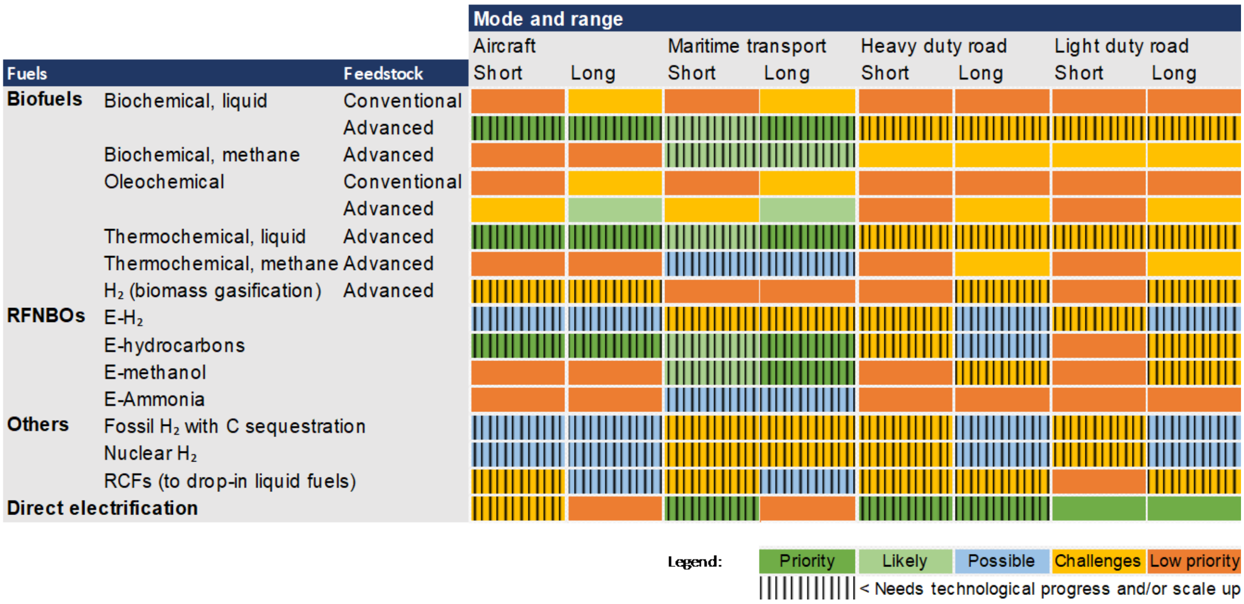
Source: author elaboration developed for this analysis.

4.3. Summary of all factors

Table 4-3 summarises the qualitative evaluation of all fuels and their link with the main transport end-use applications. It is based on the assessments presented in Table 4-1 (technical feasibility) and Table 4-2 (availability and alignment with sustainability constraints) and combining these with the cost assessments discussed in Chapter 2. In doing so, it provides insights on which fuel is best suited for which application.

Even though it has been based on an accurate desk review and literature evidence, Table 4-3 remains the appreciation of the authors and should only support decision makers by providing the broad picture in one visual.

Table 4-3 Match making between fuels and transport modes – Summary of all factors



			Mode and range							
			Aircraft		Maritime transport		Heavy duty road		Light duty road	
Fuels		Feedstock	Short	Long	Short	Long	Short	Long	Short	Long
Biofuels	Biochemical, liquid	Conventional	🟧	🟨	🟧	🟨	🟧	🟧	🟧	🟧
		Advanced	🟩▥	🟩▥	🟢▥	🟩▥	🟨▥	🟨▥	🟨▥	🟨▥
	Biochemical, methane	Advanced	🟧	🟧	🟢▥	🟢▥	🟨	🟨	🟨	🟨
	Oleochemical	Conventional	🟧	🟨	🟧	🟨	🟧	🟧	🟧	🟧
		Advanced	🟨	🟢	🟨	🟢	🟧	🟨	🟧	🟨
	Thermochemical, liquid	Advanced	🟩▥	🟩▥	🟢▥	🟩▥	🟨▥	🟨▥	🟨▥	🟨▥
	Thermochemical, methane	Advanced	🟧	🟧	🟦▥	🟦▥	🟧	🟨	🟧	🟨
	H_2 (biomass gasification)	Advanced	🟨▥	🟨▥	🟧	🟧	🟧	🟨▥	🟧	🟨▥
RFNBOs	E-H_2		🟦▥	🟦▥	🟨▥	🟨▥	🟨▥	🟦▥	🟨▥	🟦▥
	E-hydrocarbons		🟩▥	🟩▥	🟢▥	🟩▥	🟨▥	🟦▥	🟧	🟨▥
	E-methanol		🟧	🟧	🟢▥	🟩▥	🟧	🟨▥	🟧	🟨▥
	E-Ammonia		🟧	🟧	🟦▥	🟦▥	🟧	🟧	🟧	🟧
Others	Fossil H_2 with C sequestration		🟦▥	🟦▥	🟨▥	🟨▥	🟨▥	🟦▥	🟨▥	🟦▥
	Nuclear H_2		🟦▥	🟦▥	🟨▥	🟨▥	🟨▥	🟦▥	🟨▥	🟦▥
	RCFs (to drop-in liquid fuels)		🟨▥	🟦▥	🟨▥	🟦▥	🟨▥	🟨▥	🟧	🟨▥
Direct electrification			🟨▥	🟧	🟩▥	🟧	🟩▥	🟩▥	🟩	🟩

Legend: 🟩 Priority 🟢 Likely 🟦 Possible 🟨 Challenges 🟧 Low priority

▥ < Needs technological progress and/or scale up

Source: author elaboration developed for this analysis.

Key insights emerging from Table 4-3, also reflecting the broader discussion developed in Chapters 2 and 3, point to the following considerations:

Direct electrification from renewable and other low-carbon resources is the best option for the decarbonisation of road transport. It is also well suited for the transition of inland navigation and short-sea shipping vessels. Key challenges relate to supply chain bottlenecks of critical materials linked with geopolitical issues.

Biofuels, if drop-in, have the advantage of a high compatibility profile with existing fuels. They also have a competitive cost profile, especially in the near term if compared with other options. However, they face availability limitations when supply is focused on sustainable feedstocks, if their scope of adoption includes road transport. These constraints are not only applicable to the European context, but also to global dynamics initiated by policies developed in Europe (Searchinger et al., 2022). Availability constraints are also influenced in the longer term by the fact that there will be competing demand for biogenic carbon from sectors other than transport – in particular the construction industry and the chemical industry (ETC, 2021). This suggests that their best use needs to be focused on transport modes for which a transition towards direct electrification is subject to higher costs and technical feasibility challenges, such as aviation and maritime transport. Price gaps between biofuels and e-hydrocarbons, even in long-term assessments, are also a reason to underline the importance for policymakers of requiring strict sustainability conditions.

The case of biomethane in transport is hampered by competing demand in sectors (for example, the steel industry) where biomethane shall replace fossil methane. This is especially the case in the near term, following the war in Ukraine (Trinomics, 2022). It also has difficulties to piggyback on the natural gas infrastructure. For example, European demand for natural gas vehicles is not picking up while natural gas prices are rising. In addition, the limited scope to reduce life-cycle GHG emissions from fossil methane also limits prospects for future demand growth, in a decarbonising context.

Amongst RFNBOs, **e-hydrocarbons** are subject to cost, technology readiness and energy efficiency challenges, limiting their capacity to contribute at scale to the transition in the very near term. They are also subject – like all other RFNBOs – to much lower sustainability constraints from land use requirements if compared with biofuels. Like hydrogen for large-scale industrial plants, e-liquids can benefit significantly from the increased reliance of the energy system on renewable electricity, with important cost reduction prospects. A key advantage of e-hydrocarbons with respect to hydrogen is the far easier capacity to be transported, stored and distributed to transport vehicles, while relying on existing infrastructure. While proposed European legislation pragmatically allows for sourcing CO_2 point sources to produce e-liquids (European Commission, 2023), effective GHG emission abatement in the longer term will require technologies like DAC technologies and electrochemical CO_2 reduction. These require major developments to increase their level of technology readiness. The prospects of cost reductions for hydrogen and electricity production, including beyond the borders of the EU, as well as the ease of handling, make e-liquids a relevant option for decarbonising transport modes that cannot shift towards direct use of electricity by 2050 due to technical limitations and cost barriers. E-liquids are therefore most suitable for shipping and aviation. For aviation, e-liquids (namely e-hydrocarbons) have an advantage over other RFNBOs, as they can be produced with the very specific chemical properties needed for turbojet aircraft.

Renewable hydrogen, also a RFNBO, has the same advantages in terms of cost reduction opportunities as e-liquids. Like nuclear hydrogen, it has the benefit of not relying on DAC and electrochemical CO_2 reduction technologies, while being a low-carbon option. Unlike fossil hydrogen with carbon sequestration (a strict condition, in addition to others, to make it available with low life-cycle emissions), it can see its cost competitiveness increase independently from fossil energy prices.

However, all types of hydrogen face significant technical challenges and high costs to be transported, stored and distributed to transport vehicles. Trucks may be a candidate for hydrogen use from a technical perspective, but a growing body of evidence shows that fuel cell trucks risk being outcompeted by battery electric ones, especially in the near term. This is similar to what happens for buildings when comparing hydrogen for space heating with electrically powered heat pumps. Part of the reason is that hydrogen transport, storage and distribution costs are hard to abate if volumes of hydrogen distributed remain limited and focused on a very specific end-use. Another part is the need to scale up fuel cell production to cut unit costs for these devices, and this is challenging because direct electrification has a better cost competitiveness profile also in the car market[50].

All types of hydrogen also face important technical challenges for direct usage as an energy carrier on large shipping vessels and long-distance aircrafts due to their low volumetric energy density and the need for liquefaction. Its role is far more likely to emerge as a success story to replace fossil-based hydrogen in existing uses (fertiliser production, chemical plants), new industrial uses (such as steelmaking or chemical plants), and as a feedstock combined with biogenic carbon, allowing to increase biofuel yields in PBtL plants, which may be seen as a hybrid form of biofuels and RFNBOs.

E-methanol and e-ammonia are relevant RFNBOs for the shipping sector, due to lower production costs than e-liquids and lower investment risks for the development of new fuel distribution infrastructures. E-ammonia has the advantage of lower costs and no reliance, even in the long term, on technologies requiring atmospheric carbon capture (DAC), which still have low technology readiness. Methanol has the advantage of lower toxicity and greater ease of handling compared to ammonia. With adequate investments in infrastructure, methanol and ammonia may outcompete liquid e-fuels

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[50] Due to effects on the scale of demand and product development, i.e. lower near-term cost competitiveness of FCEVs may have long-lasting implications too.

in shipping. Toxicity limits the scope to see them used on a large-scale in other transport modes, particularly for ammonia.

RCFs and RFNBOs using concentrated carbon sources of fossil origin can facilitate emissions reductions in industry and transport in the near term (while point sources of fossil carbon are widespread), especially in aviation and shipping, but they are limited by the temporary/transitional opportunity to deliver deep decarbonisation.

Fossil fuels with emissions offsetting (not included in Table 4-3) are not analysed in depth due to a number of performance related factors. Offsets developed to date mainly consist of offsetting through forestation projects, with emission absorption times occurring over decades. This is not aligned with the immediate emission production times through fuel combustion. These practices are exposed to significant risks of delaying the reduction of GHG concentrations. To be effective for deep decarbonisation, technological solutions involving the geological storage of CO_2 emissions require carbon sources that are either part of a closed loop (e.g. atmospheric capture or non-fossil carbon) or are capable of resulting in net-negative CO_2 emissions. They are therefore also subject to limitations, despite being able to technically compete in terms of cost minimisation. Additional constraints derive from the need for a complex regulatory and enforcement framework to ensure effectiveness, raising doubts about the effectiveness of offsetting solutions.

The insights developed in this chapter, along with the considerations of Chapter 3, are used in the next chapter to identify the energy requirements needed by a decarbonised transport sector in the EU. These are necessary for the assessment of finance and investment needs, also developed in Chapter 5, which outlines the key priorities for policy developments.

5. FINANCE AND INVESTMENTS NEEDS

Key findings

- A decline of **annual expenditure** for transport energy needs in the long term largely depends on the extent of cost reductions for sustainable fuels. Based on current sustainable fuel cost estimates, the annual expenditure is expected to reduce at a much slower pace than the energy demand of the transport sector associated to its sustainable transition.
- The significant **differences in the energy mix between 2030 and 2050** means that action is needed to accelerate the technological developments that will allow the diversification of energy supplies at lower costs, focusing on no-regret options, whilst tackling sustainability issues.
- It is crucial to **leverage** the significant cost declines observed in the recent past, for example, the production costs of vehicle batteries or the generation cost of renewable electricity. The latter is a key component of the production cost for the majority of sustainable fuels. Cost declines are still needed for electrolyser production (which can benefit from scale increases), the optimisation of the use of biogenic carbon in PBtL processes, DAC and electrochemical CO_2 reduction (requiring technological progress, in addition to scale increases).
- The supporting infrastructure needed are fuel-specific, and would require reinforcing the electricity system, developing a dedicated hydrogen network including storage, and adapting the existing oil and liquid infrastructure to accommodate a higher share of biofuels.
- A cooperative approach between public and private sectors is needed for infrastructure development, (e.g. on technical standardisation, vehicle compatibility, or on ensuring minimum market coverage).

5.1. Investment needs in line with the European energy transition goals

5.1.1. Sustainable energy use scenario for transport in 2030 and 2050

A summary of the energy requirements suggested by the scenario analysis for the European transport sector described in Section 3.3 is included in Figure 5-1. The total demand for biofuels, renewable hydrogen, other RFNBOs, and electricity by 2050 that is analysed for finance and investment needs (Table 5-1) is aligned with the ranges identified in Section 3.3.

Table 5-1 Ranges of possible sustainable fuel demand by type and transport sub-sector with a 100% sustainable fuel mix associated to electrification and energy efficiency, by 2050

EJ	Aviation	Maritime	Road (Heavy-Duty)	Road (Light-Duty)	TOTAL
Biofuels	0.8-1*	1*	(marginal)	(marginal)	1.8-2*
RFNBOs (of which:)	1.4-1.5	1	0.1-0.2	(marginal)	2.5-2.7
e-hydrocarbons	1.2-1.3*		(marginal)		
e-hydrogen	0.2*		0.1-0.2		
Electricity	(marginal)	(marginal)	1	1.5	2.5
TOTAL	2.2-2.5	2	1.1-1.2	1.5	**6.8-7.2**

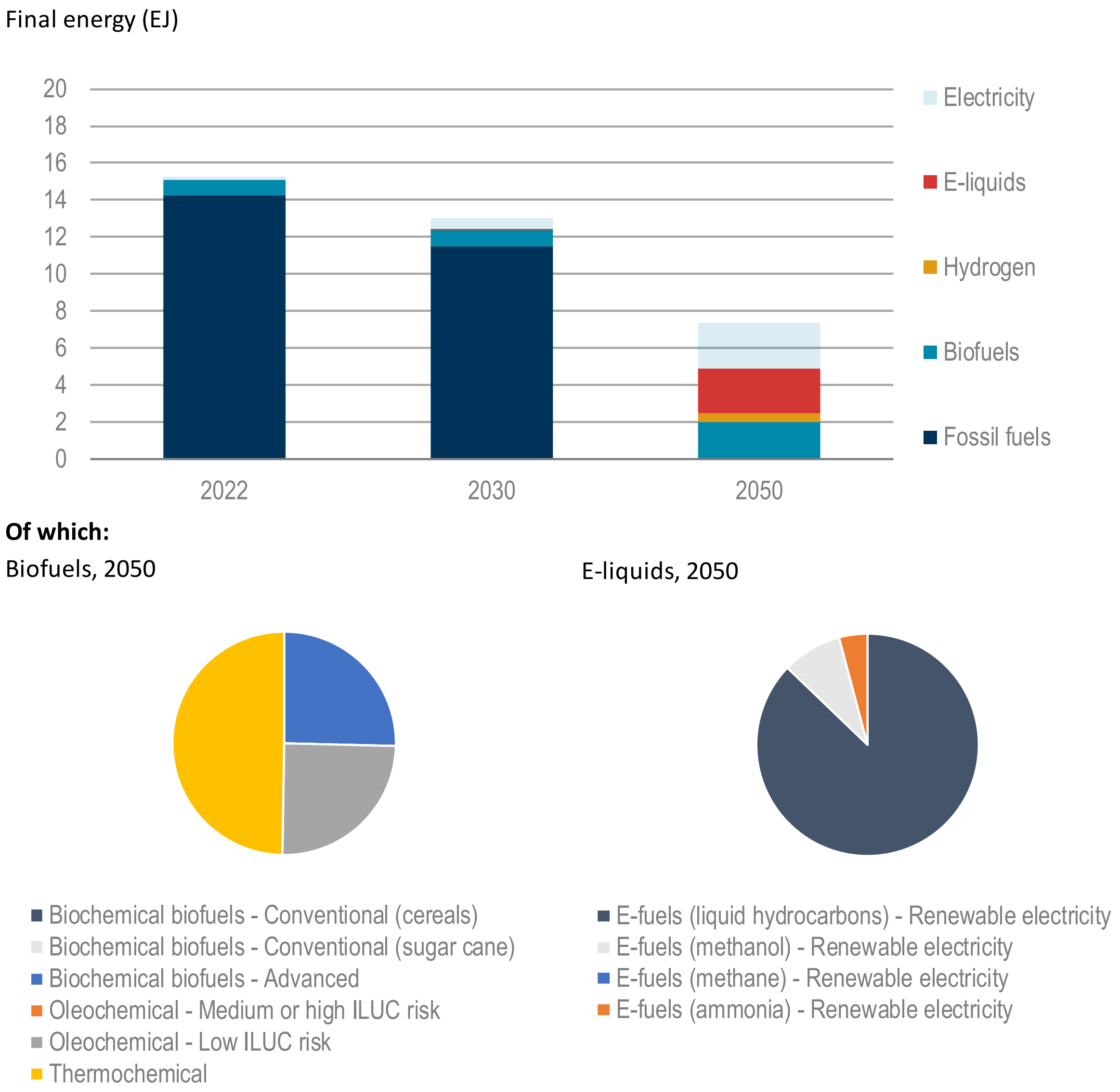
*liquid

Notes: These estimated ranges directly stem from the scenarios analysis of Chapter 3 and the sub sectorial in-depth analysis of Section 3.3. In particular, figures for aviation are broadly consistent with the second and third paragraphs of section 3.3.1; figure for maritime are broadly consistent with the last two paragraphs of Section 3.3.2; figures for road are broadly consistent with the second-to-last paragraph (heavy-duty) and the eighth paragraph (light-duty) of Section 3.3.3. As also mentioned in the above-mentioned chapter and sections, it is important to keep in mind that i) these estimates consider no or very limited residual fossil fuel use, hence depict a full transition to sustainable fuels and energy sources by 2050; ii) the quantities presented in this table also result from assumptions associated to total activity, energy efficiency and direct electrification per sub-sector by 2050.

The total transport energy use by fuel and the finance and investments needs considered in this chapter take into account the analysis on sustainability profiles and costs developed in Chapter 2 ("Overview of the different transport fuels"). It also stems from the analysis of existing scenarios and the critical analysis of the sustainable, economic and practical suitability of different fuels for different modes done in Chapter 3 ("Critical review of sustainable fuel prospects in transport") and Chapter 4 ("Which fuel for which transport mode").

In particular, the analysis developed in these previous chapters justifies the relatively large relevance of thermochemical biofuels from advanced feedstocks considered in the bottom-left pie chart of Figure 5-1. The same stands for the relevance of cellulosic and waste residues as feedstocks for biofuel synthesis via biochemical pathways and for oleochemical pathways given the low indirect land-use change (ILUC) risk of feedstocks in biofuel synthesis (Figure 5-1, bottom-left pie chart).

Figure 5-1 Final energy use by fuel type in the transport sector, EU, 2022, 2030 and 2050 (authors' own scenario)



Source: Authors' own elaboration developed for this analysis, based on figures in Table 5-1.

Note: Feedstocks for advanced biochemical and for thermochemical pathways include waste and residues from agriculture and forests that are sustainably managed.

In line with the considerations developed in Chapters 2, 3 and 4, Figure 5-1 shows:

- An acceleration of direct electrification for the end uses that can be electrified, which is paired with very significant energy efficiency improvements, especially in a context where electricity generation is progressively decarbonised[51].
- Energy efficiency improvements, including in modes that are hard to electrify, namely aviation and shipping. All energy efficiency improvements are evident in the net reduction of final energy demand between 2022 and 2030, and even more in 2050. Energy efficiency also comprises behavioural changes such as flying less and consuming more locally produced food[52].

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[51] For more information, see Section 3.2.

[52] For more information, see Section 3.2.

- A biofuel supply shift from the current mix of mainly food and feed crops, in particular cereals and vegetable oil, towards waste-based and sustainably produced lignocellulosic feedstocks with hydrogen integration via PBtL processes. These are crucial to maximise biofuel yields from biogenic carbon and to reduce land use pressures[53].
- An increased capacity for both renewable hydrogen and its derivatives to complement or even replace biofuels in transport, given the challenges faced by biofuels regarding sustainability and land use requirements, especially with increasing production volumes[54].

Regarding the last point, there is globally a greater reliance on renewable hydrogen, both for hydrogen as energy carrier and other RFNBOs, in comparison with hydrogen production from fossil fuel sources with CCS (due to increased challenges emerging regarding fossil fuel prices) or with hydrogen production from electrolysis with nuclear electricity (due to long lead times for nuclear capacity to come on stream and higher costs vs renewables like solar and wind)[55].

Figure 5-1 also reflects a dominance of non-alcoholic liquid hydrocarbons, combined with reduced quantities of liquid fuels in 2050 vs 2022, thanks to an increase of electricity use and other energy efficiency and systemic improvements in transport. This reflects a limited scope for the use of ammonia and methanol in sectors other than maritime transport.

5.1.2. Investment needs

Estimates of the expenditures associated with the energy requirements in the scenario presented in Figure 5-1 are summarised in Figure 5-2. These combine the volumes of fuels taken into consideration in Figure 5-1 and mid-point estimates of fuel costs emerging from the review developed in the "Costs" section for each fuel in Annex A (Annexes A.1.6, A.2.6, A.3.5, A.4.5, A.5.6, A.6.5, A.7.6 and A.8.5).

Table 5-2 Fuel costs assumptions: 2022, 2030 and 2050

	Total costs (USD/GJ)		
Fuel	**2022**	**2030**	**2050**
Fossil fuels	21	19	16
Fossil fuels (including current taxation rate)	50.3	48.3	45.3
Biochemical biofuels - Conventional (cereals)	24	24	24
Biochemical biofuels - Conventional (sugar cane)	20	20	20
Biochemical biofuels - Advanced	47	38	30
Oleochemical	44	35	30
Thermochemical	42	38	30
Hydrogen - Renewable electricity, requiring transport	88	72.5	62
Hydrogen - Renewable electricity, production on-site	68	56.5	48
Hydrogen - Fossil based (CCS), requring transport	84	79	70
E-fuels (liquid hydrocarbons) - Renewable electricity	97.1	62.6	52.1
E-fuels (methanol) - Renewable electricity	96.7	61.5	50
E-fuels (methane) - Renewable electricity	97.2	61.2	48.7
E-fuels (ammonia) - Renewable electricity	66.5	45.8	26.3
Electricity - EU mix	111.1	69.4	41.7

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[53] For more information, see Section 2.2.

[54] For more information, see Sections 2.2 and 2.3.

[55] Should geopolitical challenges leading to high fossil fuel (typically gas) costs be lifted, gas prices decline, and carbon capture technologies be demonstrated as successful abatement technologies, low-cost natural gas could also potentially be an alternative feedstock for sustainable hydrogen production. Nuclear electricity, given likely higher production costs in comparison with renewables in the future, could emerge more prominently in the energy mix mainly in cases where renewable electricity from solar and wind, as well as technologies allowing for greater grid flexibility, were to face significant constraints.

Source: Assumptions for elaborating this table reflect the considerations highlighted in the "Costs" sections developed for each fuel in Annex A (Annexes A.1.6, A.2.6, A.3.5, A.4.5, A.5.6, A.6.5, A.7.6 and A.8.5) (using an average single value for cost ranges). For fossil-based pathways, limited cost reductions vs a 2022 baseline reflect the uncertainty regarding future price formation mechanisms, affected by supply and demand developments, and likely subject to volatility. Price evolution should also integrate a sizable share of the cost of fuel transport, storage, and distribution infrastructure per unit energy.

These fuel costs assumptions reflect:

- Particularly high costs for energy commodities and food crops in 2022 (due to the markets after the Covid-19 pandemic and the Russian invasion of Ukraine). This affects oil in particular, which is assessed at 100 USD/barrel (21 USD/GJ[56]); electricity is at 0.4 USD/kWh (111.1 USD/GJ).
- Moderate declines in prices of fossil energy and agricultural commodities especially in the 2030 timeframe.
- Cost reductions due to technology learning and, to the degree feasible, scale increase, for advanced biofuels and RFNBOs.
- Stronger declines in electricity prices in comparison with fossil fuel prices, reflecting: i) the exceptional consequences in place during the Spring and Summer of 2022 (with European electricity prices largely affected by the surge in natural gas prices); ii) measures intended to reform electricity markets to enable lower end-user costs; and iii) expectations for an increased reliance on low-cost and low-carbon electricity in a more integrated power system (IEA, 2022).
- A contextual availability of low-cost and low-carbon electricity, particularly renewable-based, at scale, for the production of RFNBOs, which are strongly dependent on the low cost of electricity production to ensure that production costs can effectively decline.

In addition, there will be a need for significant infrastructure-related investments for the new energy carriers that are currently not transported or distributed at scale (see Section 5.2.2). These are integrated in the fuel costs assumptions in Table 5-2. These infrastructure investment requirements are primarily related to hydrogen, though some methanol and ammonia infrastructure already exists. Additional infrastructure needed for these fuels would be mainly used in maritime transport. Renewable e-hydrocarbons would rely on the existing infrastructure, without need for changes[57].

The challenges posed by the increase in transport and distribution infrastructure costs are also a key reason behind a larger reliance on e-liquids rather than hydrogen in the scenario presented in Figure 5-1, across all modes, as also discussed in Chapter 3 ("Critical review of sustainable fuels prospects in transport"). Important scale-up challenges exist for the production of e-liquids[58], but less so for their transport and distribution.

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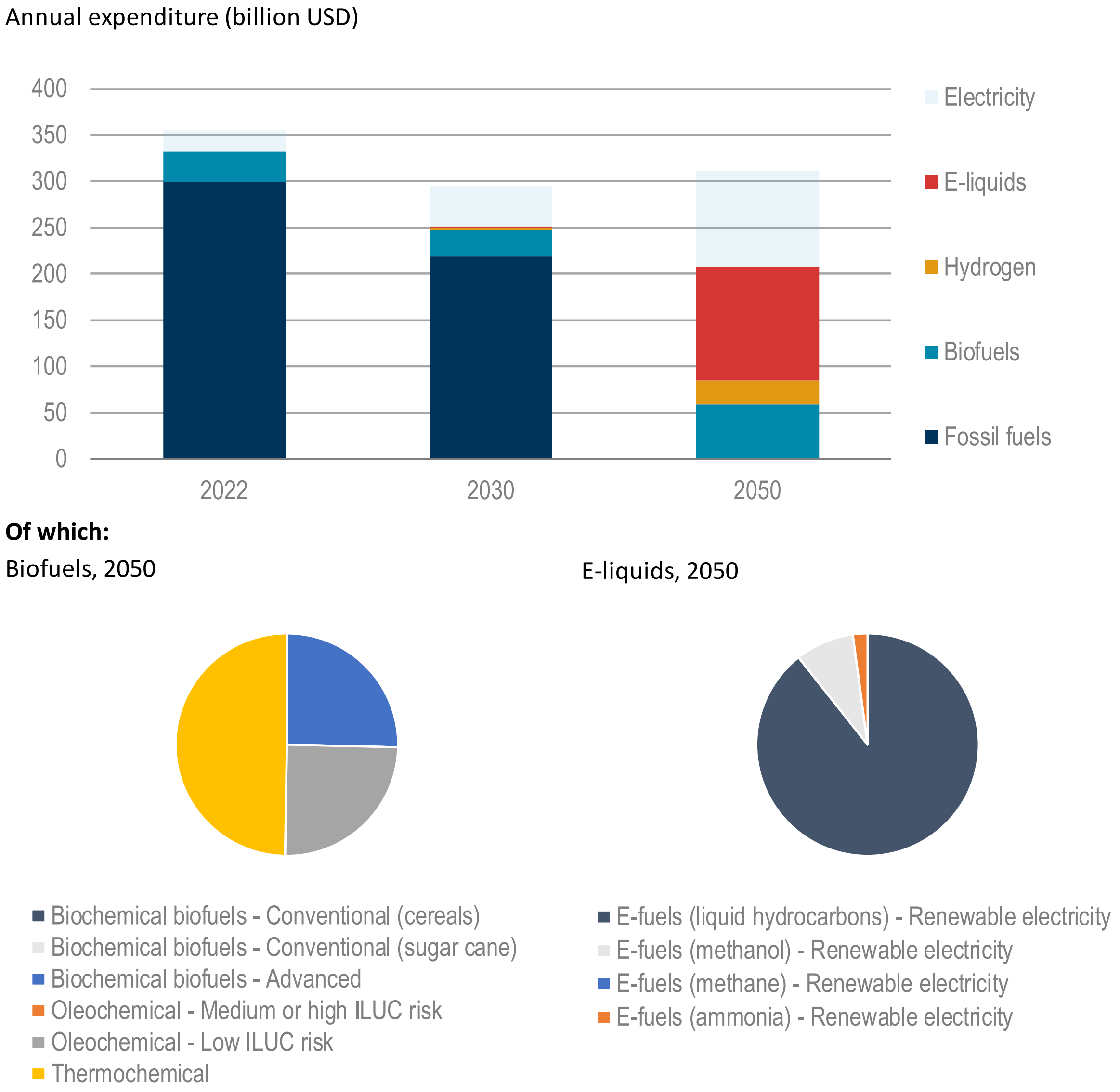
[56] Accounting for 20% refining losses.

[57] Additional investments will also be needed to renew vehicle fleets. Their total cost depends on the evolution of costs of vehicle powertrains, their design characteristics, including in particular parameters (e.g. battery size, vehicle weight), and technologies which improve energy efficiency. These costs are not included in the estimates developed here, which are focused on fuels.

[58] Because of the low technology readiness of some devices and processes involved in their synthesis, and for technologies reliant on direct air capture, also because of their current cost and energy intensity.

Figure 5-2 Annual energy expenditures by fuel type in the transport sector, EU, 2022, 2030 and 2050, (authors' own scenario)



Source: Authors' own elaboration developed for this analysis, based on Figure 5-1 (i.e. on Table 5-1) for fuel quantities, and on Table 5-2 for costs.

Note: Feedstocks for advanced biochemical and for thermochemical pathways include waste and residues from agriculture and forests that are sustainably managed.

The trends characterising Figure 5-1, Table 5-2 and Figure 5-2 lead to two important considerations:

- While there is an important reduction of the overall amount of energy required to support transport activity due to better efficiency (Figure 5-1), the higher cost of sustainable alternatives to fossil energy per unit of energy leads to a more limited decline of annual expenditures (Figure 5-2). The latter largely depend on the extent of cost reductions for sustainable fuels that can be achieved thanks to innovation and technological progress. The shift to affordable renewable electricity is of paramount importance in the 2050 transport fuel mix depicted in Figure 5-1. Renewable electricity is at the heart of 70% of this fuel mix (direct electrification plus hydrogen plus e-liquids in Figure 5-1), via direct electrification but also via the production of RFNBOs (e-liquids and hydrogen)[59]. This shift, paired with strong energy efficiency improvements, enables the significant transition of the transport energy mix post 2030 and towards 2050 in the scenario in Figure 5-1 without leading to net increases in the annual expenditures (Figure 5-2).

- Failing to deploy renewable electricity at scale and at an affordable price would create significant challenges. Firstly, meeting the European decarbonisation goals would be far more challenging due to the much higher volumes of primary energy needed if electricity did not significantly contribute to the 2050 transport energy mix. This would bring significant sustainability issues associated with these higher quantities of primary energy. Secondly, should reliance on traditional fossil fuels continue, the EU would be far more exposed to increases in fossil energy prices due to higher demand paired with higher exposure to changes in supply volumes. This could stem from unilateral decisions by the main fossil energy producers such as the Organisation of Petroleum Exporting Countries plus Russia (OPEC+).

5.2. Nature of the investments required

Even accounting for uncertainties in the choices made here, the characteristics of Figure 5-1 and Figure 5-2, and in particular the significant differences in the energy mix between 2030 and 2050, point towards the need to undertake significant action allowing the acceleration of technological developments.

5.2.1. Renewable electricity and fuel production

In this context, it will be crucial to build on the very significant recent reductions in production costs of renewable electricity, as well as on the progress achieved on battery costs[60]. These developments are already leading to important changes in investment decisions towards transport electrification, thanks to clear prospects for net savings in terms of total cost of ownership.

However, similar investment decisions in liquid and/or gaseous sustainable fuels such as biofuels and RFNBOs are lagging behind. A first reason for this lies in the higher costs and lower readiness of some of the technologies enabling their production. Additional limitations for the mobilisation of investments relate to the challenges associated with the sustainability of conventional biofuel production. This is especially relevant in the case of rapid scale-ups, as already discussed in Section 2.2 dedicated to biofuels.

Cutting costs for technologies that desalinate and electrolyse water are a crucial focus for RFNBOs. It is also relevant for advanced biofuels and the optimal use of biogenic carbon, given the need for affordable renewable hydrogen for renewable PBtL processes. Cutting costs of direct air capture (DAC) and the electrochemical reduction of CO_2 is also likely to be a major enabler of a large-scale development of renewable e-hydrocarbons, along with cost reductions in renewable electricity production.

Making progress in technology readiness and costs reductions for the production of liquid and/or gaseous sustainable fuels is particularly relevant for the modes that are hard-to-electrify. Such progress will therefore be particularly important in meeting the sustainability and decarbonisation requirements

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[59] For the production of RFNBOs, the electricity could be produced outside of Europe (e.g. if justified by lower costs such as in particularly sunny regions), and the RFNBOs imported.

[60] And expectations for continued capacity to come at low costs, despite the current inflationary pressures on commodity markets.

for the maritime and aviation sectors that are enshrined in the European Climate Law (European Commission, 2021).

5.2.2. Infrastructure

Another challenge is the need for infrastructure developments for many of the sustainable fuels. This is most relevant for hydrogen, methanol and ammonia, as they are currently not in use as energy carriers for transport vehicles. This is also crucial for electricity, given the importance of direct electrification in the decarbonisation of transport (Figure 5-1).

Several infrastructure developments needed to enable a transition to a diversified, sustainable and decarbonised fuel mix in 2050 are already spelled out in the Alternative Fuels Infrastructure Regulation (AFIR) proposed by the European Commission in the context of the 'Fit for 55' policy package (European Commission, 2021). These include publicly accessible chargers for electric road vehicles, shore-side electricity supply in ports, infrastructure for electricity supply for stationary aircraft in airports, infrastructure to enable methanol and/or ammonia bunkering in the maritime sector, and refuelling stations for hydrogen-powered vehicles. This is complemented by the provisions of the Energy Performance in Buildings Directive recast for the deployment of private chargers in public buildings and multi-dwelling homes.

Hydrogen stations are deemed most relevant for long distance and heavy-duty road transport in the proposed Alternative Fuels Infrastructure Regulation, despite remaining questions on the economic competitiveness of this approach with respect to direct electrification (ITF, 2021, ITF, 2022, Gründler and Kammel, 2021, Plötz, 2022 and discussed in Section 3.3.3). In addition, competition for available sustainable hydrogen may exist with the industry sector. Concerns about distribution infrastructure needs in the industry sector are lower compared to the transport sector, as sustainable hydrogen could substitute for the already-existing demand for fossil-based hydrogen in large-scale industrial plants, in particular steel mills and chemical facilities. In addition, the need for refuelling of single mobile vehicles is by definition more distributed than for static, large-scale industrial facilities, hence the need for a denser infrastructure network in transport. The sustainable hydrogen produced for industrial facilities could also be used as a feedstock for transport fuel production, e.g. for PBtL fuels.

Electric road systems for heavy-duty vehicles are also a relevant infrastructure option for major road branches. Such systems are not fully covered in the Alternative Fuels Infrastructure Regulation proposal but have the potential to deliver net cost benefits in comparison with hydrogen (ITF, 2022), adding to resource efficiency benefits (ITF, 2021).

Infrastructure that supports a transition to a diversified, sustainable, and decarbonised fuel mix in 2050 also includes electricity transmission and storage networks, and offshore grids for renewable energy. Transport, storage, and distribution facilities are also very relevant for hydrogen. These are all covered in the priority thematic areas identified in the revision of the Trans-European Transport Network (TEN-T) Regulation, where hydrogen is part of the broader smart gas grids, and which include also a cross-border CO_2 network. This is mostly relevant for industrial facilities, and eventually also for large shipping vessels (European Commission, 2021)[61].

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[61] A CO_2 network could also be relevant, if paired with DAC powered by low-carbon electricity, to enable net negative emissions. Negative emissions could be offsetting residual positive emissions and, if paired with conventional fuels from fossil resources, could represent an additional decarbonisation option to those reviewed in Section 2.2. As discussed briefly in Section 2.3, the pairing of negative emissions and the extraction of fossil hydrocarbons could be economically competitive with e-fuels or PBtL if the sum of the costs of sequestering carbon, extracting fossil fuels, and refining is lower than the cost of producing sustainable biofuels, RFNBOs, or RCFs. Barriers faced by

5.3. Timing of the investments and relevance of different stakeholders

Table 2-15 gives an overview of the role of different stakeholders and financial assets for different focal areas of infrastructure and sustainable technology developments. It highlights the pairs with the greatest relevance (green shading) for the energy transition in transport. The chronological sequence of investment areas is represented via the top-to-bottom list of tasks of Table 5-3. Its focus on infrastructure development and technological improvements is also deliberate, since both are key enablers of the transition and both require rapid action.

Table 5-3 Relevance of stakeholders and financial assets in various areas of the energy transition in transport

		Stakeholders							Financial assets	
		Public sector			Private sector					
Focal area	**Task**	Governments, public authorities	Sovereign innovation funds	Academia	Energy companies	Vehicle manufacturers	Transport infrastructure operators	Vehicle operators	Venture capital	Equities (stocks), bonds (fixed-income)
Infrastructure development	Technical standards	🟩	🟥	🟩	🟩	🟩	🟨	🟨	🟥	🟥
	Ensuring minimum	🟩	🟩	🟥	🟩	🟨	🟨	🟨	🟩	🟨
	Scaling up, deployment	🟨	🟨	🟥	🟩	🟨	🟩	🟨	🟨	🟩
	Maintenance	🟨	🟥	🟥	🟩	🟥	🟩	🟥	🟥	🟩
Technological improvement	Research, development	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟩	🟥
	Demonstration	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨
	Scaling up, deployment	🟨	🟨	🟥	🟩	🟩	🟩	🟩	🟨	🟩

Note: green = high relevance; yellow = meaningful involvement; red = low relevance.

Source: elaboration developed for this analysis based on the stakeholder views that emerged during the course of this study/ or consulted within the context of this study.

5.3.1. Infrastructure development

Public and private stakeholders' roles and contributions

Table 5-3 points to the importance of a cooperative approach between public and private sector stakeholders in the early stages of infrastructure development. Government action is particularly relevant in early technical standardisation work[62], which is a key pre-requisite for risk mitigation of infrastructure-related investments, and in guaranteeing minimum infrastructure availability. The table flags that governments can also stimulate infrastructure developments with interventions that support innovative start-ups, using tools that include loans and investments by sovereign funds. As in the case of interventions by other stakeholders of the financial system, the higher risks characterised by these

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this approach are similar to those faced by biofuels and e-fuels and mainly relate to pressures on land use for biogenic carbon production, high primary energy and air processing requirements for DAC. Additional barriers relate to the geopolitical challenges associated with a continued reliance on fossil energy.

[62] For example, charging stations require the definition of characteristics of connectors and communication protocols that enable their industrial production avoiding a proliferation of proprietary and incompatible systems, that happens thanks to the work of standardisation organisations, in cooperative activities involving governments, industry and other stakeholders.

investments are counterbalanced by the greater potential for growth offered by the technologies supported, given their alignment with clean energy and sustainable mobility goals.

Table 5-3 also shows the need for a pro-active contribution by the private sector for these early stages of infrastructure deployment, in particular by energy companies. The role of industry (including both energy and infrastructure operators) in mobilising private capital grows significantly during phases of scale-up, deployment, and eventually maintenance of infrastructure, where investments become gradually less exposed to risk. In these later stages of infrastructure development, governments are likely best placed as regulators as opposed to direct investors.

The role of vehicle manufacturers

Vehicle manufacturers also have a role to play across the different phases of infrastructure development, given the essential role of access to energy for the vehicles they produce. Adequate charging/refuelling infrastructure is key for the reduction of the risk profile of their investments. A similar role also applies to vehicle operators, even if the scale of capital investments that are exposed to risks is generally smaller than for vehicle manufacturers.

Key examples of an active involvement of vehicle manufacturers in infrastructure development emerge from recent decisions in the field of electric mobility, with significant investments by car manufacturers in the deployment of chargers, in some cases through joint ventures. Electric mobility reinforces opportunities for a close relationship between the financial sector and other public and private sector stakeholders. A concrete example that illustrates this is the recent announcement by Ionity, a joint venture by several European automotive companies, to invest EUR 700 billion in a rapid electric vehicle charging network (Ionity, 2021)[63]. This decision was taken jointly with a major manager of financial assets, Blackrock, and was motivated by the acknowledgement of the central role of electric mobility to achieve net-zero targets and the desire to diversify investments. The presence of a major manager of financial assets to support this initiative signals the growing relevance given by the financial sector to the need to mitigate risks associated with low asset utilisation[64]. The importance to minimise risks of asset stranding emerges from the work of the Financial Stability Board and its Task force on Climate related Financial Disclosure (TCFD, 2017). This example also helps illustrate the role of different financial assets in investment portfolios and highlights the importance of including, when taking investment decisions, a diversified combination of assets subject to higher risks (including venture capital), and not only traditional assets (such as equities and bonds).

5.3.2. Technological improvements

Research, development and demonstration phases

Table 5-3 shows a progressive shift from joint public and private sector involvement in the early phases of technology investments towards private sector investments in the scale-up phase. Governments, public authorities, and academia have a central role in funding and carrying out research leading to

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[63] Similar actions are being undertaken by major vehicle producers, with the set-up of a joint venture aiming to kick off the European charging infrastructure for heavy-duty vehicles (Volvo group, 2022). This is not yet involving joint funding by investment managers (as in the case of the early days of Ionity).

[64] Stranded asset risks are due to shortened lifetime for facilities requiring fossil energy (which could be an alternative investment choice), faster depreciation and therefore lower return on the investments. Other risks also supporting an investment shift towards infrastructures capable of supporting a transition to low-carbon energy relate to economic development without decoupling from GHG emissions and climate impacts, since this could lead to tensions and drawbacks that may slow it down.

technological improvements. They are also crucial throughout the development and demonstration phases, as well as in the subsequent deployment phase.

Scale-up and deployment phase

The deployment phase, which brings technologies to the mass market, remains delicate as it coincides with the so-called "valley of death". This is a space of uncertainty between the opportunities offered by novel technological solutions and the success of their large-scale commercialisation. Ensuring that the deployment phase is successfully bridged requires careful analysis of the "manufacturing readiness" of the technologies and their market demand prospects.

In this phase, the alignment of both technical aspects (generally under the responsibility of private sector stakeholders) and policy (role of public authorities) is important for the commercial success of the technologies. This alignment is crucial for technological innovations to bridge this phase taking advantage of economies of scale. This can either be "vertically", i.e. through the increase in the size of the facilities concerned, or "horizontally", i.e. through the number of products manufactured.

The capacity to adapt to the scale of demand adoption, piggybacking on opportunities that gradually become available during the scale-up, is a key enabler for a technology in its deployment phase. The progressive introduction of innovative solutions in portions of the market that have a higher readiness to pay (e.g. premium/luxury vehicles, when looking at the car market) is a key example of this gradual scale-up. Another one is the possibility to rely - at least partly – on existing infrastructure, as in the case of advanced drop-in biofuels or liquid RFNBOs or electric vehicles. This favours low-regret investment choices and reduces the risk profile of the investments[65].

Joint funding by the private sector and public authorities can also be an effective tool to overcome the hurdles of the deployment phase and the investment risks associated.

The role of policy mechanisms to support investments

As mentioned above, policy is crucial in the deployment phase, as it can be a key determinant of the emergence of large-scale demand for a new energy and/or transport technology.

An example of tools used to deal with this challenge for energy technologies is the Loan Programs Office (LPO) of the United States Department of Energy. These loan programs support private sector investments for projects that lack access to debt capital (due to their risk profile) by offering loan guarantees and facilitating access to capital (DOE, n.d.).

A key stated goal of the LPO is to provide a "bridge to bankability" for technologies that need a boost to move across the deployment phase, into commercialisation. In particular, the scope of action of the LPO covers the first commercial-scale deployment to help companies address scale-up challenges, the next few commercial-scale deployments to demonstrate ability to mitigate construction risks and apply learnings, and the commercial scale up to further benefit from technology learning and scale. The LPO also supports the gap between public and commercial debt through education to overcome private debt market misunderstanding (DOE, n.d.).

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[65] For example, in the case of heavy-duty road vehicles, still subject to some degree of uncertainty between a shift to electricity or renewable hydrogen, an initial low regret solution could be the strengthening of the high-voltage network in proximity of the main motorways. The reason is that the network upgrade is needed by many of the solutions being considered: high power chargers, electric road systems, battery swapping and renewable hydrogen. Starting from a reinforcement of the network can help take final investment decision on the devices that would need to use it at a later stage, when technology developments allow for better visibility on the most appropriate option, while still ensuring that progress can be made for the deployment of key pre-requisites (MIMS, 2022 and Armaroli et al., 2022).

A European example of supporting programmes moving in the same direction of the LPO is the case of the Important Projects of Common European Interest, bringing together knowledge, expertise, financial resources, and economic stakeholders from across the EU (European Commission, n.d.).

More broadly, a prominent example of sustainable finance policy with the stated aim to reduce the risk profile of investments directed towards sustainable projects and activities, is the European Taxonomy Regulation (European Commission, n.d.). The mechanism it uses is the establishment of a clear and transparent set of criteria providing companies, investors and policymakers with appropriate definitions for which economic activities can be considered environmentally sustainable. Overall, a range of other policies serve the purpose of reducing risks for investments on clean energy and sustainable mobility. These will be the focus of the discussion developed in Chapter 6.

6. EXISTING AND POSSIBLE POLICY MEASURES TO ADDRESS BARRIERS TO DECARBONISE THE TRANSPORT SECTOR

Key findings

- **Key barriers** to the deployment of sustainable fuels in transport can be grouped into market, financial, capacity and technical barriers.
- These include **varied national levels of ambition** translating into limited scope for large-scale cross-border initiatives; higher **production costs** for sustainable fuels; lack of specific technical knowledge and understanding; limited **availability of sustainably** produced feedstocks; limited availability of other raw materials including minerals for batteries; uncertainty regarding the **technical suitability** of some types of sustainable fuels and their match to end-use applications in transport; lack of **dedicated infrastructure** for fuels that are not "drop-in" fuels due to chicken-and-egg investment risks; a **low technology readiness level** for some fuels requiring further RD&I, pilot schemes and the demonstration of their ability to be scaled up.
- **Existing EU policies and proposals in the 'Fit for 55'** package address most of these barriers and aim to accelerate the shift to sustainable fuels, the deployment of the required infrastructure and the changes in vehicle powertrain technologies, such as zero tailpipe emissions for new light vehicles by 2035. This should **enhance regulatory certainty** and encourage the **development of strategic alliances** to deploy the value chain across Europe and beyond.
- **Other overarching policy measures are key to decarbonise transport**, such as the revision of the Energy Taxation Directive, and the inclusion of road transport in a specific Emission Trading Scheme.
- The **Renewable Energy Directive (RED) revision proposal** increases the ambition of GHG emission reductions in transport to a 13% reduction in life-cycle GHG emissions intensity by 2030. Due to the **current heavy reliance on food- and feed-crops**, the increase in renewable energy reliance can exacerbate the near-term **pressure on less sustainable feedstocks**, despite the anticipated phase out of soy and palm oil.
- Two regulations closely linked to the RED revision proposal introduce additional requirements: **ReFuelEU Aviation**, with a **mandatory share of SAF**, and **FuelEU Maritime**, mandating **limits on the GHG intensity of energy** used on board ships, and the use of onshore power supply in EU ports.

6.1. Overview of key barriers to the uptake of sustainable fuels for transport

6.1.1. Policy barriers

The **lack of a clear feedstock eligibility** framework causes a lack of long-term certainty and may result in limited motivation for market parties to make investment decisions. Existing regulatory barriers, such as **subsidies for fossil fuels** (Fossil fuel subsidy tracker, 2022) hamper the competitiveness of sustainable fuels. **Diverging national ambition levels** may translate into less attractive business cases for initiatives developed by international operators (existing bilateral or multilateral agreements may need to be amended in certain cases, such as taxing aviation fuel used for international flights). The lack of **public acceptance of policies** may be based on a poor track record with previous initiatives (e.g. concerns about land use and sustainability). These barriers can be exacerbated by the lack of global policy and regulatory harmonisation for coherently and consistently assessing life-cycle emissions and defining the sustainability of a feedstock or process.

6.1.2. Market barriers

The **higher production costs** of sustainable fuels hamper their competitiveness with the fossil fuels that they are supposed to replace. The current spikes in fossil fuel prices, caused by the invasion of Russia in Ukraine, improve the competitiveness of sustainable fuels (in particular those based on cellulosic feedstocks), but it is unclear to what extent the higher fossil fuel price levels will be structural. The nature of the fuel production, distribution and supply processes involves multiple investors along the entire supply chain, leading to more **intricated market insecurities** as each step of the chain needs to deliver at the same time. Lack of competitiveness for EU transport operators compared to **third-country transport operators** that are not subject to the EU regulatory regime (e.g. for carbon taxation of fuels) represents another barrier, leading to the risk of fraud.

6.1.3. Financial barriers

The **size of investment** required to develop, produce and supply sustainable fuels is a major barrier to their uptake, as is the risk perceived by investors and financial actors. This is particularly the case where substantial new production, distribution, storage and bunkering infrastructure is required. Current **uncertainties in the energy market** and the associated price volatility may increase the hesitance of potential investors because of the lack of long-term visibility. There may also be limited incentive to invest in sustainable fuels because of the **uncertainty whether penalties** for not meeting regulatory requirements will be enforced and whether the size of those penalties would be large enough to affect investment decisions.

6.1.4. Capacity barriers

A major energy transition will require a wide range of skills and knowledge amongst all relevant stakeholders, including public policymakers and industry staff. A lack of **specific technical knowledge and understanding** will be a substantial barrier to the uptake of sustainable fuels. As discussed in the previous chapters for RFNBOs, there needs to be a **sufficient supply of renewable energy** which in turn will be dependent on available natural resources (e.g. wind, sunlight, or hydropower). However, the use of renewable electricity for production of transport fuels should not jeopardise direct electrification (e.g. building heating or passenger cars), as that would be a more efficient use of the same renewable energy. Thanks to the better efficiency, it would also be more effective to reduce reliance on fossil fuels as a complement to renewables for electricity production.

The limited **availability of resources and sustainably produced feedstocks** (e.g. vegetable oil, green hydrogen) needed to produce transport fuels will constrain the potential to scale up and displace petroleum-based fuels. **Competition for biomass resources with other sectors of the economy** will require the need for prioritisation by decision makers and investors to ensure availability for the uses where biomass offers the highest added value and for which there are limited alternatives.

Scale and the long **lifetimes of transport assets** present barriers to the pace at which sustainable fuel technologies can be adopted and scaled up. New powertrain technologies available today will take decades to be adopted across fleets, due to the lifetime of the vehicles (roughly 25 years for ships and aircraft, roughly 15 for road vehicles). New fuel technologies will struggle to ramp up in a way that can replace current fossil fuel demand, in the absence of major energy efficiency improvements. The development of completely new infrastructure, with bespoke requirements such as fuel handling and distribution, can lead to chicken-and-egg investment risks, and therefore cost increases.

6.1.5. Technical barriers

There is still uncertainty regarding the **technical suitability of different types of sustainable** fuels and their match to the broad diversity of end-use applications in transport. Hence, further research and demonstration will be crucial to clarify which pathway to take according to resource availability and sustainability.

Certain sustainable fuels (e.g. hydrogen, ammonia) are not compatible with the existing transport infrastructure. New, dedicated infrastructure will be needed for electricity and for fuels that are not "drop-in" fuels. This may include bunkering and fuelling facilities, and in some cases, there will be cooling and handling requirements. For certain fuels, modifications to existing engines are also needed. Appropriate standards need to be developed for transporting, handling and using hydrogen, ammonia or methanol. Finally, some fuels have still a low technology readiness level and further RD&I, pilot schemes and the demonstration of the ability to scale up will be necessary. This includes CCU technologies to effectively and meaningfully reduce life-cycle emissions, and Direct Air Capture to successfully and economically deploy at scale (see Sections 2.2. and 2.3).

6.2. Assessment of the existing policy framework

The focus of this section is first on assessing the EU's 'Fit for 55' policy package, followed by other EU policies under development and then examples of best practices from third countries.

6.2.1. The EU 'Fit for 55' policy package

The so-called 'Fit for 55' package, which refers to the delivery of the EU target of reducing net GHG emissions by at least 55% by 2030 compared with 1990 (European Commission, 2020), was proposed by the European Commission in July 2021 (European Commission, 2021). With this package, the Commission aimed to strengthen existing policy actions and complements them with new polices. These policies, which are now being examined by the Parliament and the Council, are designed to ensure that the EU can meet the requirements of the European Climate Law (European Union, 2019) in a way that is coherent with the Green Deal strategy. The policies included in the package cover all sectors of the economy and encompass a wide range of tools, embedding regulatory requirements and economic/financial policies to kick start the process, accompanied by deep transformations across many aspects of the European society, industry and economy.

Many of the policy proposals included in the 'Fit for 55' package and earlier policy actions are intended to mobilise actions to accelerate changes in vehicle powertrain technologies and the energy vectors that they use, addressing the issue from a life-cycle perspective. The package is intended to provide regulatory certainty in line with the middle-term climate ambition, and to encourage the development of strategic alliances to deploy the value chain across Europe and beyond.

Importantly, the 'Fit for 55' package takes a 'multi-faceted' approach, utilising a range of approaches to incentivise measures aimed at decarbonisation. 'Fit for 55' encompasses a broad context across many sectors but here we focus on the aspects relevant to the uptake of sustainable fuels within transport.

Tailpipe CO_2 emission standards

A key piece of the 'Fit for 55' proposal is the requirement to reach zero tailpipe emissions for new light vehicles by 2035, with intermediate targets for 2030 at 55% (passenger cars) and 50% (vans) reductions versus a 2021 baseline (European Commission, 2021). The proposal, recently adopted by the European Parliament (European Parliament, 2023), has the advantage of providing clear regulatory signals to the industry. It also enables leverage of the major technological developments that should further bring down battery costs and the costs of producing low-carbon electricity, to ensure that global competitiveness for this strategic industrial sector is maintained. Additional merits relate to the emphasis on both energy efficiency and GHG emission abatement.

Challenges in this proposal focused on tailpipe GHG emissions relate mainly to the need for a clear life-cycle perspective for all concerned technologies. The methodology needs to ensure that net-zero emissions are reached not only by vehicles with zero tailpipe emissions, but also by vehicles that use sustainable fuels, by reducing the global sustainability footprint (addressing e.g. sustainable feedstock availability or raw material sourcing for battery manufacturing). The response to this perceived gap is the comprehensiveness of measures proposed by the Commission to ensure that there is indeed a life-cycle approach to GHG emissions, even if this is enforced through a combination of different measures, targeting different regulated entities. Key examples of **complementary instruments to the tailpipe CO_2 regulation** are: regulatory requirements on the carbon content of fuels (via the Renewable Energy Directive - see European Commission, 2022 for different updates), regulatory requirements on the carbon content of battery manufacturing (integrated in the proposed European Battery Regulation, for which the Parliament and the Council have reached a provisional agreement[66]), several policies aiming to decarbonise electricity generation, ranging from the Emissions Trading System (European Commission, n.d.) to the electricity supply rules introduced in 2019 (European Commission, n.d.), and proposals by the Commission to decarbonise gas supply (European Commission, 2021).

The high increase in the amount of materials needed for battery manufacturing is an important challenge. If it does not act effectively to establish its own electric vehicle and battery industry (in addition to the development of related supply chains, including through international partnerships and the sourcing of the materials they need), the EU risks to lose international competitiveness and hence employment to other regions (in particular China and other countries in Asia) that have been able to mobilise investment and have a technological advantage in this area.

The challenges also need to be analysed in light of very recent policy developments across the Atlantic, as in the case of the “Executive Order on America’s Supply Chains” (White House, 2021), the “Executive Order on Tackling the Climate Crisis at Home and Abroad” (White House, 2021), the “American Jobs Plan” (White House, 2021) and the recent “Inflation Reduction Act” (Congress, 2022), all covering extensively the topic of the transition towards electric vehicles, supply chain shifts and impacts on jobs.

The proposal to reach zero tailpipe emissions for new light vehicles by 2035 is also closely linked with other proposals, in particular the **Alternative Fuel Infrastructure Regulation** (European Commission, 2021) to ensure the appropriate infrastructure, the revision of the **Energy Taxation Directive** aiming to align the taxation of energy products (European Commission, 2021) and the inclusion of transport and buildings in the **Emissions Trading Scheme** (ETS) (European Commission, 2021).

Other policy initiatives that also complement this proposal are a similar regulation on the CO_2 emissions of heavy road vehicles, initially expected by the end of 2022, proposed in February 2023 and including requirements for 45% emissions reductions from 2030, 65% reductions of CO_2 emissions from 2035, and 90% emissions reductions from 2040, along with a broadened coverage of vehicle categories (European Commission, 2023). This is mirrored by the recently approved Advanced Clean Trucks

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[66] See European Commission (2020), European Parliament (2022), BMUV (2022) and European Parliament (2022)

regulation in California (CARB, 2022) and complemented by the proposed Euro 7/Euro VII standards for the abatement of emissions of local pollutants from road vehicles (European Commission, 2022).

Proposed road transport in the EU ETS

The 'Fit for 55' package includes a proposal (European Commission, 2021) to create a separate new Emissions Trading System (ETS) for road transport and buildings, with fuel distributors as regulated entities. The Council and the Parliament reached a provisional political agreement regarding this matter in December 2022 (European Parliament, 2022, European Council, 2022). Starting in 2027, this instrument will add a carbon pricing element to the consumer prices for these fuels, ensuring that there is a signal passing to consumers to stimulate investments in energy efficiency and energy diversification (EPRS, 2022). Fuel taxes and ETS were already flagged as first best CO_2 instruments, as they incentivise all relevant CO_2 reduction options (Schroten et al., 2022).

The proposal is accompanied by the creation of a **Social Climate Fund** (European Commission, 2021). In the proposal, this is intended to use 25% of the expected revenues raised from the new ETS for road transport and buildings to alleviate the challenge posed by the increased cost of energy to end-users such as households, micro-enterprises and transport users. The fund would be matched by an equivalent budgetary allocation by EU Member States. Following the proposal, there are risks flagged that the fund could be insufficient to shield the most vulnerable end-users from the impacts of the policy. Other critiques pointed towards the greater consideration of sustainable transport options than on compensation/support for energy efficiency and diversification investments for consumers (European Parliament, 2022) and included calls to suspend the EU ETS more broadly, due to the increase in energy prices observed in the recent past (Euractiv, 2022). This has been rejected by the Commission.

The political agreement of the Parliament and the Council of December 2022 confirmed the creation of a separate ETS for the buildings and road transport sector and fuels for additional sectors, with a start date in 2027. Part of the revenues raised through the ETS extension to buildings and transport (up to a maximum amount of EUR 65 billion) shall feed a dedicated Social Climate Fund, via the EU budget (European Parliament, 2022 and European Council, 2022).

Aviation in the EU ETS and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

Since 2012, the EU ETS has covered CO_2 emissions from flights within Europe (i.e. intra-EEA flights) by all airlines, European and non-European alike (European Commission, 2022).

Regulators can allocate a share of free permits to limit carbon leakage[67] in industries with strong international competition. In the 'Fit for 55' policy package, an alternative approach has been proposed to progressively phase out free allocations of allowances to airlines (European Commission, n.d.). This approach seeks to address the risk of carbon leakage and fuel tankering from airports outside the EU by ensuring that imported products are subject to equivalent carbon pricing as domestic products. The revision of the EU ETS for aviation's text adopted by the European Parliament in June 2022 (European Parliament, 2022) strengthens the measures aiming to deal with carbon leakage, suggesting to include flights that are flying out of the European Economic Area within the scope of the ETS. A provisional deal reached in December 2022 between the Parliament and the Council settles on a scope that covers intra-

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[67] Carbon leakage is a situation that can arise when companies transfer production to other countries that have more relaxed emissions requirements in order to save costs. This can lead to an increase in overall emissions (European Commission, n.d.).

EEA flights (including departing flights to the United Kingdom and Switzerland) (European Commission, 2022, European Parliament, 2022 and European Council, 2022).

Flights not covered by the EU ETS will be subject to the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) under the International Civil Aviation Organisation (ICAO). Emissions from these flights will be offset once their total international CO_2 emissions exceed 85% of the 2019 levels, according to recent deliberations (ICAO, 2022). To avoid double counting of emissions, offsets must be clearly accounted for. ETS allowances are not accepted under CORSIA, while offsetting credits are not accepted by the EU ETS.

The inclusion of aviation in the EU ETS should provide a stronger price signal than via CORSIA. Furthermore, as a regional initiative, the EU ETS can limit the fuel tankering and carbon leakage risks that result from non-universal schemes and serve to drive ambition for a global carbon pricing scheme for international aviation aligned with the goals of the Paris agreement. The weaker price signal from CORSIA is a key reason why, according to the agreement reached by the EU co-legislators in December 2022, after an assessment in 2025, the Commission may make a proposal to extend the scope of ETS to all flights departing from the EEA (European Council, 2022).

The discussions and negotiations on the Commission proposal also touched on the allocation of ETS revenues to a support scheme to speed up the use of sustainable aviation fuels and led to an agreement on this issue in the provisional deal of December 2022 (European Commission, 2022).

Importantly, the deal reached in December 2022 will also create a new system for airlines to monitor, report and verify non-CO_2 emissions and climate effects of aviation, which make up two thirds of aviation's total climate impact (European Commission, 2022).

Maritime in the EU ETS

The ‘Fit for 55’ proposal also includes the enlargement of the scope of the EU ETS[68] to maritime transport for emissions taking place when ships are at berth in EU ports, and emissions from intra-EU voyages (European Commission, 2021). Discussions, concluded in December 2022, led to the proposal to include 50% of emissions from extra-EU voyages. This proposal is confirmed in the agreement, which sets a start date of 2027 (European Council, 2022 and Hagberg, 2022). Ships over 5000 gross tonnes are covered. General cargo vessels and offshore vessels above 400 gross tonnes (and below 5000) will be included from 2025 in the regulation regarding the reporting of emissions, already applicable to larger vessels. Their inclusion in the EU ETS will be reviewed in 2026 (Hagberg, 2022).

The creation of a new ‘Ocean Fund’, bound to use 75% of ETS revenues from shipping to support the transition to an energy-efficient and climate-resilient maritime sector, was also under discussion before the December agreement (EPRS, 2022, European Parliament, 2022).

The inclusion of the maritime sector in the EU ETS is a key development to ensure that fuel used in ships is subject to carbon pricing, addressing the fact that this was one of the key sectors still exempt from it (OECD, 2019). This initiative, as well as the introduction of a cap on shipping emissions, has crucial importance beyond the EU, since the intergovernmental negotiations at the International Maritime

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[68] Article 5.1 of the FuelEU Maritime regulation proposal: “From 1 January 2030, a ship at berth in a port of call under the jurisdiction of a Member State shall connect to on-shore power supply and use it for all energy needs while at berth” (EC, 2021). The proposed sustainable Fuels Infrastructure Regulation also includes provisions for Member States to ensure installation of a minimum shore-side electricity supply for certain seagoing ships in maritime ports and for inland waterway vessels (EC, 2021).

Organisation (IMO) on the implementation of the Initial Strategy on Reduction of GHG Emissions from Ships have shown limited progress.

The challenges regarding maritime transport in the ETS comprise an increased layer of complexity in international negotiations for global emissions reductions[69] and the volatility of the CO_2 price resulting from a market-based mechanism, especially relevant if this is specific to the sole maritime sector[70].

Other challenges include the risk of a diversion of investments from efficiency improvements towards GHG emission allowances (including those arising outside the sector[71]) and limited capacity to stimulate the uptake of low-carbon fuels and other innovative emission-saving technologies, due to the likely low end-user price signals.

The risk of split incentives (shipowners paying for energy efficiency measures but not reaping the benefits) between ship operators and owners, and in particular the risk that shipowners do not take action on energy efficiency, is also tackled by increased transparency requirements on actual ship performance, thanks to the EU Monitoring, Reporting and Verification (EU-MRV) system for ships. This is already in place and allows the price signals to be passed through to asset owners, who would then be stimulated to invest in energy efficiency and fuel switching technologies. This is also addressed by the proposed obligation to pass carbon prices to charterers, therefore also stimulating them to take action to minimise their carbon emissions. The agreement reached in December 2022 by the Parliament and the Council includes nitrous oxides (N_2O) and methane emissions within the scope of what will be monitored (Hagberg, 2022).

Update to the 2003 Energy Taxation Directive

The ‘Fit for 55’ package encompasses a revision of the Energy Taxation Directive (ETD) aimed at ensuring that energy taxes account for the carbon content of fuels (European Commission, 2022). This proposal addresses, amongst others, the major existing gap between the large amount of GHG emissions caused by aviation and maritime transport and the small portion of energy use subject to taxation (OECD, 2019).

The revision of the ETD is important to correct major distortions in place, not only in transport, that disconnect energy taxation from climate and energy efficiency objectives. The revision would remove disadvantages for clean technologies and introduce higher levels of taxation for inefficient and polluting fuels, complementing carbon pricing through emissions trading. Ensuring that environmental impacts (external costs) are properly reflected in the taxation structure is also crucial to avoid misleading messages for businesses and residential consumers, thereby reducing the risk to push them towards investment choices that may face increased risks of becoming stranded or increasingly expensive due to climate policy.

Taxes on electricity and fuels would be aligned based on their energy content (rather than on volume or weight as currently applied) and environmental performance, and, more specifically, to end tax exemptions or reductions for fossil fuels used in road transport, intra-EU air transport, maritime transport and fishing. Some of the most significant changes resulting from this change would impact

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[69] This is due to the tension between the need to act at the IMO level (preferable) and the slow pace of progress of the IMO negotiations on the subject.

[70] To address this, as in the case of the ETS for transport and buildings, the Fit for 55 package included proposals - then approved in December 2022 by the Parliament and the Council (European Parliament, 2022 and European Council, 2022) - to revise and strengthen the EU ETS Market Stability Reserve. The measure is intended to address a structural imbalance between the supply and demand for allowances in the market, due to the build-up of a surplus of emission allowances since 2009, and to improve the resilience of the EU ETS to major shocks (European Commission, 2021).

[71] The application of EU-ETS to international aviation (for intra-EU flights) has not resulted in any reduction to absolute emissions from this sector (Hughes, 2020).

the use of Liquefied Petroleum Gases and natural gas (CNG and LNG) for transport, which are often subject to low or zero rate taxes despite their fossil origin.

Importantly, the proposal is also paired with revenue-generating tools (such as the extension of ETS to transport and buildings), enabling Member States to support vulnerable households in the energy transition and to protect them against energy poverty.

Carbon taxation of fossil fuels used for intra-EU air and maritime transport will have limited effects on inflation, due to the small impact these CO_2 taxes will have on the price of final products and services. However, measures to mitigate impacts in terms of cost for specific stakeholders (e.g. fishing vessels) may be necessary. The best way to do so is to support investments of the most exposed sectors enabling them to shift to low-carbon and energy efficient alternatives to fossil energy.

Due to the subject of the proposal, focused on tax law, its approval requires a unanimous decision of the Council. The track record of proposed changes to the ETD in the past shows significant hurdles. The Council asked the Commission to come up with proposals on how to better align the directive (dating back to 2003) with energy and climate targets already in 2008. A 2011 proposal by the Commission, setting minimum rates based on energy content and CO_2 emissions, responded to this request (European Commission, 2011). However, this proposal was not approved by the Council and was removed from the Commission's work programme in 2015.

Recast of the EU's Renewable Energy Directive (RED)

The Renewable Energy Directive (RED) establishes common principles and rules to remove barriers, stimulate investments and drive cost reductions in renewable energy technologies, across all sectors of the energy system. The first version of the directive was introduced in 2009 and an update was finalised in 2018 (RED II), addressing the use of biofuels and renewable fuels in the area of transport.

While an earlier 2003 Directive (European Union, 2003) focused mainly on the increase of biofuel supply and demand, the 2009 Directive and its 2018 update paid growing attention to the impacts of biofuels on food and feed prices and the environment, including direct and indirect land use changes and biodiversity loss. According to the 2018 RED II, renewable energy needs to account for 32% of final energy consumption in the EU by 2030 (European Union, 2018).

In transport, a specific obligation on fuel suppliers requires that the share of renewable energy within the final consumption of energy in the transport sector is at least 14 % by 2030. Obligations for food and feed crop-based fuels are frozen at 2019 levels (7% of final energy demand in road and rail transport), with a requirement to phase out options that have a high risk of inducing land use change. Renewable electricity is accounted with corrective factors due to better energy efficiency of electric vehicles compared to combustion vehicles. Sustainability criteria regarding life-cycle emissions and land use change also apply to biofuels eligible to be accounted in the share of renewable fuels.

The 'Fit for 55' package, proposed by the Commission in 2021 and currently being discussed, increases the **share of renewable energy in final consumption to 40% by 2030** (European Commission, 2021)[72]. In transport, it increases the ambition of GHG emission reductions by revising the 2030 objective to a 13% reduction in life-cycle GHG emissions intensity. Two regulations linked to the proposed revision of the RED introduce additional requirements specifically targeting aviation (ReFuelEU Aviation, focused on sustainable aviation fuels) and shipping (FuelEU Maritime, focused on low-carbon fuels for maritime transport). These changes are accompanied by an EU-wide price floor

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[72] This has been increased to 45% in the more recent RePower EU proposal (European Commission, 2022), discussed below.

pegged to the ETS carbon price, and, in the case of the ReFuel EU Aviation and FuelEU Maritime regulations, an EU-wide price ceiling set by non-compliance penalties.

In September 2022, the European Parliament proposed an upward revision (to 45%) of the share of renewable energy in the overall energy use in the EU by 2030, in line with the RePowerEU proposal released by the Commission in response to the Russia-Ukraine war, earlier in the year (European Commission, 2022). The proposal by the Parliament is paired with a reduction by at least 40% of final energy demand by 2030 (42.5% in primary energy) compared to 2007 projections, through the revision of the Energy Efficiency Directive (European Parliament, 2022). For transport, the discussion on the recast of the RED in the Parliament did not lead to changes in the 7% threshold for food and feed – despite raising concerns about global food security (T&E, 2022) while raising the ambition for GHG emission reduction by 2030 to 16%. The vote also includes what has been defined as a reduction of "red tape" and a more flexible and business-friendly regulatory environment for the green hydrogen sector (Shearman and Sterling, 2022) because of the inclusion of less stringent requirements on the additionality of green hydrogen production.

In the absence of effective strategies to lower emissions from biofuel production pathways, meeting the increased ambition of GHG emission reduction in transport may result in increased demand for biofuel feedstocks, even if GHG emission savings have been estimated to be possible with a phase out of food and feed crops (ICCT, 2021). This is despite an anticipated phase out of both soy and palm oil (2023 rather than 2030) (Goulding Carrol, 2022). Without strict sustainability criteria, this proposal could hence lead to greater near-term pressure on the use of food- and feed-based biofuels.

Meeting an increased ambition on GHG emissions reduction while remaining aligned with the sustainability goals and avoiding increased pressure on food and feed will require a progressive shift towards cellulosic (non-food-based, sustainably produced, prioritising residues) and waste-based feedstocks and towards electrification and hydrogen-based fuels. This should be associated with best practices regarding the management of these feedstocks, and an acceleration of the integration of low-carbon hydrogen in biofuel production (in PBtL).

This means that, despite increased overall ambition on the share of renewables in the EU's overall energy mix, paired with greater ambition on energy efficiency improvements, the actions stimulated by some RED amendments regarding transport (particularly on biofuel use in roads) may put additional strain on the world's food security, which is already under threat. A focus of biofuels for road transport, where suitable alternatives exist, can also be at odds with the need to maximise the availability of sustainable feedstocks for transport modes that cannot be easily electrified.

ReFuelEU Aviation

The proposed ReFuelEU Aviation Regulation (European Commission, 2021) sets new rules that oblige fuel suppliers to deliver an increasing share of sustainable aviation fuels (SAF) as part of the fuel supplied at EU airports. SAF includes synthetic aviation fuels (aviation RFNBOs), advanced biofuels produced from feedstocks such as agricultural or forestry residues, algae and bio-waste, and biofuels produced from certain other feedstocks (including cellulosic materials). These fuels count as SAFs as long as they meet the sustainability and GHG emissions criteria defined in Article 20 of RED II (therefore including requirements to ensure significant life-cycle emission reductions).

The proposed regulation also aims to tackle fuel tankering practices, which consist of taking on more fuel than required for the safe operation of a given flight at airports where fuel is cheaper, but which then generate extra emissions to carry the extra fuel. It aims at establishing an obligation for aeroplane operators to ensure that the yearly quantity of aviation fuel uplifted at any given EU airport is at least

90% of the yearly aviation fuel required. This would discourage cheaper fuel, which is potentially not sustainable, being uplifted at non-EU airports.

Fuel suppliers will be obligated to gradually increase the share of SAF supplied to operators in EU airports from 2% by 2025 to 5% by 2030 and increasing through various steps to 63% in 2050. There is a sub-obligation for synthetic aviation fuels that increases in a progressive way from 0.7% of fuel supplied at EU airports in 2030 to 28% in 2050. Consequently, up to 35% of the aviation liquid fuel demand could still be met by biofuels in 2050, an amount that would likely absorb all advanced biofuels production at that time.

As it is nested into the Renewable Energy Directive, the proposed regulation will differentiate between different types of SAF by taking into account capacity to deliver net CO_2 emission savings on a life-cycle basis. For instance, RFNBOs can only be counted towards targets if they have GHG emissions savings of at least 70%. Accounting will be based on a life-cycle approach, ensuring credits from GHG capture are not double-counted (European Union, 2018).

Non-compliance fines that are at least double the price difference between SAF and conventional aviation fuels will be introduced (European Commission, 2021). This strengthens the incentive to invest which depends on the certainty around non-compliance penalties and their value.

In July 2022, amendments proposed by the European Parliament included a revision of the SAF definition, to include hydrogen and electricity, and an increase in the minimum shares of SAF that should be made available at EU airports (2% in 2025, increasing to 37% in 2040 and 85% by 2050). The amendments of the Parliament also include the creation of a support scheme aiming to accelerate the decarbonisation of the aviation sector, as already flagged in the discussion regarding the ETS (European Parliament, 2022, European Commission, 2022).

Due to their disproportionate climate impact per passenger-kilometre (Transport & Environment, 2021), private jets should be included within the scope of the ReFuelEU Regulation (or complementary policy instruments), and their transition to SAF should be accelerated in comparison with the general schedule of SAF targets in the proposed regulation. This would be aligned with the fact that private jets serve high-income individuals (Transport & Environment, 2021), who are best-placed to frontload SAF demand and spur investments in SAF production, and it would also be aligned with the "Just Transition" concept. An alternative could be to adopt complementary policy instruments that would allow the legislators to address impacts that could affect this specific air travel segment.

FuelEU Maritime

The proposed FuelEU Maritime Regulation (European Commission, 2021) focuses on driving the shift towards using low carbon fuels in shipping by mandating limits on the GHG intensity of energy used on board a ship, and by mandating use of onshore power supply in EU ports. It requires a full life-cycle assessment of the fuel supply chain to determine emissions of CO_2 equivalents (including methane and nitrous oxide) from the energy used. Progressive reductions of the GHG intensity of energy used on board are required, which would start with a 2% reduction in 2025 compared to the 2020 baseline, followed by a 6% reduction by 2030 and a 75% reduction by 2050.

Requirements contained in the Commission proposal apply to all energy used on board a ship in or in-between EU ports but only to 50% of the energy usage on ships sailing to or from ports in third countries. This approach will address the potential for carbon leakage and maintain the competitiveness of the EU maritime transport sector and is consistent with the agreement reached between the Parliament and the Council in late 2022 on the inclusion of maritime transport in the EU ETS (Hagberg, 2022).

Responsibility for compliance will lie with the shipping company. Technological neutrality is ensured by the life-cycle GHG-based approach defining the obligations. This enables both technologies like LNG and those with high GHG emission abatement capacity to contribute, even if the scope for meaningful emission abatement for LNG of fossil fuel origin is limited.

The life-cycle approach, i.e. considering a 'well to wake' approach as well as CO_2 equivalent emissions of methane and nitrous oxide, will address some of the limitations of the IMO policy framework (IMO, n.d.), which is still limited to the CO_2 emissions created on-board the ship, i.e. a 'tank to wake' approach.

Similar to the case of private jets in the ReFuelEU Aviation provisions (see previous Section "ReFuelEU Aviation"), large leisure/luxury ships, as well as the broader spectrum of recreational boats, are reasonable targets – from an equity perspective – for the early adoption of legislation requiring GHG emission abatement. A recent analysis focusing on the revision of the Recreational Craft Directive (European Commission, 2013) points to the fact that, similar to cars and trucks, recreational crafts are also cases for which the most likely paths for a significant reduction of GHG is the adoption of purely electric (and to a lesser extent of hybrid-electric) propulsion systems (Panteia et al., 2021). Key barriers identified to date, for these policy developments, are related to challenges with practical implementation, e.g. engines being sold separately from boats (Panteia et al., 2021).

Alternative Fuels Infrastructure Regulation (AFIR)

The existing Alternative Fuels Infrastructure Directive (European Union, 2014) requires Member States to develop national policy frameworks for ensuring sufficient coverage of recharging and refuelling infrastructure. The 'Fit for 55' package includes a proposal for a regulation updating the earlier directive that would set a number of mandatory national targets for the deployment of alternative fuels infrastructure in the EU. The proposal addresses mainly road vehicles, but also vessels and aircraft.

The existing directive relies on national policy frameworks, proposed by Member States and assessed by the Commission. Reports by the Commission assessing its effectiveness concluded that it had a positive impact on the uptake of alternatively fuelled vehicles, but also that the overall European market for alternative fuel infrastructure is still in an early development phase (European Commission, 2021, European Commission, 2021). Other assessments with a focus on charging infrastructure for electric vehicles also flagged important heterogeneities in the degree of deployment of alternative fuel infrastructure for transport vehicles (European court of Auditors, 2021).

The proposed regulation (European Commission, 2021) would require European Member States to ensure the construction of a minimum network of charging and refuelling stations along the TEN-T, including several urban nodes. This is in addition to the development of a wide range of technical standards. The choice of a regulation, rather than a directive, follows calls from both original equipment manufacturers (OEMs) and non-governmental organisations (NGOs) for greater political commitment (ACEA, BEUC and T&E, 2021).

The regulation is also a better fit to integrate binding requirements on alternative energy infrastructure distribution facilities. The proposed regulation introduces minimum requirements for light and heavy-duty vehicles. It also covers electric road systems, but only in terms of technical standards. For light vehicles, minimum requirements for publicly accessible recharging stations (i.e. physical installations for the recharging of electric vehicles) are expressed in terms of power output per vehicle, with thresholds set at 1 kW for BEVs and 0.66 kW for PHEVs. For both light and heavy vehicles, the proposed regulation also includes geographical availability requirements. These are expressed both in terms of maximum distance from each other (60 km) and power output per recharging pool (i.e. one or more recharging stations at a specific location), at different points in time - 2025, 2030 and 2035. Electric Road Systems are considered as an emerging technology. Their integration is therefore limited to a recognition as alternative fuel infrastructure, and does not include regulatory requirements (ITF, 2021).

Requirements for road vehicles using hydrogen focus on heavy vehicles to the year 2030. These include minimum station capacity (2 t/day) and geographical availability, expressed in terms of maximum distances between refuelling points, differentiating between gaseous hydrogen at 70 MPa (150 km) and liquid hydrogen (450 km) on the core and TEN-T comprehensive networks. The proposed regulation also requires that publicly accessible hydrogen refuelling stations be deployed in each urban node by 2030.

For **maritime** transport, the proposed regulation requires that at least 90% of demand for shore-side electricity supply is met in TEN-T core and comprehensive maritime ports with relevant traffic, by 2030. It also sets requirements for shore-side electricity supply for inland waterway vessels. For **aviation**, it mandates that electricity supply for stationary aircrafts is available at all gates used for commercial air transport operations at TEN-T core and comprehensive network airports by 2025, and at all outfield posts used for commercial air transport operations by 2030 (European Commission, 2021).

The proposed regulation also includes provisions requiring the development of national policy frameworks, for portions of the European transport network not included in the TEN-T (i.e. those with national and/or regional interest, in every Member State).

The proposed regulation has the advantage of providing clear signals on the relevance of a surge in investments for transport electrification, and the risk of supporting, for road transport, a deployment of hydrogen distribution facilities that do not match the availability of low-cost, low-carbon hydrogen. The opportunities to rely on low-carbon hydrogen vs direct electrification may remain limited if renewable electricity is not yet widespread and available at competitive cost. Additional challenges derive from difficulties in achieving cost reductions and economies of scale for fuel cells production, since many applications see direct electrification as a more competitive option. Lower energy efficiency for hydrogen fuel cell vehicles versus electrification also risks to lead to increased overall energy demand including natural gas consumption, which is in several EU Member States still the marginal technology used for electricity generation (currently also with very high costs) (Trinomics, 2022).

Other drawbacks are the limited ambition of the AFIR on infrastructure developments enabling a shift in shipping fuels towards options like e-methanol and e-ammonia (CATF, 2022), and limited flexibility to adjust the capacity of chargers to traffic flows. The proposal also defines lower than needed power capacity for charging pools for low emission trucks, and higher than needed requirements for hydrogen, likely anticipating increasing chances for hydrogen to contribute to the decarbonisation of the road transport sector (ICCT, 2020).

6.2.2. Other EU policies

CO_2 emissions from heavy-duty road vehicles

On 14 February 2023, the European Commission proposed CO_2 limits for heavy goods vehicles, requiring new trucks by 2040 to cut emissions by 90% and all new city buses to have zero emissions from 2030[73], in line with the vision outlined already in 2020, by the EU's Sustainable and Smart Mobility Strategy (European Commission, 2020).

The existing requirements are based on a regulation introduced in 2019 (European Union, 2019) and require that the average CO_2 emissions of the EU fleet of certain types of new HDVs be reduced by 15% from 2025 onwards and by 30% from 2030 onwards. The targets are determined relative to the reference CO_2 emissions calculated from the data of 2019 and 2020 (EEA, 2022).

The expected proposal is inherently linked with provisions included in the AFIR for heavy-duty vehicles. This will require specific consideration of the role that may be played by direct electrification – already expected to be central for most of the vehicle categories (BMVI, 2020, MIMS, 2022) - and the share that could be covered by RFNBOs for HDVs.

EU Taxonomy Regulation and other tools related with sustainable finance

A key initiative for green finance was the creation of a common classification system, or a "taxonomy", for environmentally sustainable economic activities. The EU Taxonomy Regulation, which was agreed on in July 2020, focuses on the reorientation of financial flows towards European policy priorities by establishing a European Union-wide classification of economic activities that are considered sustainable (European Commission, n.d.). The regulation and its delegated acts are instrumental in ensuring that public EU funds can be effectively earmarked for climate mitigation. The Taxonomy Regulation should therefore help drive investments towards sustainable measures.

The definition of a classification of sustainable activities is grounded in the context of regulatory developments aiming to align the decisions taken by investors, corporations and other entities with governments' visions for developing the energy and the transport systems in alignment with the Paris Agreement. The classification follows work initiated by the Financial Stability Board (FSB) with the creation, in 2015, of the Task Force on Climate-Related Financial Disclosures (TCFD) and the ensuing release, in 2017, of its climate-related financial disclosure recommendations.

Other EU policy instruments adopted in the area of sustainable finance complement the taxonomy, such as the Sustainable Finance Disclosure Regulation (SFDR) (European Commission, 2022), the low-carbon benchmarking methodologies, the voluntary 'Green bond' standard (European Commission, n.d.) and the adoption of a framework aligned with the green bond principles of the International Capital Market Association (ICMA) for the NextGenerationEU bond issuance (European Commission, 2021). The Corporate Sustainability Reporting Directive (CSRD) lays down the rules on disclosure of non-financial and diversity information by large companies and has also recently been adopted (European Parliament, 2022).

Details defining sustainable activities can have important implications for choices made by major actors in the capital markets and investment choices made by industry and, more broadly, by the private sector.

In the EU Taxonomy Commission Delegated Regulation (C(2021)2800), road transport economic activities classified as sustainable include cars with up to 50 g CO_2/km of tailpipe emissions until 2025 (therefore including plug-in hybrid electric vehicles, PHEVs), and zero tailpipe emissions of CO_2 after that (therefore excluding PHEVs). It also includes buses, two-wheelers, three-wheelers, and light commercial vehicles with zero tailpipe emissions of CO_2 and heavy trucks that emit less than half of the average CO_2 emissions/km of all vehicles in the same vehicle category (European Union, 2021, ITF, 2021). Regarding energy and fuels, the economic activities include infrastructure dedicated to the

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[73] EU proposes 90% CO2 emissions cut by 2040 for trucks | Reuters

operation of vehicles with zero tailpipe CO_2 emissions. In particular, these include electric charging points, electricity grid connection upgrades, hydrogen fuelling stations and electric road systems (ERSs).

Economic activities relevant to **aviation** and classified as sustainable in the EU taxonomy include the construction, modernisation, maintenance and operation of infrastructure that is required for zero tailpipe CO_2 operation of aircraft.

For **maritime** transport, economic activities aligned with substantial contributions to climate change mitigation include the manufacturing, purchasing, financing, chartering (with or without crew) and operation of vessels for performing passenger transport (sea, coastal and inland) with zero direct CO_2 emissions (European Union, 2021)[74]. Retrofits leading to 10% energy savings also qualify, until 2025, as long as they are not targeting vessels that are not dedicated to the transport of fossil fuels. For maritime transport, the Taxonomy Regulation also flags that it will be necessary to further assess maritime shipping and, where appropriate, to establish technical screening criteria for maritime shipping applicable as of 2026.

The activities aligned with substantial contributions to climate change mitigation cover electricity and hydrogen as well as biofuels (European Union, 2021, ITF, 2021). For **electricity** (and heat), they include: generation from renewable solar, wind, hydro, geothermal energy, and gaseous and liquid fuels leading to less than 100 g CO_2e/kWh; biomass fulfilling the sustainability criteria defined in RED II (ITF, 2021). Since 2022, nuclear and gas energy activities are also included, under strict conditions (European Commission, 2022). For **biofuels**, a substantial contribution to climate change mitigation is recognised if food-and feed crops are not used for the manufacture of biofuels for use in the transport sector and for the manufacture of bioliquids.

For **hydrogen**, sustainable activities include the construction of hydrogen storage facilities, the development of transmission and distribution networks, the manufacturing of technologies for producing hydrogen and hydrogen-based synthetic fuels, as well as the production of hydrogen and hydrogen-based synthetic fuels, provided that they have life-cycle GHG emissions savings of 73.4% for hydrogen and 70% for hydrogen-based synthetic fuels, relative to a fossil fuel benchmark of 94 g CO_2-eq/MJ.

NextGenerationEU plan

NextGenerationEU is a major (more than €800 billion) temporary recovery instrument to help repair the immediate economic and social damage brought about by the coronavirus pandemic. A substantial proportion (30%) of its budget, and more than 37% of the Recovery and Resilience Facility (RRF), the centrepiece of NextGenerationEU, will be dedicated to fighting climate change (European Commission, 2022). It includes, across Member States, expenditures dedicated to the deployment of infrastructure needed for the delivery of low-carbon energy to transport vehicles. In parallel, the Commission intends to raise up to 30% of the NextGenerationEU funds through the issuance of green bonds and use the proceeds to finance green policies. The first green bond issuance took place in October 2021 (European Commission, 2021).

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[74] Until 2025, sustainable activities also cover hybrid and dual fuel vessels that derive at least 25% of their energy from zero direct (tailpipe) CO_2 emission fuels or plug-in power and vessels that have an attained Energy Efficiency Design Index (EEDI) value 10% below the IMO Energy Efficiency Design index (EEDI) requirements applicable on 1 April 2022, as long as these vessels can run on zero direct (tailpipe) CO_2 emission fuels or on fuels from renewable sources (European Union, 2021). Coastal vessels enabling modal shifts from roads with at least 50% emission savings are also included until 2025.

The differences between the Taxonomy Regulation and the choice to opt for the Green Bond Principles of the ICMA to fund the NextGenerationEU plan illustrate a fundamental misunderstanding in the way the EU debates in the field of climate, energy, and sustainable finance policy. The reason for this misunderstanding is a mix up between the taxonomy debate, which was intended to provide a gold standard on certain investments, with the hope that markets will favour and appreciate their green premium, and the structure of Europe's future energy mix (Tagliapietra, 2022). The latter, rather than the former, is likely more aligned with the end result of the sustainable activities included in the Taxonomy, following a political negotiation.

European Partnerships

In June 2021, the Commission proposed to set up 10 new European Partnerships between the European Union, Member States and/or the industry. The goal is to accelerate the transition towards a green, climate neutral and digital Europe, and to make the European industry more resilient and competitive. The EU aimed to provide nearly €10 billion of funding that the partners would match with at least an equivalent amount of investment. This combined contribution was expected to mobilise additional investments in support of the transitions, and create long-term positive impacts on employment, the environment and society. Relevant partnerships for transport are:

- The Clean Aviation Joint Undertaking, which builds upon the Clean Sky Joint Undertaking by pulling together knowledge, capabilities and experience from the private and public sectors to develop cutting-edge technologies as part of the transformational leap in aircraft performance in the 2030s.
- The Clean Hydrogen Joint Undertaking, which supports research and innovation activities in hydrogen technologies in Europe. It builds upon the success of its predecessor, the Fuel Cells and Hydrogen Joint Undertaking. It aims to scale up the development and deployment of the European value chain for safe and sustainable clean hydrogen technologies, strengthening its competitiveness to support business, especially SMEs.

Industrial alliances

Other EU policy efforts aim to promote innovation and enhance economic competitiveness and resilience in the European industrial system. This aims to facilitate stronger cooperation and joint action between stakeholders in a context that is expected to transform rapidly and significantly due to digitalisation, clean energy, and sustainable mobility technologies.

The materialisation of these efforts is best represented by the European industrial alliances, which are complementary to the research activities of the Horizon Europe programme (European Commission, 2022) by being more oriented towards industrial development.

Examples with direct relevance for transport include the European Battery Alliance, the Alliance for Zero-Emission Aviation and the Renewable and Low-Carbon Fuels Value Chain Industrial Alliance, which is directly related with renewable and low-carbon fuels for the aviation and waterborne sectors (European Commission, 2022). Others, which also have relevance for transport technologies, currently include the European Clean Hydrogen Alliance, the European Raw Materials Alliance, the Circular Plastics Alliance, the European Alliance for Industrial Data, Edge and Cloud and the Industrial Alliance on Processors and Semiconductor Technologies.

Such alliances can address a pressing societal challenge through the co-ordination of many stakeholders and ensure the consistency and complementarity of public and private investments to drive a systemic change through impact-driven but realistic goals within a certain timeframe and budget. They have the advantage of clearly spelling out the value and goal of investments in research and innovation.

European Sustainable and Smart Mobility Strategy

The European Sustainable and Smart Mobility Strategy, which follows the 'European Green Deal' communication and precedes the 'Fit for 55' proposals, already lays the foundation for how the EU transport system can achieve its green and digital transformation, with the stated objective of becoming more resilient to future crises (European Commission, 2022).

The Strategy makes explicit reference to goals like the market readiness of zero-emission large aircraft by 2035, at least 30 million zero-emission cars to be in operation on European roads by 2030, nearly all cars, vans, buses as well as new heavy-duty vehicles to be zero-emission by 2050, zero-emission marine vessels to be market-ready by 2030 and scheduled collective travel for journeys under 500 km to be carbon neutral.

It also mentions clearly – amongst other priorities – the importance to support research and innovation on competitive, sustainable and circular products (implicitly including transport fuels) and to incentivise their demand by end-use.

REPowerEU Plan

The European Commission recently issued an important communication on the REPowerEU plan, with a stated aim to end the EU's dependence on Russian fossil fuels while continuing to tackle the climate crisis.

Key actions meant to increase the resilience of the EU-wide energy system include enhanced energy savings, accelerated roll-out of renewable energy (increasing the EU's 2030 target for renewables from the 40% of the Green Deal to 45%) and the diversification of gas supplies.

This initiative, clearly related to the conflict in Ukraine and not only with the Green Deal and the Climate Law, adds important security-related considerations to those focused on climate action, setting a likely trend that, due to the importance of energy efficiency and energy diversification for energy demand, will likely impact also other policymaking processes affecting sustainable fuels.

Additional investments of EUR 210 billion are needed between May 2022 and 2027 to phase out Russian fossil fuel imports, which are currently costing European taxpayers nearly EUR 100 billion per year (European Commission, 2022). The RRF is at the heart of the REPowerEU Plan implementation, providing additional EU funding. Member States should add a REPowerEU chapter to their Recovery and Resilience Plans to channel investments to REPowerEU priorities and make the necessary reforms.

6.2.3. Best practices

The policy review covers the extensive range of measures enacted or being considered in the EU to foster climate and other environmental action, while also responding to the need to ensure continued socio-economic development, responding to the complex challenge of a transition towards a model that meets the ambition of the UN Sustainable Development Goals.

A range of different countries has started to take significant steps to facilitate a transition towards clean energy, not only on the grounds of environmental and climate policy, but also on those of energy security and energy diversification. A relevant example is China, which has been a global leader on the development of e-mobility, the establishment of a battery industry and the scale up of renewable energy manufacturing, enabling important cost reductions for key low-carbon technologies globally.

Several countries have also taken measures to diversify the fuel and, more broadly, the energy mix. These policies have been focusing first on the replacement of petroleum products with alternative forms of energy, such as gaseous fuels. They also addressed direct replacements, such as biofuels. In more recent times, they started to factor in energy efficiency improvements, integrating ways to account for the substitution of fuels used in combustion engines with electricity.

These polices achieved limited success globally, as shown by the large share of oil-based fuels still characterising the transport sector, even if they did lead to relevant shares of alternative fuel production and use in specific countries and/or sub-national entities.

Important challenges and limitations faced by policies that attempted to switch from petroleum fuels to alternative options, as discussed in Chapter 2, include land use requirements, the risk of direct or indirect competition for land use with food crops, significant water needs in cases based on biomass that require irrigation, and the reliance on fossil energy inputs for fertilisers and conversion facilities. Few policy frameworks have been capable to promote effectively the use of sustainable transport fuels (including biofuels).

The case of California is very relevant, since this US State has been a leader in taking market-based measures aiming to reconcile socio-economic development, sustainability and innovation, but also in implementing instruments that specifically focus on sustainable fuels. California's Low Carbon Fuel Standard (LCFS) – a measure that combines regulatory and pricing mechanisms to support technological developments for the decarbonisation of fuels (CARB, n.d.) – has been a significant source of inspiration for alternative fuel policies developed by other governments. Like many of the policies that focused on alternative fuels, it focused mostly on road transport. More recently, it started to expand into aviation, as an opt-in option.

Other examples of policies focused on alternative transport fuels can be found in Brazil and Canada, as discussed in Chapter 2. Brazil, in particular, has a long-lasting history of policy actions on biofuels. It has recently introduced its programme RenovaBio to reduce the carbon intensity of the Brazilian transportation matrix by expanding the use of biofuels and – similar to California's LCFS, creating a carbon credit market to offset emissions of greenhouse gases by fossil fuels.

Canada has also followed the footsteps of California by establishing such low carbon fuel policy, at the level of provinces, starting from British Columbia, and now moving towards the adoption of a similar approach nationwide, with the Clean Fuel Regulations[75].

Norway also adopted measures that are conceived in a similar way to the experiences developed in California, combining regulatory requirements, pricing instruments and ways to leverage the revenues raised through these pricing instruments. These measures help to promote technology progress, innovation, and achieve cost reductions, making low-carbon fuels increasingly available, in a way that enables both better affordability and increased availability, while respecting sustainability constraints.

Recently, the establishment of the Inflation Reduction Act in the United States (Congress, 2022) has added a new layer of interventions aiming to promote both the availability and affordability of low-carbon fuels. This initiative leverages years of experience with technology and research funding available in the US Department of Energy, its network of National Laboratories and a range of programmes that have been developed to accelerate technological developments across different areas of the energy system. It uses debt-related levers, rather than pricing mechanisms, to finance technological developments and cost reductions (including via economies of scale), with the objective

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[75] Clean Fuel Regulations - Canada.ca.

to facilitate investments, mobilising private capital alongside public funds to accelerate the technology transition towards clean energy. In doing so, it also helps to reduce asset stranding risks arising from increased urgency on action on climate and biodiversity.

The following sections elaborate on policy tools combining regulatory, pricing, and financing mechanisms to accelerate clean energy technology development, focusing on a selection of policy practices that have valuable features to inform the EU policy debate (and, especially in the case of the IRA, simply cannot be left aside), picking them from the general overview developed above.

California's Low Carbon Fuel Standard

The Low Carbon Fuel Standard (LCFS) is a policy first developed in California (CARB, n.d.), and then adopted – albeit with some modification - in other jurisdictions[76]. The aim is to decrease the carbon intensity of transportation fuels by at least 20% by 2030 and provide an increasing range of low-carbon and renewable alternatives, which reduce petroleum dependency and achieve air quality benefits.

The LCFS combines regulatory requirements on declining carbon intensities of fuels and carbon pricing policy elements. It provides decentralised incentives for investments in low-carbon fuel production technologies by rewarding fuels that outperform the carbon intensity reduction required by the LCFS and penalising those uncapable to meet them.

The LCFS sets a standard for the life-cycle carbon intensity of fuel that is set to tighten over time. Fuels with a carbon intensity below the standard generate credits, while those above generate deficits. A set of rules for trading carbon credits help facilitate compliance allowing regulated entities (fuel suppliers or companies producing, importing, distributing or selling fuel) to trade with one another to meet the target. The trading of credits establishes a prevailing market price affected by a variety of factors, including the supply of credits relative to expected emissions, the cost of abatement, underlying economic conditions, perceptions of political or market risk, and in some cases, the effect of speculative investors (ITF, 2021).

A LCFS tends to provide stronger support for sustainable fuel deployment than carbon pricing. This is because revenue directly provided to sustainable fuel producers are at typically higher credit prices than carbon prices under a tax or an emission trading scheme. LCFS systems also tend to retain revenue within the transportation system since credit transactions occur between fuel distributors. However, as an LCFS sets an emissions intensity target and not an emissions cap, it does not provide an incentive to reduce output to the same extent as a carbon emission cap (Yeh et al., 2021).

Like other policies targeting low-carbon sustainable fuels, a well-designed LCFS can be a sharp and targeted decarbonisation instrument if environmental and administrative safeguards are in place. Adequate sustainability criteria are key to ensure that fuels are sustainable and have lower life-cycle emissions than conventional fuel options (ITF, 2021).The LCFS that was first implemented in California[77] in 2011, mandating a decrease in the life-cycle carbon intensity of fuels by at least 20% by 2030 (CARB, 2018). To do this it allowed regulated entities to trade credits which are generated according to the well-to-wheel emission savings of different technologies.

A blending mandate, combined with an ETS to provide a price floor and non-compliance penalties to provide a price cap, can work in a way that is similar to the LCFS. This is especially true if the mandate

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[76] In the province of British Columbia (Canada) (Government of British Columbia, 2022), and, in the US, in the states of Oregon and Washington, while being considered in seven other states, according to CAIA Association (2022).

[77] It is now also in place in Oregon, Washington state and, beyond the US, in British Columbia.

includes specific requirements for advanced and low-carbon fuels, paired with higher penalties. This is due to the penalties that can create a stronger incentive to invest in fuels that have high CO_2 emission saving capacity, even when they are still at low technology readiness levels (ITF, 2021)[78].

Expanding and focusing policy instruments like the LCFS to the case of aviation and maritime fuels will be crucial, in Europe and elsewhere, to ensure that policies using the mechanisms set out by the LCFS can be effectively applied to the modes of transport needing them the most.

Brazil's RenovaBio

The Brazilian National Biofuel Policy (RenovaBio) has a focus on biofuels (ethanol, biodiesel, biomethane, biokerosene for aviation and others), considering them not only as a way to reduce GHG emissions, but also in light a "strategic role" (including for energy security) in the Brazilian energy matrix (MME, 2021). The policy also promotes the national biofuel industry (IEA, 2019).

Similar to California's LCFS, the policy includes national carbon intensity targets, currently set until 2030, and allocated among distributors of fuels (including fossil fuels) in proportion to their market share (MME, 2021). It includes also mechanisms allowing to certify biofuels based on their GHG emission and energy efficiency profile, and the creation of the Biofuel Decarbonisation Credit (CBIO). Fuel distributors need to achieve the carbon intensity target by demonstrating the required amount of CBIOs. If they do not, they are subject to non-compliance penalties.

To be eligible for the generation of credits, the biomass processed in the plants cannot come from the areas where there has been suppression of native vegetation (MME, 2021). The policy has recently been complemented by a specific loan program with incentivised conditions for supporting the development of carbon reduction projects (IEA, 2022, BNDES, 2022).

As in the case of the LCFS, a key limitation of Brazil's RenovaBio is its focus on road fuels. This is a case where direct electrification has more chances to deliver net savings in GHG emissions and energy use, especially if combined with electricity produced without thermal energy losses from wind, solar and hydroelectric facilities. Aviation and maritime transport, both more likely to require low-carbon and sustainable fuels to decarbonise and diversify their energy mix, are not at the core of the policy. A second limitation is the focus on fuels, without the integration of electricity and related energy efficiency advantages, nor hydrogen[79].

Canada's Clean Fuel Regulations

Canada's Clean Fuel Regulations is based on instruments that are similar to those first developed with California's LCFS, first adopted in British Columbia (British Columbia, n.d.) and now being expanded nationwide. A key feature of the first proposal of the Clean Fuel Regulations is that they would have gone beyond regulating the GHG intensity of just liquid transport fuels, to include gaseous and solid fuels in industry and buildings. In their final version, though, it was narrowed to cover only liquid fossil fuels, like gasoline, diesel, and oil, which are mainly used in the transport sector (Government of Canada, 2022).

In transport, Canada's Clean Fuel Regulations include requirements for liquid fossil fuel (gasoline and diesel) suppliers to gradually reduce the carbon intensity of the fuels, leading to a progressive decrease,

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[78] The strength of the incentive to invest in advanced fuels depends on the certainty around non-compliance penalties and their value. A sufficiently high carbon tax on jet fuel could also act as a floor price for a fuel-blending mandate, creating more certainty for investment in lower-carbon fuel production (ITF, 2021).

[79] Hydrogen and hydrogen-based fuels are not currently within the scope of the policy, since definition of low carbon hydrogen, the regulation of production and use of the fuel and other hydrogen-related incentives are yet to be developed, in Brazil (BNAmericas, 2022).

starting on 2023, of approximately 15% (below 2016 levels) in the carbon intensity of gasoline and diesel used in Canada by 2030 (Government of Canada, 2022). Canada's Clean Fuel Regulations also include the establishment of a credit market: regulated parties (producers and importers of gasoline and diesel) must create or buy credits to comply with the reduction requirements. Like the LCFS, the regulations foresee a maximum price. Since 2019, every jurisdiction in Canada has a carbon pricing mechanism. The federal government also sets minimum national stringency standards so that all carbon pricing systems are comparable and effective in cutting GHG Emissions (Government of Canada, 2022).

The reduction in carbon intensity of the Clean Fuel Regulations is based on a life-cycle accounting approach. Effects related to indirect land use change are handled only via land-use and biodiversity (LUB) criteria, excluding biofuels made from feedstock that do not adhere to these criteria (Environment and Climate Change Canada, 2020, Government of Canada, 2022). Electric vehicles and low-carbon electricity are integrated in the regulations with instruments (energy efficiency ratios) that account for the energy efficiency advantage resulting from electrification.

Marine vessels for inland navigation are included in the scope of application of the regulations, except for those having a non-Canadian port as their destination (Government of Canada, 2022). In aviation, SAFs are exempt from carbon taxes and eligible to create compliance credits under the Clean Fuel Regulations. The regulations do not include an obligation to reduce the carbon intensity of jet fuel. However, an action plan sets an aspirational goal of 10 percent SAF use by the year 2030 (Transport Canada, 2022).

Canada's Clean Fuel Regulations are complemented by investments in the Clean Fuels Fund, aiming to increase support for domestic production and adoption of low-carbon fuels. These include biofuels, also certified according to their life-cycle emissions, and hydrogen, with the aim to help implement early opportunities identified in the Hydrogen Strategy for Canada (Government of Canada, 2022).

The Norwegian NO_X Fund

Nitrogen oxide emissions from shipping have been taxed by Norway since 2007. However, instead of paying this tax, firms that operate ships in Norwegian waters can choose to pay a NO_X fee related to the NO_X emissions of the ship (Norwegian Tax Administration, n.d.). These revenues can then fund innovative projects aimed at reducing NO_X emissions from ships. Companies that join the NO_X Agreement are entitled to an exemption from the tax on NO_X from the date that the enterprise affiliates with the NO_X Agreement.

Between 2008 and 2019, the NO_X Fund supported approximately 1330 projects that were reducing NO_X emissions, donating over NOK 4.4 billion (EUR 410 million). Of this amount, around NOK 1.2 billion (EUR 110 million) was used to stimulate LNG-powered ships (ITF, 2020). Other projects have been related to shore power, selective catalytic reduction, batteries and energy efficiency.

As a pricing mechanism, the NO_X Fund helps to reduce emissions from shipping both directly and through stimulation of innovation of new projects and solutions. It could potentially be developed into a model for CO_2 or GHG Fund for shipping. For instance, a CO_2 fund has been proposed for the Norwegian transport sector (Pinchaslk and Hovi, 2017) and the Norwegian Airline Industry Association has called for a CO_2 fund specifically for aviation (ITF, 2020). Heimvik (2020) argued that such refunded emission payments (REP) schemes have qualities that could make it appealing to regulators, especially if an effective emission tax is unfeasible (ITF, 2020).

The Inflation Reduction Act of the United States

The Inflation Reduction Act (IRA) was signed into law in August 2022 (Congress, 2022). It marks the most significant action the Congress has taken on clean energy and climate change in the United States (White House, 2022). The act includes billions of investments directed to several climate-related priorities, spanning well beyond sustainable transport fuels, but also including them.

Key targets of the investments include the modernisation of the electric grid, the construction of a nationwide network of electric vehicle chargers, measures aiming to strengthen the battery supply chain, expansions of public transit and passenger rail networks, the scale up of new clean energy and emissions reduction technologies, to improve resilience in physical and natural systems, and clean up legacy pollution in communities.

Thanks to the scale of the investment and the support it can give to reduce asset stranding risks, in a decarbonising context, the measure is also expected to create new, high-quality jobs (White House, 2022).

Regarding non-petroleum-based fuels for cars, trucks, and the aviation sector, the IRA covers investments on the sale and use of higher blends of ethanol and biodiesel, it extends existing tax incentives for a range of alternative fuels, including biodiesel, renewable diesel, and second-generation biodiesel. It includes also a Sustainable Aviation Fuel Credit to incentivise the production of sustainable aviation fuels that result in at least 50% less GHG emissions than petroleum-based jet fuel, taking into consideration a life-cycle accounting approach (White House, 2022).

Regarding advanced technologies for aviation, the act also includes almost USD 300 million of funds for the Alternative Fuel and Low-Emission Aviation Technology Program at the Federal Aviation Administration. This intends to award grants to projects that produce, transport, blend, or store sustainable aviation fuel or projects that develop, demonstrate, or apply low-emission aviation technologies, which are technologies that significantly improve aircraft fuel efficiency or reduce greenhouse gas emissions (White House, 2022).

The IRA also includes a range of new clean fuel production tax credits, applicable to road transport and aviation fuels that meet particular emission reduction and social (e.g. on wages and apprentices requirements) performances. Credits cover fuels used in road transport and aviation. Major funding allocations and credits, also conditional to carbon intensity and social performance-related parameters, are also applicable to hydrogen, the development of technologies like DAC and CCS, the reduction of emissions of methane and other GHG (Weaver, 2022, White House, 2022). Tax credits are also available for a range of alternative fuels, some of which have lower life-cycle emissions than conventional petroleum fuels (AFDC, n.d.).

Other credits target clean electricity, energy efficiency, clean vehicles (including electric vehicles, and covering new, second-hand cars, as well as commercial vehicles), and clean energy manufacturing. For renewable energy and batteries for clean vehicles, in particular, they include specific domestic content requirements (RSM, 2022), reflecting a stated desire to grow domestic supply chains (White House, 2022). Similar to the case of clean fuels, specific funds (USD 3 billion for cars and 1 billion for heavy vehicles) are allocated to support loans to manufacture clean vehicles and their components in the United States.

Critical aspects of the Inflation Reduction Act and European response

Key aspects of the IRA, including in particular its protectionist provisions and a strong focus on tax breaks and production subsidies (with inevitable budgetary implications), have been the subject of criticism in Europe as they were deemed to be at risk of leading to unfair competition.

Planned responses are meant to: adjust the EU's own rules to facilitate national and European public investments in the transition, work with the US to address some of the most concerning aspects of this law and further accelerate the EU's transition to green energy (European Commission, 2022).

More specifically, the Green Deal Industrial Plan (European Commission, 2023) recently presented by the European Commission, includes proposals regarding:

- A Net-Zero Industry Act, to identify goals for net-zero industrial capacity and provide a regulatory framework suited for its quick deployment. The technologies concerned include batteries, crucial for the electrification of the transport vehicles, and solar panels, wind turbines, heat pumps, electrolysers and carbon capture utilisation and storage (CCUS), needed for the abundant and low-cost supplies of renewable electricity and heat that are necessary for advanced decarbonised fuels.
- The Critical Raw Materials Act, to ensure sufficient access to those materials, like rare earths, as they are vital for manufacturing the technologies that will underpin the low-carbon economy.
- The reform of the electricity market design, to make consumers benefit from the lower costs of renewables.
- A Temporary Crisis and Transition Framework, aiming to boost investments for a faster roll-out of renewable energies, to support the decarbonisation of the industry and the production of equipment necessary for the net-zero transition. This would allow Member States to support the production of key technological components already listed earlier: batteries, solar panels, wind turbines, heat pumps, electrolysers and CCUS (European Commission, 2023).
- A revision to the General Block Exemption Regulation ("GBER"), which enables Member States to directly implement aid measures, without having to notify them ex-ante to the Commission for approval. Among others, the GBER revision will contribute to further streamline and simplify the roll-out Important Projects of Common European Interests (IPCEI) (European Commission, 2023).
- Work on the establishment of a European Sovereignty Fund, to support investments in manufacturing of net-zero technologies, complementing in the mid-term the near-term availability of funds via the REPowerEU, InvestEU[80] and the Innovation Fund.
- The establishment of a Net-Zero Industry Academies to roll out up-skilling and re-skilling programmes in strategic industries.
- The continuous development of the EU's network of Free Trade Agreements and other forms of cooperation with partners to support the green transition, including the possibility to create a Critical Raw Materials Club.

In March 2023, actual legislative proposals have been released by the Commission on the Temporary Crisis and Transition Framework Net-Zero Industry Act, relaxing State aid rules (European Commission, 2023), an amendment to the General Block Exemption Regulation (European Commission, 2023), the

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[80] The InvestEU Programme supports sustainable investment, innovation, and job creation in Europe over the period 2021 and 2027. It builds on the successful model of the Investment Plan for Europe, which mobilised more than €500 billion in the period between 2015 and 2020 (InvestEU, n.d.).

Critical Raw Materials Act and the reform of the electricity market design (European Commission, 2023, European Commission, 2023 and European Commission, 2023).

7. POLICY RECOMMENDATIONS

7.1. Main takeaways

7.1.1. Transport fuels

As described previously, the **decoupling of economic activity** from total energy demand is especially relevant for sustainable fuels because it reduces the overall pressure on primary energy and resource needs, freeing up more opportunities to make sustainable fuels sustainably available. Energy demand in the transport sector can also be reduced by **electrifying transport modes wherever feasible**.

Biofuels have a promising cost profile, especially in the near term, if compared with other options, but they face availability limitations of sustainable feedstocks that will hamper their scale up. A shift towards waste-based biofuels should also consider indirect land use change risks and the rising bioeconomy, with possible pressure on accessing feedstocks.

Production of all **RFNBOs** (hydrogen, e-liquids, methanol, ammonia) should rely only on renewable electricity to ensure a long-term decarbonisation. RFNBOs are subject to much lower sustainability constraints from land use requirements, as long as the renewable electricity is not produced from bioenergy. Furthermore, the high requirements of RFNBOs for renewable electricity need to be balanced against competing uses of such energy that are more energy efficient, including road transport and heat pumps for low temperature heating.

Renewable hydrogen (produced as an RFNBO) faces significant technical challenges, high costs, and dedicated infrastructure requirements to be transported, stored and distributed to transport vehicles.

E-liquids face challenges including cost, technology readiness, energy efficiency and other challenges, limiting their capacity to contribute at scale to the transition in the very near term. E-liquids can be used as direct substitutes for their fossil equivalents.

7.1.2. Which fuel for which transport mode

The best match between transport modes and sustainable fuels will depend on a number of factors including:

- Capacity of a fuel type to meaningfully contribute to life-cycle GHG emission abatement;
- Resource availability and sustainability impacts, addressing pressure on resources such as food production, land-use, water, and related material requirements.
- Technical feasibility, such as safety requirements, environmental hazards, energy density and weight of on-board storage.
- The need for new, repurposed or directly using the existing infrastructure, considering the need to minimise the risks of stranded assets. Hydrogen and a high share of biochemical or FAME (oleochemical pathway) fuels require new infrastructure, which could possibly lead to stranded assets, while HVO/HEFA, thermochemical fuels and e-liquid are fully compatible with fossil-based fuels. Although renewable e-ammonia and e-methanol could potentially take advantage of existing infrastructure, this is very under-developed in comparison with the scale of potential needs.
- Minimising cost is especially important for technologies that require international coordination of investment in infrastructure.

Direct electrification is the best option for the decarbonisation of road transport, rail transport, and is also well suited for the transition of inland navigation and short sea shipping vessels, and possibly also for short-haul aircraft. In road transport it is a clear leader for light transport decarbonisation, and increasingly also for heavy-duty vehicles.

Due to the challenges associated with land use for energy production, it will be critical to prioritise the use of renewable electricity, at least when availability is limited, for direct consumption in energy efficient devices and storing it in batteries. Increases in **sustainable bioenergy** production should be prioritised for use in sectors likely to see increases in demand such as the construction industry, bio-based materials, aviation and maritime transport, rather than in transport segments that can be more easily electrified.

Hydrogen trucks could be a candidate for the use of **renewable hydrogen**, from a technical perspective, but they are likely to be outcompeted by battery electric trucks. They would also require substantial infrastructure investments, without solid prospects allowing for a sufficiently high usage rate to cut costs. Hydrogen also faces important technical challenges to be used directly as energy carrier on large shipping vessels and long-distance aircraft, due to its low volumetric energy density and the need for liquefaction. The use of renewable hydrogen as a fuel for trucks and for handling or logistics equipment could eventually be leveraged via hydrogen clusters, despite remaining challenges to scaling up fuel cell production.

Prospects for cost reductions make **renewable hydrogen derivatives**, and in particular **e-liquids,** one of the likely best options available to decarbonise modes that cannot shift towards direct use of electricity by 2050. This is relevant to aviation and long-distance shipping in particular, while also ensuring that low-carbon electricity is available at scale. One of their advantages is that they can make use of the existing infrastructure, and do not require new engines.

E-methanol (one of the e-liquids) and **e-ammonia** (one of the RFNBOs) are especially relevant options for the shipping sector, due to lower production costs than e-liquids. They have lower investment risks compared to hydrogen for the development of new fuel distribution infrastructures, or, where it exists already, they can make use of the existing infrastructure. E-ammonia has the advantage of lower costs and no reliance on carbon from Direct Air Capture or concentrated sources, initially. Methanol has the advantage of a lower toxicity and ease of handling in comparison with ammonia. With adequate investments in new infrastructure, conducting pilots, and addressing safety requirements for distribution, storage on ships and use in propulsion systems, they may outcompete e-liquids in shipping. One alternative could possibly be the use of methanol in the gasoline blend, but energy efficiency losses would remain a major issue. In any case, focusing on hydrogen clusters offers synergies for ammonia and methanol, as their decarbonised production requires low-carbon hydrogen.

Recycled Carbon Fuels (RCF) can be relevant as an instrument to facilitate near-term emission reductions in modes where direct electrification faces major barriers, such as long-distance aviation and shipping. However, they are not an appropriate option for a long-term deep decarbonisation goal.

A strict regulatory regime needs to be developed to ensure that **offsetting** developments leads to effective GHG savings. Offsetting costs should be borne by fossil fuel producers. Offsetting should not be considered as an option for transport decarbonisation *per se*, but rather as an instrument that could help reducing further GHG emissions.

7.2. Policy recommendations

The EU policy framework, including the ongoing proposals, contains all critical components for the decarbonisation of transport by tackling, among others, the deployment of sustainable fuels. The results of this analysis propose several policy recommendations to address possible remaining gaps and weaknesses.

7.2.1. Reinforce all policies conducting to decarbonisation at the least cost

- More energy efficient and less polluting powertrains. The requirement to reach zero tailpipe emissions from new light vehicles (passenger cars and vans) by 2035 is crucial, and so is the recent proposals on tailpipe emission cuts for trucks. Due to better cost competitiveness vs other powertrain and energy pairs, this will also require the acceleration of the deployment of electric charging points across Europe, in the frame of the proposed Alternative Fuel Infrastructure Regulation.
- Maximising all-electric km per unit of battery capacity installed on vehicles and appropriate sizing of batteries and vehicles, focusing early electrification requirements on highly utilised light and heavy duty fleets, can effectively reduce demand for energy and battery materials. Establishing CO_2 emissions limits for new light vehicles that depend on their size, to discourage the deployment of unnecessarily large and heavy passenger vehicles, can be an effective option to supplement the focus on highly utilised vehicles. The introduction of regulatory limits on battery size could also prevent the inefficient use of primary materials that may be subject to supply availability challenges.
- Behavioural changes that reduce energy demand. For example, by stimulating the use of public transport and by replacing short-distance flights with train travel, especially on corridors where rail connections already exist and where expected traffic allows to justify, economically and environmentally, additional investments in rail infrastructure (since infrastructure construction comes with significant amounts of upfront emissions).
- Regulatory developments on speed limits and road space allocation could also support changes in behaviour, as they alter the speed and safety profile of different modes of transport.
- Where electrification is not the least cost technology option, prioritise other technologies with lower cost, energy and resource efficiency. This should consider the need to develop transport, storage, and distribution infrastructure and ensure that sufficient volumes of fuels can guarantee the economic viability of a sustainable fuel type. This is especially relevant for choices between hydrogen and other fuels, given the technical difficulties to handle hydrogen, despite greater energy efficiency to produce it from low-carbon electricity.

7.2.2. Articulate goals and requirements for sustainable fuels

- Regulatory requirements for fuels used in maritime transport could be articulated further, not only taking an approach focused on life-cycle GHG emission reductions, but also including specific RFNBO shares, as in the case of aviation.
- To offer more flexibility, life-cycle GHG emission saving requirements for aviation and shipping shall include the possibility to account for renewable or other forms of low-carbon electricity and hydrogen, also accounting for energy efficiency benefits (most relevant for shipping).

- Early supply of SAF and sustainable and advanced fuels for aviation and maritime transport, including RFNBOs, can be facilitated by the inclusion of a book and claim system[81], to enable cost reductions and scale increases.
- Private jets should be included within the scope of the ReFuelEU.
- Large recreational/luxury crafts, not included in the FuelEU Maritime Regulation, shall be early candidates for ambitious revisions of the regulatory framework governing their emissions (such as the update of the Recreational Craft Directive). Lighter craft can also benefit from increases in the rates of electrification of road vehicles, as they use a similar set of technologies.
- The rules defining life-cycle emissions of hydrogen and its derivatives include a trade-off between costs and GHG emission and fossil energy use. If the objective is the minimisation of emissions, as long as low-cost hydrogen storage is not available, the additionality, geographical and temporal matching rules for RFNBO production shall be maintained, especially in the initial scale-up of electrolytical hydrogen production (Zeyen et al., 2022). This is especially important with a need to minimise natural gas use as a marginal electricity production option, with clear implications for energy security. A regulatory environment with annual matching for the initial scale-up of electrolysis could ease investments, but it would come with the disadvantage of additional emissions and thermal electricity demand until the electricity grid becomes significantly decarbonised. Annual matching would be far more aligned with opportunities for emission reduction with increasing rates of grid decarbonisation.

7.2.3. Strengthen carbon pricing policies and phase out subsidies for fossil fuels

- Clear pricing signals provided via the ETS and/or the ETD are required to encourage the development and investment in sustainable fuels for transport. It is however crucial to recognise that these instruments should be accompanied to facilitate the just and equitable transition.
- Carbon pricing policies should be paired with mechanisms capable of directing the revenues they generate towards the support of innovation and for re-distributional measures. Existing initiatives – such as the Social Climate Fund – should be confirmed, or even reinforced.
- Carbon pricing for EU domestic and international aviation is essential (i.e. via ETS and/or CORSIA framework, as long as the latter can provide more effectively clear price signals). Without meaningful improvements in CORSIA, the ETS shall cover all flights departing from the European Economic Area (“EEA”), including flights bound for non-EEA destinations, leaving only inbound flights subject to CORSIA.
- It is important to ensure that the dual ETS/CORSIA system does not lead to carbon leakage. This requires close monitoring in the initial phase of implementation of the ETS revision.
- Continuing to participate in international negotiations at the ICAO is crucial to raise the global ambition on climate policy. In the absence of meaningful developments in international negotiations related to carbon pricing in aviation, the set-up of Carbon Border Adjustment Mechanism-like instruments for aviation is likely needed to ensure continued progress towards decarbonisation without negative impacts on the sector due to carbon leakage.
- It is important to ensure there is maritime carbon pricing in place (i.e. via ETS), including for at least 50% of non-intra-EU voyages, leaving a window of opportunity for IMO progress on the remaining 50%. Continued participation in international negotiations at the IMO is necessary to raise the global ambition on climate policy.

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[81] A Book-and-Claim is a system that decouples the consumer from the actual physical product while they are still allowed to claim the CO_2 reduction that their purchase achieves.

- It is important to ensure that there is carbon pricing for road transport, via ETS extension and/or ETD. For road transport, a fixed carbon pricing instrument may be preferred, since this is already in place for its main fuels in the context of the ETD, and since it is less subject to the risk of price volatility.

7.2.4. Increase RD&I spending, deployment support, the stimulation of investments in manufacturing capacity, including de-risking strategies

- Research, Development and Innovation (RD&I) spending on key enabling technologies will be vital to prove and mature their efficacy and to lower their costs. This is important for facilitating multiple pathways for the transition and for deployment of sustainable fuels in particular. Key enabling technologies include direct air capture (as CCU will not be sufficient to guarantee low emissions, unless the carbon source is biogenic) and the electrochemical reduction of CO_2.
- Other technologies – namely batteries, electrolysers, solar panels, wind turbines and heat pumps – are more likely to benefit from deployment support and the stimulation of investments in manufacturing capacity, even if they can also benefit from continued RD&I investment. To achieve overarching goals like peace, global progress and development, in addition to global progress towards climate change mitigation, it will be important to ensure that deployment support remains aligned with increased trade cooperation with as many countries as possible (Demertzis, 2023). The EU requires a fully integrated European solution, regarding the completion of the single market, the harmonisation of corporate governance and disclosure rules, the strengthening of State Aid rules and changes of competition rules. (Garicano and Verhofstadt, 2023).
- Support for pilot and demonstration projects are important to speed up the identification of the most suitable sustainable powertrains and energy pairs for specific applications and reduce investment risks. This should consider two key elements: the viability of scaling up, including feedstock availability, and the required infrastructure investments (including internationally). Similar to selecting the BEV route as most appropriate for cars some 10 years ago, the goal should be to focus efforts one or two priorities per transport mode. The selection should also be coordinated internationally with key players. This exercise will help avoid stranded assets while ensuring that no-regret options are rolled out and deployed at scale at the appropriate pace.
- Pilots, demonstrations and other de-risking strategies are needed to enable greater investments. For maritime transport, they can help develop green shipping corridors, especially if paired with clusters where industrial supply and demand for hydrogen is or will be concentrated.
- Increased spending on the development of technical standards applying to the safety, handling and other requirements for the use, transport and storage of sustainable fuels, can accelerate change. This is another key pre-requisite for risk mitigation of infrastructure-related investments.
- RD&I agendas should remain open to a possible phase-in of hydrogen use in heavy-duty road, or even in maritime and aviation, considering the scale-up challenges of alternative technologies.

7.2.5. Infrastructure options and priorities

- Focus first on 'low regret' options for infrastructure investments, especially in the near-term. In this context, the expansion of the public charging points infrastructure for electric cars has a

very low risk of failure, and so does the reinforcement or flexibilisation of the electricity network. The proposed revisions to the Alternative Fuel Infrastructure Directive should therefore focus first on direct electrification.
- A hydrogen transport and distribution network for transport needs careful consideration, as it should first require successful demonstration projects around industrial "hydrogen valleys" or clusters, supporting the transition to renewable hydrogen in industries.

7.2.6. Support the scale up and accompany the transition

- Establish an enabling framework for the smooth scale up of the most suitable technologies for the decarbonisation of the different transport modes and of the fuel production, transport, distribution and storage infrastructure that they need, to encourage investments. Prioritising measures that encourage the development of technologies required by the most cost-effective powertrain and energy pairs can help to ensure that the transition towards decarbonisation and sustainability is accompanied by industrial development, mitigating the risks of deindustrialisation.
- Adopt or strengthen financial and technical instruments capable of de-risking investments in low-carbon cost-effective technologies and their supply chains. This includes measures that require the alignment of investments with sustainability (and/or greater transparency to evaluate that this alignment is in place), since they can help selectively reduce the cost of capital for options aligned with the objectives of the European Green Deal.
- Scale up in the near-term deployment support and the stimulation of investments in manufacturing capacity batteries, electrolysers, solar panels, wind turbines and heat pumps, in addition to CCUS (not as relevant for low-carbon transport vehicles and fuels).
- Consider the same type of measures in the medium-term for direct air capture and the electrochemical reduction of CO_2.
- A major energy transition will require a wide range of skills and knowledge spanning across different domains, particularly in mining, mineral conversion, battery manufacturing, electrolyser production, and digital technologies facilitating the integration and the optimisation of systems. It will be important for Europe and governments to support and cooperate with industry for the up-skilling and re-skilling of the workforce.
- In transport, electrification will have significant impacts in the automotive sector, with skills transitioning from combustion technologies towards electro-chemistry. As combustion will still remain relevant in shipping and aviation, fostering a joint transition of different transport modes may prove beneficial to manage transitional impacts.
- As early movers will likely be rewarded with long lasting economic benefits, as long as investments are well aligned with least cost and sustainability requirements, it will be necessary to build skills rapidly. Due to the depth of the changes needed, enhancing technical capacities will likely be necessary in a range of professions. This will include but will not be limited to investors, policymakers, researchers, and workers employed in manufacturing, in the energy and the construction sectors.

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This study provides the European Parliament's Committee on Transport and Tourism (TRAN) with an assessment of the potential of sustainable fuels to decarbonise the transport sector, and help the sector achieve the 2050 decarbonisation goals. It assesses their potential for use in maritime, aviation and road transport, considering their technology readiness, feedstock availability, sustainability of supply, resource and energy efficiency, and the most appropriate match-making between fuels and applications.

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