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Climate protection in aviation and maritime transport: Roadmaps for achieving the climate goal

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Climate protection in aviation and maritime transport: Roadmaps for achieving the climate goal

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Abstract: Climate protection in aviation and maritime transport – Roadmaps for achieving the climate goal

The climate neutrality of air and sea transport can hardly be achieved without the accelerated use of almost GHG-neutral fuels. Such fuels are generated from renewable electricity and are thus called electro fuels or (synthetic) e-fuels. To illustrate how these e-fuels can be made available and how to ensure that in both sectors only such fuels are used, several policy roadmaps have been sketched. In terms of e-fuel supply, there are significant differences between aviation and maritime transport: While e-kerosene is widely identified and accepted as future fuel for aviation, a single prospective fuel has not yet emerged for maritime transport. Currently, there is a challenging dilemma for policy makers. On the one hand, the transition towards defossilizing international transport should be accomplished by 2050, requiring that the right decisions are made sooner rather than later. Particularly for shipping, the main goal for the years ahead is, on the other hand, to limit the number of e-fuels pursued. Unless a dominant fuel or fuels are supported by a critical mass of countries, it will hardly be possible to trigger the economies-of-scale dynamics required to accomplish the transition. Our assessment also shows that the first regulatory steps must be taken immediately on all levels. National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible and are actively supported by policy initiatives at European and international level. The years up to 2025 are decisive for achieving defossilization of aviation and maritime transport. If appropriate policies are not set in place by then, at least at national and European level, it will be difficult to achieve the goal of defossilization by 2050.

Kurzbeschreibung: Klimaschutz im Luft- und Seeverkehr – Roadmaps für die Erreichung des Klimaziels

Die Klimaneutralität des Luft- und Seeverkehrs ist, ohne den beschleunigten Einsatz von nahezu treibhausgasneutralen Kraftstoffen, kaum zu erreichen. Solche Kraftstoffe werden aus erneuerbarem Strom erzeugt und daher als Elektrokraftstoffe oder (synthetische) E-Kraftstoffe bezeichnet. Um zu veranschaulichen, wie diese E-Kraftstoffe zur Verfügung gestellt werden können und wie sichergestellt werden kann, dass in beiden Sektoren nur solche Kraftstoffe verwendet werden, wurden mehrere politische Roadmaps skizziert. Was die Versorgung mit E-Kraftstoffen angeht, gibt es erhebliche Unterschiede zwischen dem Luft- und dem Seeverkehr: Während E-Kerosin als zukünftiger Kraftstoff für den Luftverkehr weithin bekannt und akzeptiert ist, hat sich für den Seeverkehr noch kein einziger potenzieller Kraftstoff herauskristallisiert. Derzeit stehen die politischen Entscheidungsträger vor einem schwierigen Dilemma. Einerseits soll der Übergang zur Defossilisierung des internationalen Verkehrs bis 2050 vollzogen werden. Dies bedeutet, dass die richtigen Entscheidungen eher früher als später getroffen werden müssen. Insbesondere für die Schifffahrt besteht das Hauptziel für die kommenden Jahre darin, die Anzahl der angestrebten E-Kraftstoffe zu begrenzen. Solange nicht eine entscheidende Anzahl von Ländern einen oder mehrere dominierende Kraftstoffe unterstützt, wird es kaum möglich sein, die für den Übergang erforderliche Dynamik der Größenvorteile auszulösen. Unsere Bewertung zeigt auch, dass die ersten regulatorischen Schritte sofort auf allen Ebenen unternommen werden müssen. Die nationalen Regierungen müssen sicherstellen, dass die politischen Maßnahmen, den Investoren und Betreibern Anreize und Orientierungshilfen bieten, so bald wie möglich verabschiedet und durch politische Initiativen auf europäischer und internationaler Ebene aktiv unterstützt werden. Die Jahre bis 2025 sind entscheidend, um die Defossilisierung des Luft- und Seeverkehrs zu erreichen. Wenn bis dahin nicht zumindest auf nationaler und europäischer Ebene geeignete politische Maßnahmen ergriffen werden, wird es schwierig sein, das Ziel der Defossilisierung bis 2050 zu erreichen.

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List of abbreviations

AFC	Alkaline Fuel Cell
AIP	Approval in Principle
ASTM	ASTM International, formerly 'American Society for Testing and Materials'
atm	Standard atmosphere, equivalent to 101 325 Pa
BAU	Business as usual
CAEP	Committee on Aviation Environmental Protection
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCC	Sub-Committee on Carriage of Cargoes and Containers
CCS	Carbon Capture and Storage
CH₄	Methane
CI	Compression-Ignition
CNG	Carbon Neutral Growth
CO₂	Carbon dioxide

COGES	Combined Gas and Steam
DAC	Direct Air Capture
DME	Dimethyl Ether (C ₂ H ₆ O)
DMFC	Direct Methanol Fuel Cell
dwt	Deadweight Tonnage
EASA	European Aviation Safety Agency
ECA	Emission Control Areas
ECE	External Combustion Engine
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EJ	Exajoule (10 ¹⁸ Joule)
ESSF	European Sustainable Shipping Forum
ETD	Energy Tax Directive
FESG	Forecasting and Economic Support Group
FT	Fischer-Tropsch
GDP	Gross domestic product
GHG	Greenhouse Gas
GJ	Gigajoule
GMF	Airbus Global Market Forecast
GoE	Guarantee of Origin
H₂	Hydrogen
HEFA	Hydroprocessed Esters and Fatty Acids
HFO	Heavy Fuel Oil
HT-PEMFC	High Temperature Polymer Electrolyte Membrane Fuel Cell
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEA	International Energy Agency
IFR	Instrument Flight Rules
IGC Code	International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
ILUC	Indirect Land Use Change
IMO	International Maritime Organization

LBST	Ludwig-Bölkow-Systemtechnik GmbH
LECA	Low GHG Emissions Control Area
LNG	Liquid Natural Gas
LNG	Liquefied Natural Gas
LPG	Liquefied Petrol Gas
LSFO	Low Sulphur Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
mb/d	Million barrels per day
MCFC	Molten Carbonate Fuel Cell
MENA	Middle East & North Africa
MJ	Megajoule
Mt	Megatonne (10^6 tonnes)
Mtoe	Million tonne of oil equivalent
NECA	Nitrous Oxide Emissions Control Area
NH₃	Ammonia
NO_x	Nitrogen Oxide
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PJ	Petajoule (10^{15} Joule)
PtL	Power-to-Liquid
PtX	Power-to-Gas or Liquid
RCP	Representative Concentration Pathways
RED	Renewable Energy Directive
RoPax	Combined Roll-on/Roll-off (RoRo) and passenger ship
RPK	Revenue Passenger Kilometres
RTK	Revenue Tonne Kilometres
SAF	Sustainable Alternative Fuels
SCR	Selective Catalytic Reduction
SECA	Sulphur Emissions Control Area
SI	Spark Ignition
SIP	Synthesized Iso-Paraffins
SMCR	Specified Maximum Continuous Rating
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea

SO_x	Sulphur oxides
SPK	Synthesized Paraffinic Kerosene
SSP	Shared Socioeconomic Pathways
Toe	Tonne of Oil Equivalent, 1 toe = 41.868 GJ
ULSFO	Ultra-low sulphur fuel oil
UNFCCC	United Nations Framework Convention on Climate Change
US\$	United States Dollar
WHR	Waste Heat Recovery

Summary

In the Paris Agreement, the final document of the 2015 Climate Change Conference in Paris, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to reduce greenhouse gas (GHG) emissions in order that the global temperature increase remains well below 2°C, if possible, even below 1.5°C compared to pre-industrial levels (Article 2.1). In Article 4, the Parties agreed to aim to balance anthropogenic GHG emissions and sinks, or in other words, to strive for climate neutrality in the second half of this century. Since emissions from aviation and maritime transport are clearly anthropogenic and no other sectors are mentioned explicitly, they fall under the objectives of the Paris Agreement even without being explicitly mentioned.

Achieving climate neutrality in aviation and maritime transport will not be possible without comprehensive packages of policy instruments to incentivize reduction measures including increased efficiency through new technologies and improved operations as well as through reduced traffic. But even if these packages are implemented consistently, fossil fuels must be substituted by climate-neutral alternatives. The climate neutrality of air and sea transport can thus only succeed through the use of post-fossil fuels which are produced without generating any GHG emissions during their entire lifecycle from well to wing/wake. With the limited availability but high demand for truly sustainable biofuels, these post-fossil fuels will need to be synthesized from additional renewable electricity. Such fuels are usually called electro fuels – or (synthetic) e-fuels for short. The central questions are how to provide these fuels to the extent required in the future and how to ensure that in both sectors only such fuels are used.

To this end, we developed political roadmaps of options for a climate-neutral energy supply for air and sea transport, which could ensure the contributions of both sectors to achieving the global, European and national climate targets. As a basis for developing these roadmaps, we compiled an overview of energy demand projections with a view to estimating the quantity of renewable energy required for the defossilization of aviation and maritime transport. In a second step, we assessed the action areas which need to be ‘ploughed’ to enable the transition. We put a specific focus on barriers and potential policies to overcome them and looked at technological challenges and potentials for producing the post-fossil fuels required to power airplanes and ships. Based on these considerations, we describe potential roadmaps for the transition towards the climate neutrality of aviation and maritime transport and finally drew conclusions and provide concrete policy recommendations.

Future trends and scenarios

Based on the energy demand projections, we estimated that in 2050 the renewable electricity required to produce these e-fuels would range between 22 and 32 PWh. In 2018, the total global renewable electricity generation amounted to 6.7 PWh. Currently, each sector would require the total global renewable electricity generation if their energy demand were to be supplied by post-fossil e-fuels only. Assuming the average growth rates for wind and photovoltaics of the last 5 years, all additional renewable capacity added in the next 10 years would be required to supply the projected energy demand of both sectors with e-fuels in 2050.

Action areas

In the aviation sector, different types of policies to support the use of e-fuels could be applied; these include mandatory and gradually increasing blending quotas, green certificates or subsidies similar to feed-in tariffs for renewable energy. All these policies would avoid a costly duplication of infrastructures in fuel distribution.

In maritime shipping, existing environmental policy incentives are by no means sufficient to stimulate the use and the supply of e-fuels. However, for maritime transport a whole range of potential e-fuel options

are under discussion. Policies and actions to eliminate specific barriers to the supply and use of post-fossil fuels in shipping could therefore be of a more generic nature such as taxes. Or, since the uncertainty itself can be a major barrier to the uptake and supply of post-fossil fuels in maritime shipping, policies and actions could be aimed at reducing the uncertainty by either quickly excluding comparatively inferior options and/or by stimulating the development of flexible options, both for ships and for fuel suppliers.

Post-fossil energy supply options

In principle, it is possible to produce e-fuels in such a way that facilitates the complete transition to post-fossil energy supply in aviation and maritime transport. In addition to using additional renewable electricity for producing them, the CO₂ required for producing hydrocarbons such as e-methanol or e-diesel needs to come from non-fossil sources, too. Stringent sustainability and climate regulations covering the entire lifecycle of e-fuels are thus needed to ensure that the use of e-fuels during the transition phase contributes to absolute GHG reduction.

Among the different e-fuels, e-hydrogen and e-ammonia have the highest well-to-tank conversion efficiency. E-methanol, e-LNG and e-DME have higher conversion losses but are more efficient in production than e-kerosene or e-diesel. From the perspective of fuel production, ammonia and hydrogen thus have advantages over other e-fuels but face challenges in terms of risk, handling or infrastructure. Also, other GHG emissions including methane and nitrous oxide need to be considered. Today the production costs of e-fuels are significantly higher than those of fossil fuels and, even if this spread narrows, the costs of e-fuels will remain higher in the longer term.

Roadmaps for achieving zero emissions

The roadmaps illustrate pathways that enable the transition of global aviation and maritime transport from fossil to sustainable post-fossil fuels. Since e-kerosene is very likely to be the dominant e-fuel for long-haul aviation, we have provided only one roadmap for this sector. For maritime transport, the situation is more complex. Several e-fuels are candidates to become the dominant fuel in the future and different fuels might prevail in parallel. All candidates have distinct advantages and disadvantages without one option being clearly the best. We therefore described two roadmaps: one which focuses on promoting one potential candidate and one which pursues a technology-open approach.

The comparison of the shipping roadmaps reveals that a technology-open approach might deliver the most cost-efficient e-fuel(s) but could involve a further delay in GHG reductions and higher costs overall due to sunk costs. Deciding which of the two approaches is more appropriate is thus not clear-cut. However, for sectors which are as globally connected and intertwined as international transport, local preferences are rather a hindrance for the accelerated uptake of e-fuel required to achieve full defossilization by 2050. The limited time span that remains for the transition towards post-fossil fuels, but also the infrastructure dependency of each e-fuel type and the global nature of international transport therefore suggest that it would be wiser to focus on one e-fuel early on rather than promoting technological competition for further years.

Currently, there is a challenging dilemma for policy makers. On the one hand, the transition to defossilizing international transport should be accomplished by 2050, which means that the relevant decisions need to be made sooner rather than later. On the other hand, there is no dominant e-fuel or a limited number of feasible e-fuels in sight, particularly for shipping. For the transition to post-fossil fuels, the main goal for the years ahead is therefore to limit the number of e-fuels pursued. Unless a dominant fuel or fuels are supported by a critical mass of countries, it will hardly be possible to trigger the economies-of-scale dynamics required to accomplish the transition.

Recommendations

With the above analysis in mind, our main recommendations are:

- ▶ Coordination of policy initiatives at global level would be most effective to achieve defossilization of both sectors. However, achieving sufficiently ambitious agreements at IMO and ICAO would likely take more time than is available for achieving the temperature goals of the Paris Agreement.
- ▶ Forerunner activities at national (Germany) or regional (like-minded European states, EU) level are likely to accelerate the progress at international level.
- ▶ Implementing ‘lighthouse projects’ which demonstrate the practical feasibility of fully deploying e-fuels can trigger the transition on a larger level.
- ▶ For aviation, a drop-in fuel mandate at European level is a viable option which would trigger and ensure the increased uptake of e-kerosene in one of the major global aviation markets. However, possible competitive impacts of such a mandate have to be taken into account.
- ▶ For shipping, it is too early to identify the dominant e-fuel(s). The main goal of a transition strategy should therefore be to reduce the number of potential options, preferably to one dominant e-fuel. At EU level, this process can be supported by a technology-open e-fuel mandate, which should be converted as soon as possible into a specific mandate for one e-fuel.
- ▶ Hydrogen is a no-regret option for all e-fuels and synergies might emerge in the upscaling of e-fuel production for aviation and shipping, e.g. if intermediate or by-products of e-kerosene production were also used to produce e-fuels for the shipping sector.
- ▶ To trigger technological learning in the production of e-fuels, the deployment of these fuels will need to be subsidized early on. This will facilitate the scaling-up of generation capacities and reduce production costs. Since all potential e-fuels for aviation and maritime transport are also used as fuels or raw material in other sectors, fostering such a transition is a no regret policy. Hence, the defossilization concepts of other sectors should ideally be interlinked with the aviation and shipping roadmaps in order to generate an optimized general concept. This could apportion the costs of conversion to all sectors as they face the challenge of defossilization in parallel.
- ▶ As long as policies to increase the uptake of e-fuels are not applied at global level, subsidies for e-fuel production or consumption may be required to ensure a more level playing field with fossil fuels used elsewhere.
- ▶ Efforts to establish policies for accelerating the uptake of e-fuels under ICAO and IMO including e-fuel mandates and market-based policies need to be intensified immediately. In addition, processes need to be initiated to ensure that global fuel safety standards are further developed to enable the use of e-fuels.
- ▶ A strategic partnership between a critical mass of key countries and actors should be initiated. Such an initiative could start with a small number of countries with a significant market share in aviation or shipping, which are likely to agree on a common strategy, potentially accompanied by future e-fuel supply countries. Other countries could join the initiative later, provided that they agree with the principles and goals of the initiative. For shipping, the main goal of such an initiative would be to agree on dominant e-fuels (preferably only one) as soon as possible and no later than 2025.

Our assessment also shows that the first steps must be taken immediately on all regulatory levels. National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible and actively support policy initiatives at European and international level. The years up to 2025 are decisive for achieving defossilization of aviation and maritime transport. If appropriate policies are not set in place by then, at least at national and European level, it will be difficult to achieve the goal of defossilization by 2050.

Zusammenfassung

Im Übereinkommen von Paris, dem Abschlussdokument der Pariser Klimakonferenz im Jahr 2015, haben sich die Vertragsparteien der Klimarahmenkonvention (UNFCCC) darauf geeinigt, die Emissionen von Treibhausgasen (THG) zu reduzieren, damit der globale Temperaturanstieg deutlich unter 2 °C, wenn möglich sogar unter 1,5 °C gegenüber dem vorindustriellen Niveau bleibt (Artikel 2.1). In Artikel 4 haben sich die Vertragsparteien darauf geeinigt, ein Gleichgewicht zwischen den anthropogenen Treibhausgasemissionen und den Senken anzustreben, d.h. in der zweiten Hälfte dieses Jahrhunderts Klimaneutralität anzustreben. Da die Emissionen aus dem Luft- und Seeverkehr eindeutig anthropogen sind und keine anderen Sektoren ausdrücklich erwähnt werden, fallen sie auch ohne ausdrückliche Erwähnung unter die Ziele des Übereinkommens von Paris.

Die Klimaneutralität des Luft- und Seeverkehrs wird nicht ohne umfassende Pakete politischer Instrumente möglich sein, die Anreize für Reduktionsmaßnahmen schaffen, einschließlich Effizienzsteigerungen durch neue Technologien und verbesserte Abläufe sowie durch eine Reduzierung des Verkehrsaufkommens. Aber auch wenn diese Pakete konsequent umgesetzt werden, müssen fossile Brennstoffe durch klimaneutrale Alternativen ersetzt werden. Die Klimaneutralität des Luft- und Seeverkehrs kann also nur durch den Einsatz postfossiler Kraftstoffe gelingen, die während ihres gesamten Lebenszyklus von der Quelle bis zur Turbine oder zum Propeller keine zusätzlichen Treibhausgasemissionen verursachen. Angesichts der begrenzten Verfügbarkeit sowie der hohen Nachfrage nach wirklich nachhaltigen Biokraftstoffen müssen diese postfossilen Kraftstoffe aus zusätzlichem erneuerbarem Strom synthetisiert werden. Solche Kraftstoffe werden üblicherweise als Elektrokraftstoffe – oder kurz als (synthetische) e-Fuels – bezeichnet. Die zentralen Fragen sind, wie diese Kraftstoffe in Zukunft in dem erforderlichen Umfang bereitgestellt werden können und wie sichergestellt werden kann, dass in beiden Sektoren nur solche Kraftstoffe verwendet werden.

Zu diesem Zweck haben wir politische Roadmaps mit Optionen für eine klimaneutrale Energieversorgung des Luft- und Seeverkehrs entwickelt, welche die Beiträge beider Sektoren zur Erreichung der globalen, europäischen und nationalen Klimaziele sicherstellen könnten. Als Grundlage für die Entwicklung dieser Roadmaps haben wir eine Übersicht über Energiebedarfsprognosen erstellt, um die Menge an erneuerbarer Energie abzuschätzen, die für die Defossilisierung des Luft- und Seeverkehrs benötigt wird. In einem zweiten Schritt haben wir die Handlungsfelder bewertet, die für den Übergang ‚beackert‘ werden müssen. Dabei haben wir einen besonderen Schwerpunkt auf Hindernisse und mögliche politische Maßnahmen zu deren Überwindung gelegt sowie die Potenziale und technologischen Herausforderungen für die Herstellung der für den Antrieb von Flugzeugen und Schiffen erforderlichen postfossilen Kraftstoffe untersucht. Auf der Grundlage dieser Überlegungen beschreiben wir mögliche Roadmaps für den Übergang zur Klimaneutralität des Luft- und Seeverkehrs, ziehen schließlich Schlussfolgerungen und geben konkrete politische Empfehlungen.

Zukünftige Trends und Szenarien

Auf der Grundlage der Energiebedarfsprognosen schätzten wir, dass im Jahr 2050 der für die Herstellung der e-Fuels benötigte Strom aus erneuerbaren Energien zwischen 22 und 32 PWh liegen würde. Im Jahr 2018 belief sich die gesamte weltweite Stromerzeugung aus erneuerbaren Energien auf 6,7 PWh. Derzeit würde jeder der beiden Sektoren die gesamte weltweite Stromerzeugung aus erneuerbaren Energien benötigen, um seinen Energiebedarf ausschließlich durch postfossile e-Fuels zu decken. Geht man von den durchschnittlichen Wachstumsraten für Wind und Photovoltaik der letzten 5 Jahre aus, wäre der gesamte zusätzliche Zubau an erneuerbaren Kapazitäten in den nächsten 10 Jahren erforderlich, um den prognostizierten Energiebedarf beider Sektoren im Jahr 2050 mit e-Fuels zu decken.

Handlungsfelder

Im Luftverkehrssektor könnten verschiedene Arten von Maßnahmen zur Förderung der Verwendung von e-Fuels angewandt werden; dazu gehören schrittweise ansteigende verpflichtende Beimischungsquoten,

grüne Zertifikate oder Subventionen ähnlich den Einspeisetarifen für erneuerbare Energien. All diese Maßnahmen würden eine kostspielige Verdoppelung der Infrastrukturen für die Kraftstoffverteilung vermeiden.

Im Seeverkehr reichen die bestehenden umweltpolitischen Anreize bei weitem nicht aus, um die Nutzung und das Angebot von e-Fuels zu fördern. Für den Seeverkehr wird jedoch eine ganze Reihe potenzieller e-Fuel-Optionen diskutiert. Politische Maßnahmen und Aktionen zur Beseitigung spezifischer Hindernisse für die Bereitstellung und Nutzung postfossiler Kraftstoffe im Seeverkehr könnten daher eher allgemeiner Natur sein, z. B. in Form von Steuern. Da die Ungewissheit selbst ein großes Hindernis für die Einführung und das Angebot postfossiler Kraftstoffe im Seeverkehr sein kann, könnten Strategien und Maßnahmen darauf abzielen, die Ungewissheit zu verringern, indem entweder vergleichsweise minderwertige Optionen schnell ausgeschlossen werden und/oder die Entwicklung flexibler Optionen sowohl für Schiffe als auch für Kraftstofflieferanten gefördert wird.

Optionen für die postfossile Energieversorgung

Grundsätzlich ist es möglich, e-Fuels so zu produzieren, dass der vollständige Übergang zur postfossilen Energieversorgung im Luft- und Seeverkehr erleichtert wird. Neben der Verwendung von zusätzlichem erneuerbarem Strom für die Herstellung muss auch das CO₂, das für die Herstellung von Kohlenwasserstoffen wie e-Methanol oder e-Diesel benötigt wird, aus nicht-fossilen Quellen stammen. Strenge Nachhaltigkeits- und Klimaanforderungen, die den gesamten Lebenszyklus von e-Fuels abdecken, sind daher erforderlich, um sicherzustellen, dass die Verwendung von e-Fuels in der Übergangsphase zu einer absoluten Treibhausgasminde- rung beiträgt.

Unter den verschiedenen e-Fuels haben e-Wasserstoff und e-Ammoniak den höchsten Quelle-bis-Tank Umwandlungswirkungsgrad. E-Methanol, e-LNG und e-DME weisen höhere Umwandlungsverluste auf, sind aber in der Herstellung noch effizienter als e-Kerosin oder e-Diesel. Aus der Sicht der Kraftstoffherstellung haben Ammoniak und Wasserstoff somit Vorteile gegenüber anderen e-Fuels, stehen aber vor Herausforderungen in Bezug auf Risiken, Handhabung oder Infrastruktur. Auch andere Treibhausgasemissionen wie Methan und Lachgas (N₂O) müssen berücksichtigt werden. Heute sind die Produktionskosten von e-Fuels deutlich höher als die von fossilen Kraftstoffen, aber auch wenn sich diese Spanne zukünftig verringert, werden die Kosten für e-Fuels längerfristig höher bleiben.

Roadmaps zur Erreichung von Nullemissionen

Die Roadmaps zeigen Wege auf, die den Übergang des weltweiten Luft- und Seeverkehrs von fossilen zu nachhaltigen postfossilen Kraftstoffen ermöglichen. Da e-Kerosin sehr wahrscheinlich das vorherrschende e-Fuel für den Langstreckenflugverkehr sein wird, haben wir nur eine Roadmap für diesen Sektor erstellt. Für den Seeverkehr ist die Situation komplexer. Hier kommen mehrere e-Fuels für eine künftige Vorherrschaft in Frage oder mehrere Kraftstoffe könnten sich parallel etablieren. Alle Kandidaten haben unterschiedliche Vor- und Nachteile, ohne dass eine Option eindeutig die beste wäre. Wir haben daher zwei Roadmaps beschrieben: eine, die sich auf die Förderung eines potenziellen Kandidaten konzentriert, und eine, die einen technologieoffenen Ansatz verfolgt.

Der Vergleich der Roadmaps für den Seeverkehr zeigt, dass ein technologieoffener Ansatz zwar die kosteneffizientesten e-Fuels identifizieren könnte, aber aufgrund versunkener Kosten eine weitere Verzögerung der Treibhausgasreduzierung und insgesamt höhere Kosten zur Folge haben könnte. Die Entscheidung, welcher der beiden Ansätze der geeignetere ist, ist daher nicht eindeutig zu treffen. Für Sektoren, die so global vernetzt und verflochten sind wie der internationale Verkehr, sind lokale Präferenzen jedoch eher ein Hindernis für die beschleunigte Einführung von e-Fuels, die erforderlich ist, um bis 2050 eine vollständige Defossilisierung zu erreichen. Die begrenzte Zeitspanne, die für den Übergang zu postfossilen Kraftstoffen verbleibt, aber auch die Infrastrukturabhängigkeit der einzelnen e-Fuel-Typen und der globale Charakter des internationalen Verkehrs legen daher nahe, dass es klüger wäre, sich frühzeitig auf ein e-Fuel zu konzentrieren, anstatt den technologischen Wettbewerb für weitere Jahre zu fördern.

Die politischen Entscheidungsträger befinden sich derzeit in einem schwierigen Dilemma. Einerseits sollte der Übergang zur Defossilisierung des internationalen Verkehrs bis 2050 vollzogen sein, was bedeutet, dass die entsprechenden Entscheidungen eher früher als später getroffen werden müssen. Andererseits ist kein dominantes e-Fuel oder eine nur begrenzte Anzahl von realisierbaren e-Fuels für den Seeverkehr nicht in Sicht. Für den Übergang zu postfossilen Kraftstoffen besteht das Hauptziel für die kommenden Jahre daher darin, die Zahl der möglichen e-Fuels zu begrenzen. Solange nicht eine kritische Masse von Ländern eine oder mehrere dominante e-Fuels unterstützt, wird es kaum möglich sein, die für den Übergang erforderliche Dynamik der Skalenerträge auszulösen.

Empfehlungen

Vor dem Hintergrund dieser Analysen lauten unsere wichtigsten Empfehlungen:

- ▶ Die Koordinierung politischer Initiativen auf globaler Ebene wäre am effektivsten, um die Defossilisierung beider Sektoren zu erreichen. Die Erzielung hinreichend ehrgeiziger Vereinbarungen in der IMO und der ICAO würde jedoch wahrscheinlich mehr Zeit in Anspruch nehmen, als für die Erreichung der Temperaturziele des Pariser Abkommens zur Verfügung steht.
- ▶ Vorreiteraktivitäten auf nationaler (Deutschland) oder regionaler (gleichgesinnte europäische Staaten) Ebene werden den Fortschritt auf internationaler Ebene wahrscheinlich beschleunigen.
- ▶ Die Durchführung von ‚Leuchtturmprojekten‘, welche die praktische Durchführbarkeit der vollständigen Einführung von e-Fuels demonstrieren, kann den Übergang auf breiterer Ebene einleiten.
- ▶ Für den Luftverkehr ist ein Drop-in-Kraftstoffmandat auf europäischer Ebene eine praktikable Option, welche die verstärkte Einführung von e-Kerosin auf einem der wichtigsten globalen Luftverkehrsmärkte auslösen und sicherstellen würde. Allerdings müssen die möglichen Auswirkungen eines solchen Mandats auf den Wettbewerb berücksichtigt werden.
- ▶ Für den Seeverkehr ist es noch zu früh, das bzw. die dominierenden e-Fuels zu bestimmen. Das Hauptziel einer Übergangsstrategie sollte daher darin bestehen, die Zahl der möglichen Optionen zu reduzieren, vorzugsweise auf ein dominierendes e-Fuel. Auf EU-Ebene kann dieser Prozess durch ein technologieoffenes e-Fuel-Mandat unterstützt werden, das so bald wie möglich in ein spezifisches Mandat für ein e-Fuel umgewandelt werden sollte.
- ▶ Wasserstoff ist eine no-regret-Option für alle e-Fuels. Bei der Ausweitung der Produktion von e-Fuels für der Luft- und Seeverkehr könnten sich Synergien ergeben, z. B. wenn Zwischen- oder Nebenprodukte der e-Kerosin-Produktion auch zur Herstellung von e-Fuels für den Seeverkehr verwendet würden.
- ▶ Um technologisches Lernen bei der Produktion von e-Fuels auszulösen, muss der Einsatz dieser Kraftstoffe frühzeitig subventioniert werden. Dies wird die Ausweitung der Erzeugungskapazitäten erleichtern und die Produktionskosten senken. Da alle potenziellen e-Fuels für den Luft- und Seeverkehr auch in anderen Sektoren als Kraftstoffe oder Rohstoffe verwendet werden, ist die Förderung eines solchen Übergangs eine no-regret-Politik. Daher sollten die Defossilisierungskonzepte anderer Sektoren idealerweise mit den Roadmaps für den Luft- und Seeverkehr verknüpft werden, um ein optimiertes Gesamtkonzept zu erstellen. Auf diese Weise könnten die Kosten der Umstellung auf alle Sektoren umgelegt werden, da sie sich der Herausforderung der Defossilisierung parallel stellen.

- ▶ Solange politische Maßnahmen zur Steigerung der Verbreitung von e-Fuels nicht auf globaler Ebene ergriffen werden, könnten Subventionen für die Produktion oder den Verbrauch von e-Fuels erforderlich sein, um gleiche Wettbewerbsbedingungen wie für fossile Kraftstoffe zu schaffen, die anderswo verwendet werden.
- ▶ Die Bemühungen um die Festlegung von Maßnahmen zur Beschleunigung der Einführung von e-Fuels im Rahmen der ICAO und der IMO, einschließlich von e-Fuel-Mandaten und marktbasierter Maßnahmen, müssen unverzüglich intensiviert werden. Darüber hinaus müssen Prozesse eingeleitet werden, um sicherzustellen, dass die globalen Sicherheitsstandards für Kraftstoffe weiterentwickelt werden, um die Verwendung von e-Fuels zu ermöglichen.
- ▶ Es sollte eine strategische Partnerschaft zwischen einer kritischen Masse von Schlüsselländern und -akteuren initiiert werden. Eine solche Initiative könnte mit einer kleinen Zahl von Ländern beginnen, die über einen bedeutenden Marktanteil im Luft- oder Seeverkehr verfügen und sich auf eine gemeinsame Strategie einigen können und die möglicherweise von künftigen e-Fuel-Lieferländern begleitet wird. Andere Länder könnten sich der Initiative später anschließen, sofern sie mit den Grundsätzen und Zielen der Initiative einverstanden sind. Für den Seeverkehr bestünde das Hauptziel einer solchen Initiative darin, sich so bald wie möglich und spätestens bis 2025 auf dominierende e-Fuels (vorzugsweise nur einen) zu einigen.

Unsere Bewertung zeigt auch, dass die ersten Schritte auf allen Regulierungsebenen sofort unternommen werden müssen. Die nationalen Regierungen müssen sicherstellen, dass die politischen Maßnahmen, den Investoren und Betreibern Anreize und Orientierungshilfen bieten, so schnell wie möglich verabschiedet werden und politische Initiativen auf europäischer und internationaler Ebene aktiv unterstützen. Die Jahre bis 2025 sind entscheidend, um die Defossilisierung des Luft- und Seeverkehrs zu erreichen. Wenn bis dahin nicht zumindest auf nationaler und europäischer Ebene geeignete politische Maßnahmen ergriffen werden, wird es schwierig sein, das Ziel der Defossilisierung bis 2050 zu erreichen.

1 Introduction

In the Paris Agreement, the final document of the 2015 Climate Change Conference in Paris, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to reduce greenhouse gas (GHG) emissions in order that the global temperature increase remains well below 2°C, if possible even below 1.5°C compared to pre-industrial levels (Article 2.1). In Article 4 the Parties agreed to aim to balance anthropogenic GHG emissions and sinks, or in other words, to strive for climate neutrality in the second half of this century. Since emissions from aviation and maritime transport are clearly anthropogenic and no other sectors are mentioned explicitly, they fall under the objectives of the Paris Agreement even without being explicitly mentioned.

Achieving climate-neutrality in aviation and maritime transport will not be possible without comprehensive packages of policy instruments to incentivize reduction measures including increased efficiency through new technologies and improved operations as well as through reduced traffic. But even if these packages are implemented consistently, fossil fuels must be substituted by climate-neutral or at least CO₂-neutral alternatives, thereby leading to direct emissions reductions.

In land-based transport, the use of fossil fuels in internal combustion engines can be substituted by the direct use of renewable electricity in electric motors. In aviation and maritime transport, electric drives are unlikely to become the dominant technology for long distance journeys in the near future because of the large amount of energy required for these journeys. From today's perspective, the same is likely to apply to the direct use of regenerative energy sources such as the use of wind by sails or kites in maritime transport. Under favourable conditions, they can certainly be an emission-free support of the main drive, but as the sole drive source they will probably not play a relevant role in the future.

Against this background, it becomes clear that from today's perspective combustion engines and turbines will be the dominant propulsion technology in the aviation and maritime sectors, at least in the short and medium term and for a broad range of applications. Climate-neutrality of air and sea transport can thus only succeed through the use of post-fossil fuels which are produced in such a way that they do not result in any or only very low GHG emissions during their entire lifecycle from well to wing/wake. With the limited supply but high demand for truly sustainable biofuels, these post-fossil fuels will need to be synthesized from renewable electricity. Such fuels are usually called electro fuels – or (synthetic) e-fuels for short.¹ We subsume all types of liquid or gaseous synthetic fuels under this category such as e-ammonia, e-diesel, e-hydrogen, e-kerosene, e-methane and e-methanol. The central questions are how to provide these fuels to the extent required in the future and how to ensure that in both sectors only such fuels are used.

The overarching goal of this study was to develop political roadmaps on options for a climate-neutral energy supply for air and sea transport, which could ensure the contributions of both sectors to achieving the global, European and national climate targets. In addition, policy instruments and technological measures which aim to bring e-fuels to market maturity are proposed.

Focus, scope and terminology

In line with Germany's and Europe's goal to become climate-neutral by 2050 at the latest, aviation and maritime transport should become climate-neutral by then as well. Accordingly, the roadmaps for the transition to post-fossil fuels are much more ambitious than currently envisaged at international level. The aviation sector has adopted a basket of measures to achieve carbon-neutral growth between 2021 and 2035

¹ Other terms used for similar concepts are (sustainable) alternative fuels (SAF), power-to-liquids (PtL), power-to-X (PtX), climate-friendly fuels, low carbon fuels, climate-neutral fuels, sustainably generated electro fuels, etc. We strived to harmonize the terminology to the extent possible. However, when citing or referring to other studies, it is often more appropriate to retain the terminology used there.

but the International Civil Aviation Organization (ICAO) still does not have a long-term target for achieving climate neutrality of the sector. IMO's initial GHG reduction strategy aims to reduce annual emissions by at least 50% below 2008 levels by 2050 and to phase out GHG emissions as soon as possible in this century, using a pathway that is consistent with the Paris Agreement. The roadmaps described below show the ways in which climate neutrality can be achieved by 2050, i.e. much earlier than envisaged by policies introduced on an international level to date and by the IMO's initial GHG reduction strategy.

Currently, almost 100% of aviation and maritime transport is propelled by petrol-based fuels. This will need to change to achieve the objectives of the Paris Agreement. Ferries and short sea shipping may sail with battery-electric or hydrogen propulsion systems as some pilot projects demonstrate. Similarly, short- and possibly medium-haul flights may eventually fly with battery-electric or hydrogen-powered engines. However, long-distance, intercontinental journeys in both sectors remain a challenge. Due to the high energy demand on these journeys, battery-electric and hydrogen are unlikely to provide feasible solutions due to their much lower energy density both in terms of weight and volume compared to liquid fuels. Hence, both markets will be more segmented in terms of fuel types and propulsion technologies than they are today. Operators are likely to apply different fuel propulsion systems on short- and on long-haul journeys. Since solutions for short-haul journeys are different than for long-haul journeys, they can be considered separately. Given that long-haul journeys account for the largest share in terms of emissions, we focus on options for intercontinental flights and deep-sea shipping and largely neglect other market segments unless their solutions provide synergies for the long-distance segment.

Besides synthetic e-fuels, sustainable biofuels are another option for reducing the GHG emissions of aviation and maritime transport. They are already available, although at significantly higher prices than fossil fuels and the potential for truly sustainable biofuels is very limited. While prices might decline due to economies of scale if their use were promoted further, they face additional challenges that put their feasibility as long-term solutions into question: if produced from sustainable biomass (residues or cultivated), their potential is very limited due to much higher land surface requirements than in the production of synthetic e-fuels. In addition, they may induce additional GHG emissions through direct or indirect land use change and may be in direct competition with food production (fuel or food). Despite these risks, they may contribute to short-term GHG reductions. However, since they are unlikely to be a long-term solution for aviation and maritime shipping, we do not include sustainable biofuels within the scope of our study.

Even if GHG emissions are reduced to zero, aviation and maritime transport may still not be climate-neutral due to their non-CO₂ climate impacts, especially their impact on cloudiness. De-fossilizing the energy supply is a necessary step towards climate neutrality but is insufficient by itself. E-fuels can be synthesized to reduce non-CO₂ impacts, but additional policies will be required to eliminate non-CO₂ impacts to the best possible extent. The scope of this study is limited to GHG emissions of fossil and synthetic e-fuels. It does not cover the supplemental policies and measures to address non-CO₂ impacts.

Since most of the projections and analyses referred to in this study were conducted before the outbreak of the Covid-19 pandemic, they do not consider the impact of the pandemic. Although not over yet, it is already clear that its impact is severe and unprecedented. Projections will need to be adjusted downwards, especially for the aviation sector. For shipping, the mid-term impact will depend on the global economic recovery. It seems that maritime shipping is less affected than aviation, mostly because it transports more cargo than passengers in the main. In addition, the pandemic has revealed that some traffic can be avoided, such as business flights which have been replaced by video conferences or leisure travel because individuals have explored holiday destinations that can be reached without flying. Some of these changes may persist after the end of the crisis, with the effect that the growth rates of aviation demand might be lower than prior to the Covid-19 pandemic. Nevertheless, an end date of the pandemic is not yet in sight and the future development of the two sectors after the crisis is also not clear. Until then, the projections that are currently available still provide the most reliable basis for the design of GHG mitigation policies and the analysis of their potential impacts.

Certain synthetic e-fuels are hydrocarbons. The use of post-fossil fuels may – strictly speaking – not lead to decarbonization. However, if the carbon used to produce synthetic e-fuels stems from non-fossil sources such as ambient air or biomass, their use does not contribute to CO₂-induced global warming. Thus, in the context of synthetic e-fuels, we use the term ‘defossilization’ rather than ‘decarbonization’. In the context of long-term strategies beyond aviation and maritime shipping the term ‘decarbonization’ is more common and is correspondingly used by us, too. The use of fully defossilized synthetic fuels may still contribute to global warming, for example through the non-CO₂ impacts of synthetic kerosene at flight altitudes or through slip, leakage or boil-off of fully defossilized synthetic e-fuels such as methane or ammonia, since they are or may result in potent greenhouse gases (CH₄ and N₂O, respectively). We are aware of these impacts but there seems to be no terminology which covers all aspects adequately. Therefore, when we use ‘defossilization,’ we mean strategies which ensure that aviation and maritime transport provide their services without contributing to global warming through GHG emissions.

Structure

In chapter 2, we provide a synoptic overview of scenarios for the development of traffic performance, the implied final energy demand and the resulting greenhouse gas emissions with a view to estimating the quantity of renewable energy required for the defossilization of aviation and maritime transport. In a second step, we assess the political action fields which need to be ‘ploughed’ to enable the transition. We put a specific focus on barriers and potential policies to overcome them in chapter 3. Technological challenges and potentials for producing the post-fossil fuels required to power planes and ships are discussed in chapter 4. Based on the previous chapters, we describe potential roadmaps for the transition towards the climate neutrality of aviation and maritime transport in chapter 5. Finally, we draw overall conclusions and provide concrete policy recommendations in chapter 6.

2 Future trends and scenarios

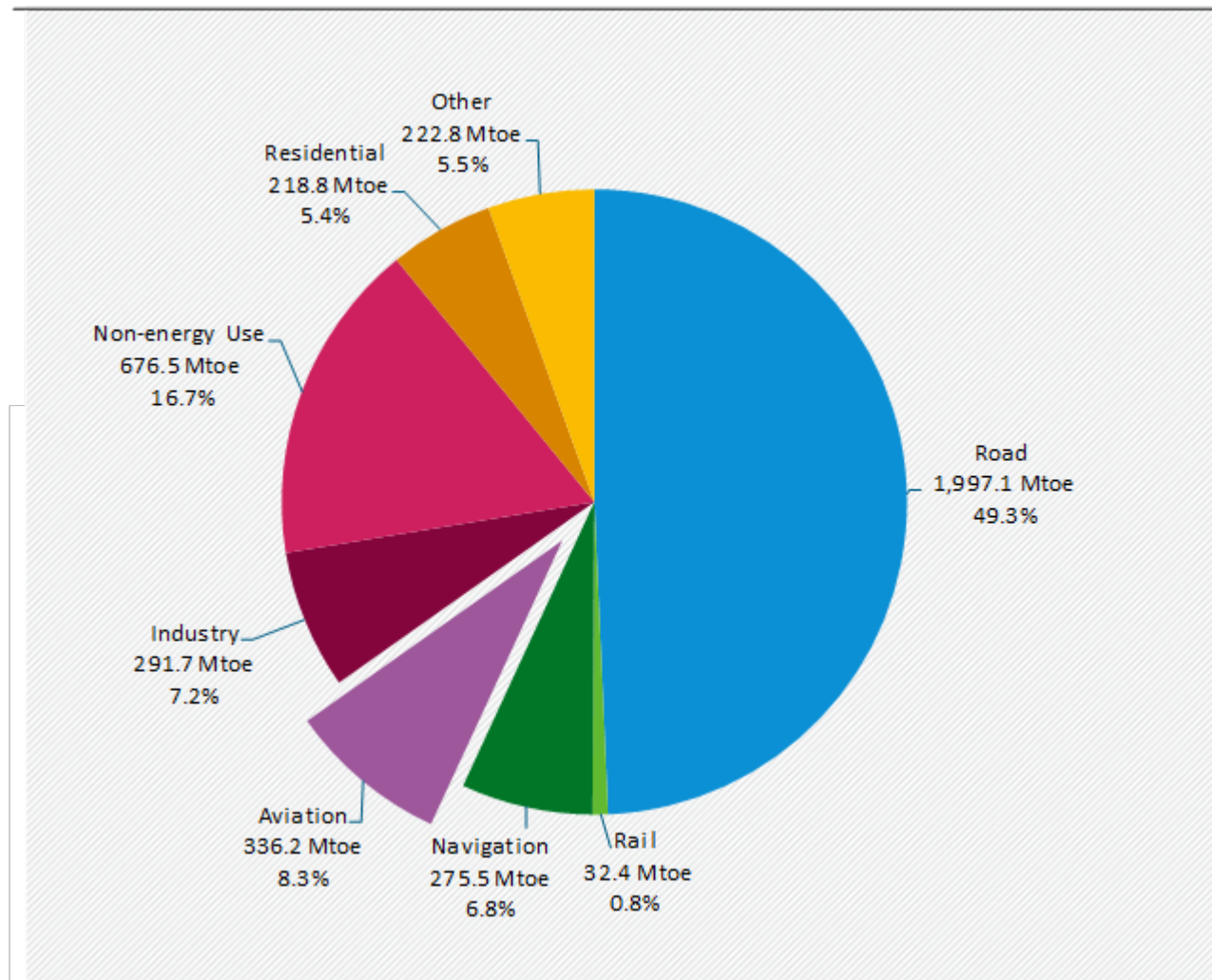
As a basis for further consideration of possible transition pathways or roadmaps, it is important to have a clear perspective of the amounts of post-fossil fuels which will be required to defossilize both sectors. In this chapter we therefore provide a synopsis of the available energy demand and emission projects for aviation (section 2.1) and shipping (section 2.2) and provide an overview of the aggregated demand of both sectors (section 2.3).

Currently, almost 100% of aviation and maritime transport are powered by petrol-based fuels (IEA 2020d). CO₂ emissions from oil combustion make up the largest share of total GHG emissions and are therefore usually the only GHG considered in existing projections. Other GHGs such as black carbon, which is relevant in maritime transport, or CH₄ or N₂O emissions, which may become relevant if LNG or ammonia are used in larger volumes, are not covered. The non-GHG impacts of aviation are also not covered. Although they are significant, their effects are still being debated (Lee et al. 2020), with the result that projections involve great uncertainties.

2.1 Aviation

Forecasts of air transport supply and demand are conducted by various stakeholders and for various purposes. Several forecasts for the short and medium term are used to optimize air traffic management and infrastructure capacity planning, often at the local or regional level. Long-term global forecasts, for example, are provided by the aeronautical industry to give an indication of future aircraft demand. Key indicators typically found in air transport forecasts are passengers, passenger kilometres or the number of future aircraft required.

Forecasts that aim to project energy demand in aviation are seldom made. Several studies that focus on forecasting global energy demand, e.g. conducted by the energy industry (BP Energy Outlook, Shell, etc.) do not show aviation as a separate sector. Due to its relatively small share, air transport plays only a minor role in global energy studies. According to IEA, aviation had a share of 8.3% in global crude oil demand in 2018 (showing an upward trend from a share of 6.4% in global crude oil demand in 2015). As measured by final energy consumption, aviation had a 3.9% share of global energy demand in 2018.

Figure 1: Aviation's share in global crude oil demand (final consumption) 2018

Source: IEA (2020b)

In this section, we present selected aviation forecasts, which cover existing forecasts on global energy consumption. Furthermore, we show the results of a specific DLR forecast, which puts a particular emphasis on a sophisticated aircraft fleet modelling and on framework data, both internal and external to the aviation sector, which influences future aviation demand. The most prominent factor internal to the aviation sector that is integrated in the DLR forecast is capacity constraints at the airport level, which severely affect demand development, fleet structure and ultimately energy demand, but have, to our best knowledge, usually not been considered in forecasts. An overview of the forecasting studies considered for this report is provided in Table 1.

Table 1: Overview of selected publications on aviation and energy forecasts

Title	Publication year	Scenario type	Indicators	Inclusion of CO ₂ data	Time-frame	Geographical Scope	Aviation energy consumption
Airbus Global Market Forecast	2019	BAU	Passenger-km, aircraft deliveries	No	2038	Global	Not included
Boeing Commercial Market Outlook	2020	BAU	Passenger-km, aircraft deliveries	No	2039	Global	Not included
Embraer Market Outlook	2020	BAU	Passenger-km, aircraft deliveries (for aircraft with up to 150 seats)	No	2029	Global	Not included
ATAG Waypoint 2050	2020	Low / high / central scenarios, including COVID-19 impacts	Passenger-km	Yes	2050	Global	Included, with several technology scenarios
EASA Environmental Report	2019	BAU (low, medium, high)	Number of Flights, NO _x and CO ₂ emissions	Yes	2035	European Economic Area	Can be derived from CO ₂ emissions data
EUROCONTROL Challenges of Growth	2018	Four scenarios with variations in economic growth and openness to globalization	Number of flights in European Airspace	No	2040	Europe	Not included
ICAO Long-Term Traffic Forecasts	2018	BAU	Passenger-km, freight-ton-km	No	2045	Global	Not included
IATA 20-year passenger forecast	2020	Three scenarios: 'Current trends', 'Return to globalization', 'Climate sentiment intensifies'	Passengers	No	2039	Global	Not included
IEA World Energy Outlook 2016	2018	1 BAU scenario ('Current Policies'), two defossilization scenarios ('New Policies' and 'Sustainable Development')	Oil demand in mb/d and Mtoe	Indirectly via oil demand	2040	Global	Global Aviation Energy Demand
BP Energy Outlook 2019	2019	Four scenarios: one high growth ('More Energy'), two stagnating ('Evolving	Energy Consumed in billion toe	Indirectly via oil demand	2040	Global	Only as part of non-road users

		Transition' and 'Less Globalisation'), one defossilization scenario ('Rapid Transition')					
Shell Sky Scenario	2018	Scenario with the aim of fulfilling the goals of the Paris Agreement	Energy consumed in EJ	Indirectly via energy demand	2100	Global	Differentiated by passenger and freight transport
DLR Capacity Constraint Forecast	2018	BAU (two forecasts – with/without airport infrastructure capacity constraints)	Passengers, passenger-km, fuel consumption, emissions	Yes	2050	Global	Included with 4D emissions inventory modelling
UBA Scenario Air Transport under consideration of environmental aspects	2018	Positive scenario including internalization of external costs, shift to rail and noise reduction	Movements, passengers, contribution to GDP, emissions	Yes	2030	Germany	Can be recalculated based on CO ₂ emissions
DIW Econ Forecast Air Transport Concept Germany	2015	Three scenarios	Passengers, cargo, connectivity (travel times), GDP	No	2030	Germany	No

Source: Authors' own compilation

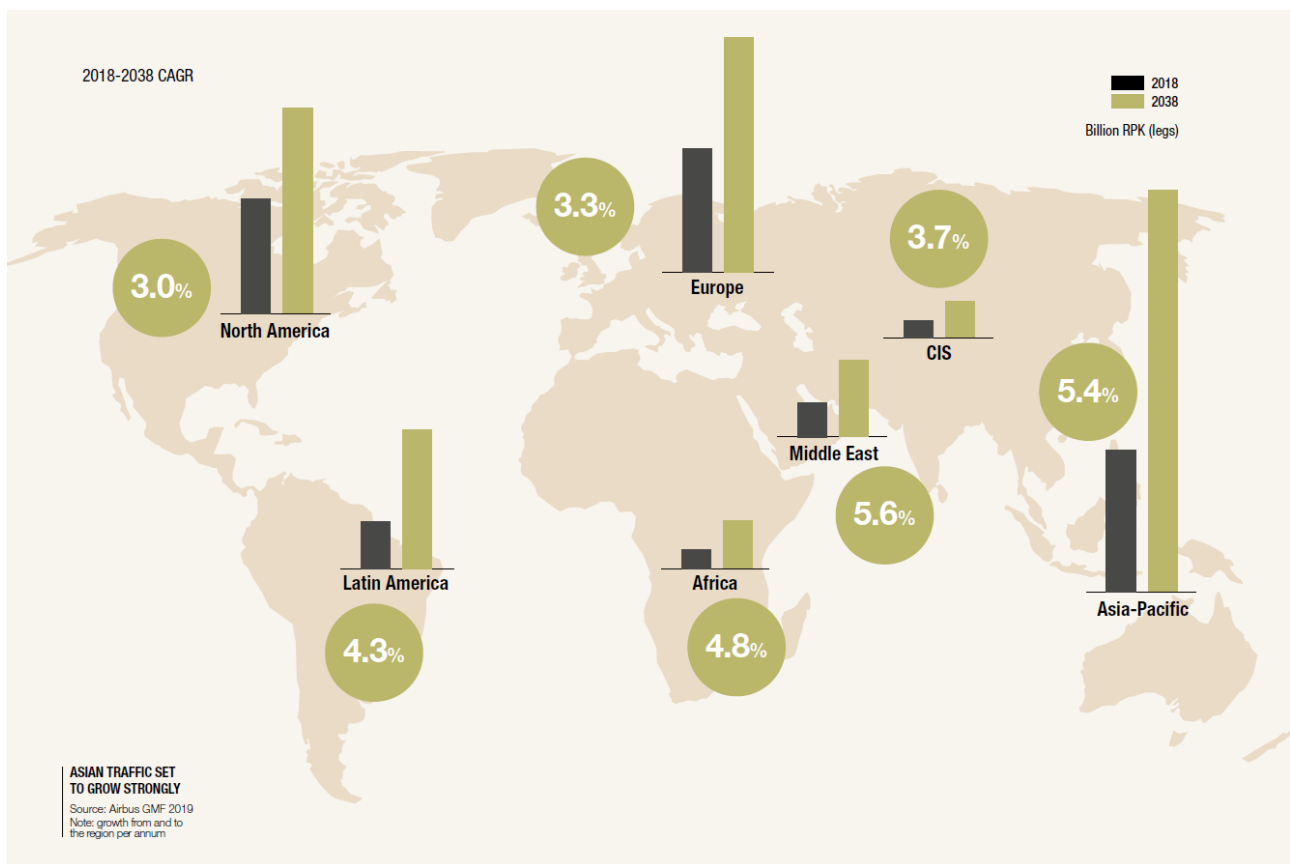
2.1.1 Projections

The following section provides a more detailed overview of the above-mentioned forecasts and summarizes their main results.

Airbus Global Market Forecast

The Airbus Global Market Forecast (GMF) is an annually published marketing instrument, which provides insights into the expectations of Airbus on global aviation development over a 20-year forecasting horizon. The main parameters published in the GMF are regionalised annual growth rates in passenger and freight kilometres, the total development of passenger and freight kilometres and the expected aircraft deliveries in each seat class. In its most recent version of the GMF, published in August 2019, Airbus expects a global growth in air transport measured in passenger kilometres of 4.3% per year, which shall result in 39 210 passenger and freighter aircraft deliveries over the next 20 years. The following figure shows the regional distribution of passenger aviation for 2018 to 2038 and the associated regional growth rates.

Figure 2: Regional growth rates in the Airbus Global Market Forecast 2019



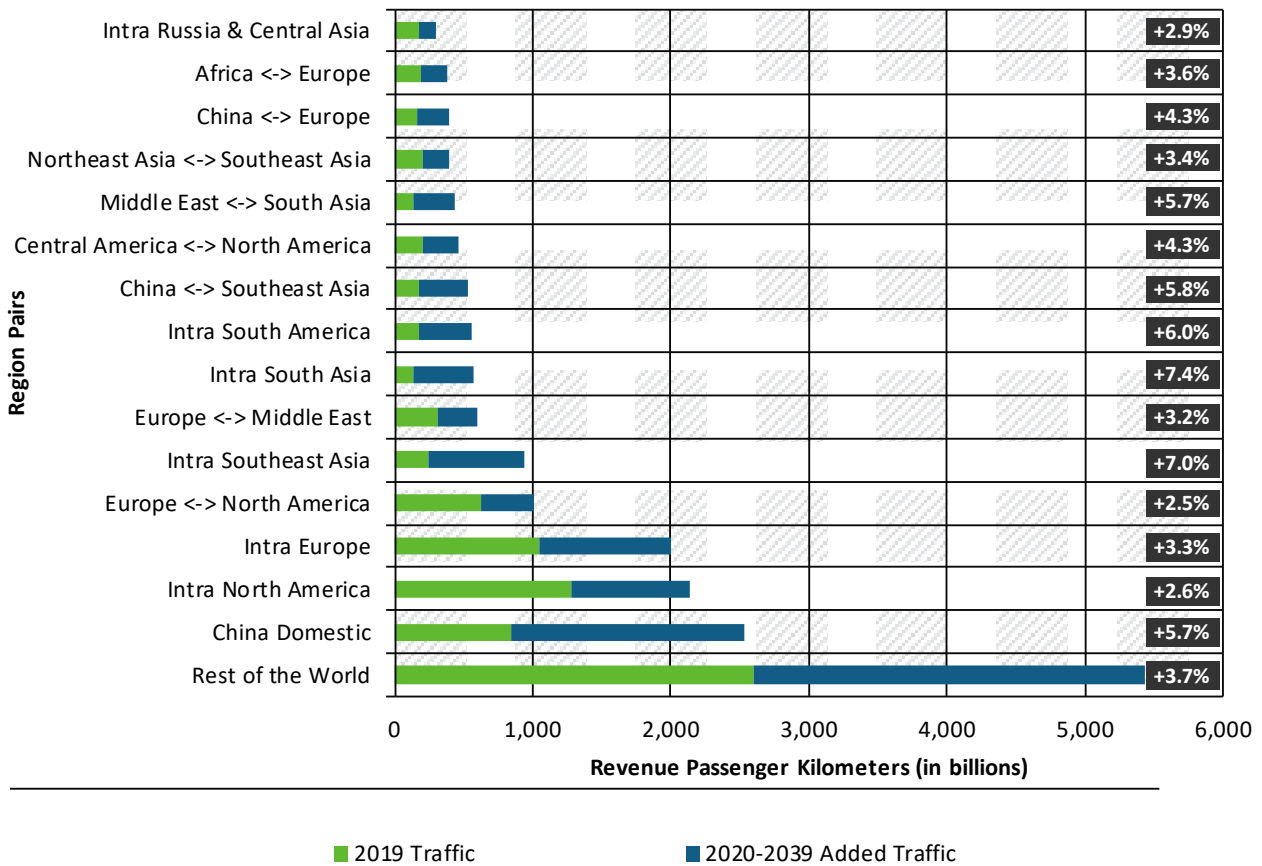
Source: Airbus (2019)

Airbus has refrained from publishing a new forecast in 2020, due to the uncertainties associated with the recovery of the aviation sector from the COVID-19 pandemic.

Boeing Commercial Market Outlook

The air transport Commercial Market Outlook (CMO) published by Boeing is similar to the Airbus GMF in terms of forecasting horizon, forecasted indicators and results. In 2020, the Boeing CMO was the first long-term forecast which incorporated the impacts of the COVID-19 pandemic. Boeing expects a global traffic growth of 4.0% up to 2039, resulting in 43 110 new aircraft deliveries. In its previous forecast published in September 2019, Boeing expected a traffic growth rate of 4.6% and 44 040 aircraft deliveries between 2019 and 2038.

Highest regional growth rates, as shown in Figure 3, are expected to occur in South and South-east Asia (7.0% and 7.4% traffic growth respectively), while the more mature markets such as those within Europe and North America or transatlantic ones are expected to experience significantly smaller growth rates of between 2.5% and 3.3%.

Figure 3: Regional growth rates in the Boeing Commercial Market Outlook 2020

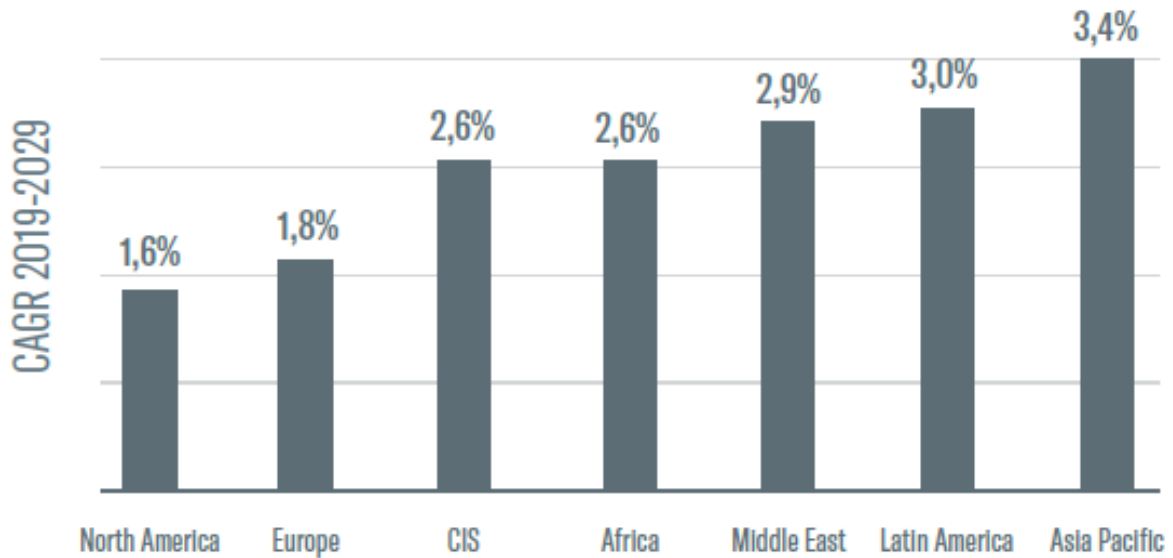
Source: Boeing (2020)

Embraer Market Outlook

As a manufacturer of business and regional jets of up to around 130 seats, Embraer publishes a similar forecast to Airbus and Boeing, typically with a 20-year forecast horizon. In 2020, Embraer also published a forecast including the impacts of the COVID-19 pandemic; it covered the global market for aircraft of up to 150 seats, but only with a forecast horizon of ten years up to 2029. For the current decade, Embraer expects a traffic growth rate of 2.6% and reduced its projection for global passenger traffic in 2029 by 19% compared to its forecast published in 2019. Embraer expects that pre-COVID-19 traffic levels will be reached again in 2024.

In its latest publication, Embraer forecasts a global annual traffic growth of 2.6%. It is forecasted that 5 500 aircraft of up to 150 seats will be delivered by 2029, of which 4 420 are expected to fall under the regional jet category and 1 080 aircraft under the turboprop category. The following figure shows the regional distribution of traffic growth. Like other manufacturers, Embraer also sees the highest potential in the Asia-Pacific region.

Figure 4: Regional growth rates 2019-2029 in the Embraer Market Outlook 2020

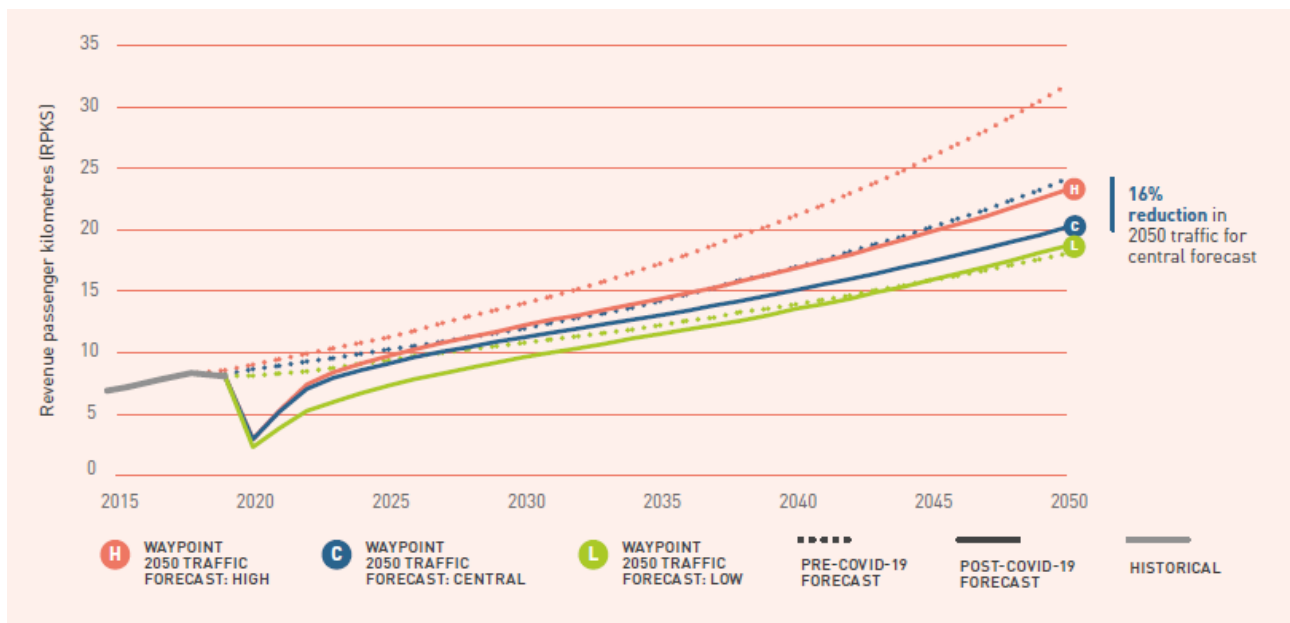


Source: Embraer (2018)

ATAG Waypoint 2050

In September 2020, the Air Transport Action Group (ATAG) published its study ‘Waypoint 2050’. This study combines an assessment of the achievements and environmental targets of the aviation industry with forecasts and the analysis of future measures to improve the environmental performance of the air transport system. The study includes traffic scenarios covering low, central and high growth cases and considers the impacts of the COVID-19 pandemic.

Figure 5: Passenger-kilometre forecast in ATAG Waypoint 2050



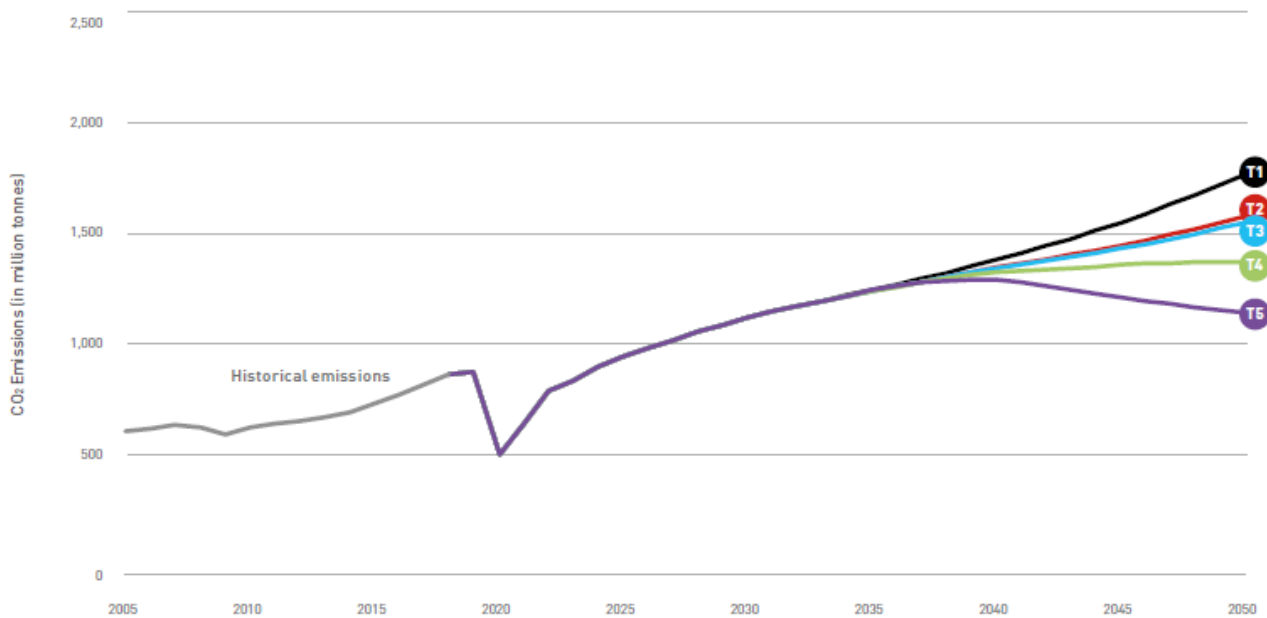
Source: ATAG (2020b)

The new high traffic forecast which considers the effects of the COVID-19 pandemic matches the previous central forecast in 2050. The new low forecast matches the old low forecast. However, the total levels of

demand will only be reached after 2040. A comparison of the central forecasts with pre- and post-COVID-19 demand levels shows that the new central forecast is 16% lower in terms of revenue passenger kilometres than the pre-COVID expectations. The average growth rate for passenger kilometres in the new central forecast is 3% p.a. between 2020 and 2050.

In order to estimate future carbon dioxide emissions of aviation, different technology scenarios are applied to the central traffic forecast. The scenarios include a baseline with current aircraft technology (T1), a conservative future evolution (T2), a new concept scenario, including blended wing bodies or open rotor propulsion (T3), electric and hybrid-electric configurations for aircraft up to 100 seats (T4) and a revolutionary scenario including hydrogen-powered aircraft up to 200 seats (T5).

Figure 6: CO₂ emissions forecast in different technology scenarios



Source: ATAG (2020b)

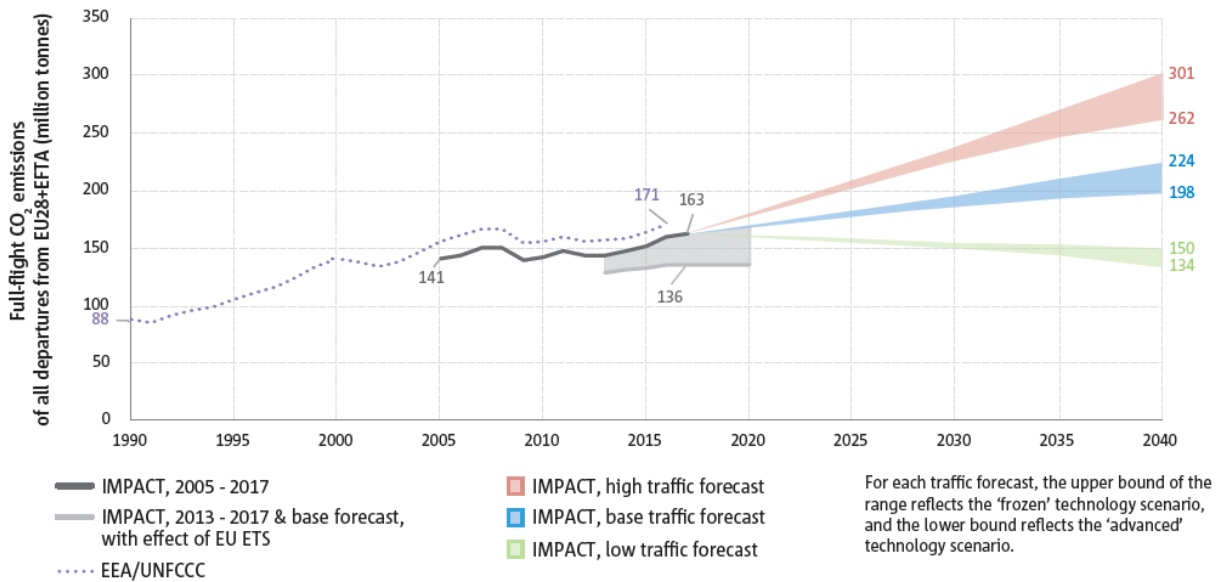
European Aviation Environmental Report

The European Aviation Safety Agency (EASA), in cooperation with the European Environmental Agency (EEA) and EUROCONTROL has published the second edition of the European Aviation Environmental Report in 2019. The report provides a broad overview of aviation sector development in Europe, including technological developments and environmental indicators. In the report, a forecast on air traffic development in Europe up to 2040 is included, with indicators such as total number of flights, number of people exposed to noise and CO₂ and NO_x emissions. The forecast is conducted for three scenarios: low, base and high traffic forecast. It is expected that the number of flights in European airspace (EU28 + EFTA) will grow from 9.56 million in 2017 to 10.1 million in the low, 13.6 million in the base and 16.1 million in the high traffic forecast in 2040, respectively. This corresponds to a compound annual growth rate (CAGR) of 0.2% in the low, 1.5% in the base and 2.3% in the high traffic forecast. The annual growth rates in the number of flights are typically substantially lower than the annual growth rates in passengers or passenger kilometres. The trends for larger aircraft on short-/medium-haul routes and for longer average flight distances continue. This results in a decoupling of flight movement growth and passenger/passenger kilometre growth to a certain extent.

For the CO₂ emissions forecast, EASA presents a bandwidth for each traffic scenario, depending on the technology assumptions. A 'frozen technology' scenario reflects a future in which the aircraft fleet remains

on today’s technology level, while the ‘advanced technology’ scenario reflects a future in which trends of improvements of specific emissions continue. It is expected that CO₂ emissions will grow from 163 million tons in 2017 to 134-150 million tons in the low traffic forecast, to 198-224 million tons in the base traffic forecast and to 262-301 million tons in the high traffic forecast in 2040. This corresponds to a CAGR of between -0.8% and -0.4% in the low traffic forecast, 0.8%-1.4% in the base traffic forecast and 2.1%-2.7% in the high traffic forecast. The following figure summarizes the historical development between 1990 and 2017 and the CO₂ emission scenarios provided by EASA for 2018 to 2040.

Figure 7: CO₂ emissions development in Europe 1990-2040



Source: EASA (2019)

EUROCONTROL Challenges of Growth

Since 2001, EUROCONTROL has published five editions of its ‘Challenges of Growth’ forecast in European airspace. The latest version (CG18) was published in 2018. The main purpose of this document is to provide insights into long-term capacity planning and the impacts of infrastructure shortages on the development of the European aviation system.

The latest edition of the forecast has a forecasting horizon of 2040, with a forecast of flight movements under instrument flight rules (IFR) as the key focus of the study. In total, four different scenarios are analyzed with different framework conditions:

- ▶ **Global Growth:** Strong global growth with technology used to mitigate sustainability challenges;
- ▶ **Regulation and Growth (Most-Likely):** moderate growth regulated to reconcile demand with sustainability issues;
- ▶ **Fragmenting World:** a world of increasing tensions and reduced globalization;
- ▶ **Happy Localism:** like Regulation and Growth, but with a fragile Europe increasingly, and contentedly, looking inwards.

EUROCONTROL states in its report that, in 2017, 10.6 million IFR flights were operated in European airspace, which surpassed the previous peak achieved in 2008.

The results of the Challenges of Growth Report 2018 are summarized in the following table:

Table 2: EUROCONTROL Challenges of Growth 2018 forecasting results

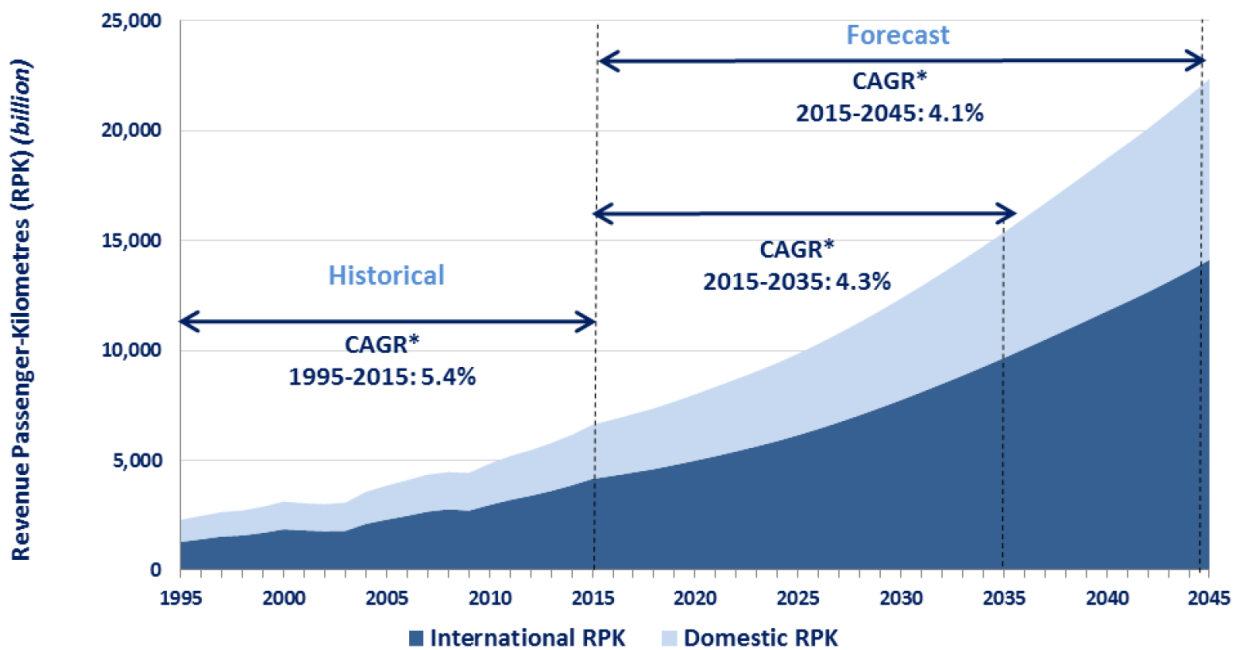
Scenario title	IFR flights in millions 2040	Total growth 2017-2040	Average annual growth
Global Growth	19.5	84%	2.7%
Regulation & Growth (most likely)	16.2	53%	1.9%
Happy Localism	14.9	41%	1.5%
Fragmenting World	11.9	12%	0.5%

Source: EUROCONTROL (2018)

A key focus of the Challenges of Growth study is a comparison of the development of the demand of flight movements in a constrained situation and the actual capability of the air transport system (airports and air traffic management). EUROCONTROL calculates for each scenario the capacity gap leading to unaccommodated demand. In the most likely scenario, the expectation is that, in 2040, 1.5 million flights will not be able to be served, leading to unaccommodated demand in the order of 8% of total demand or 160 million passengers in that year.

ICAO Long-Term Traffic Forecasts

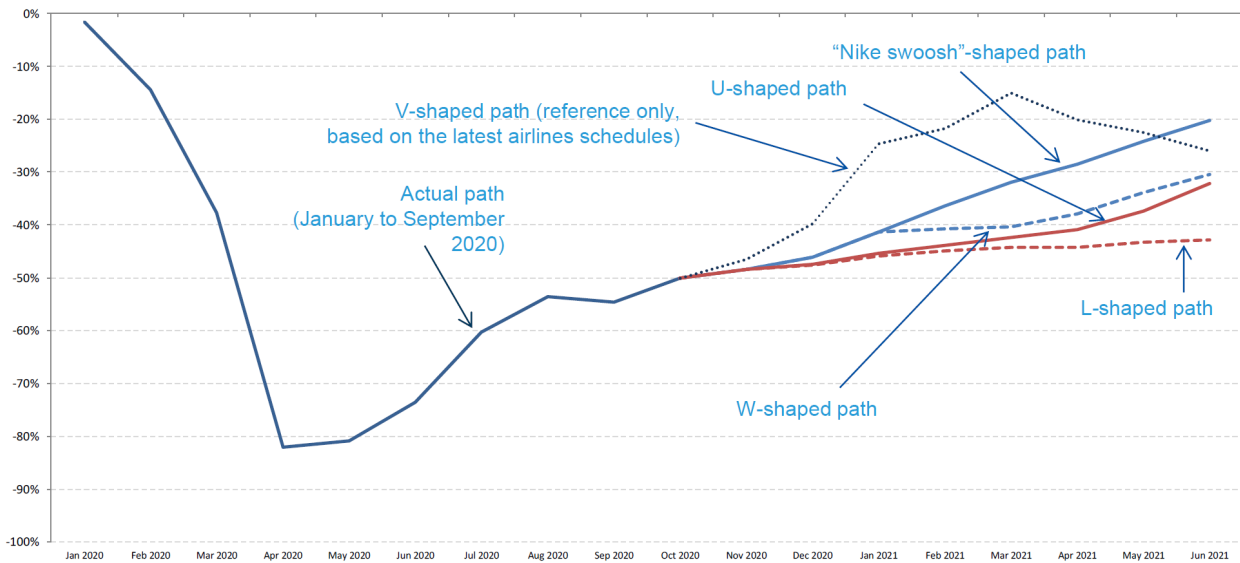
The International Civil Aviation Organization (ICAO) publishes several sets of forecasts, among them the Long-Term Traffic Forecast, regional forecasts and, more recently, short-term scenarios on the traffic development in the light of the COVID-19 pandemic. The ICAO Long-Term Traffic Forecasts document was officially published in April 2018, which contains a global forecast of passenger and cargo traffic up to the year 2045. In summary, the ICAO working group expects an average growth rate in passenger traffic of 4.1% per year between 2015 and 2045. ICAO's publications are focused on traffic development, but do not include a forecast of CO₂ emissions or non-CO₂ effects.

Figure 8: ICAO global long-Term forecast 2015-2045

Source: ICAO (2018)

During the COVID-19 pandemic, ICAO established near-term scenarios for the immediate outlook. In its November 2020 edition, a decline in global seat supply for 2020 is expected to be 51% and for the first half 2021, 30% to 37%. Due to a perceived extreme uncertainty, four different pathways for the next months are considered, as shown in Figure 9.

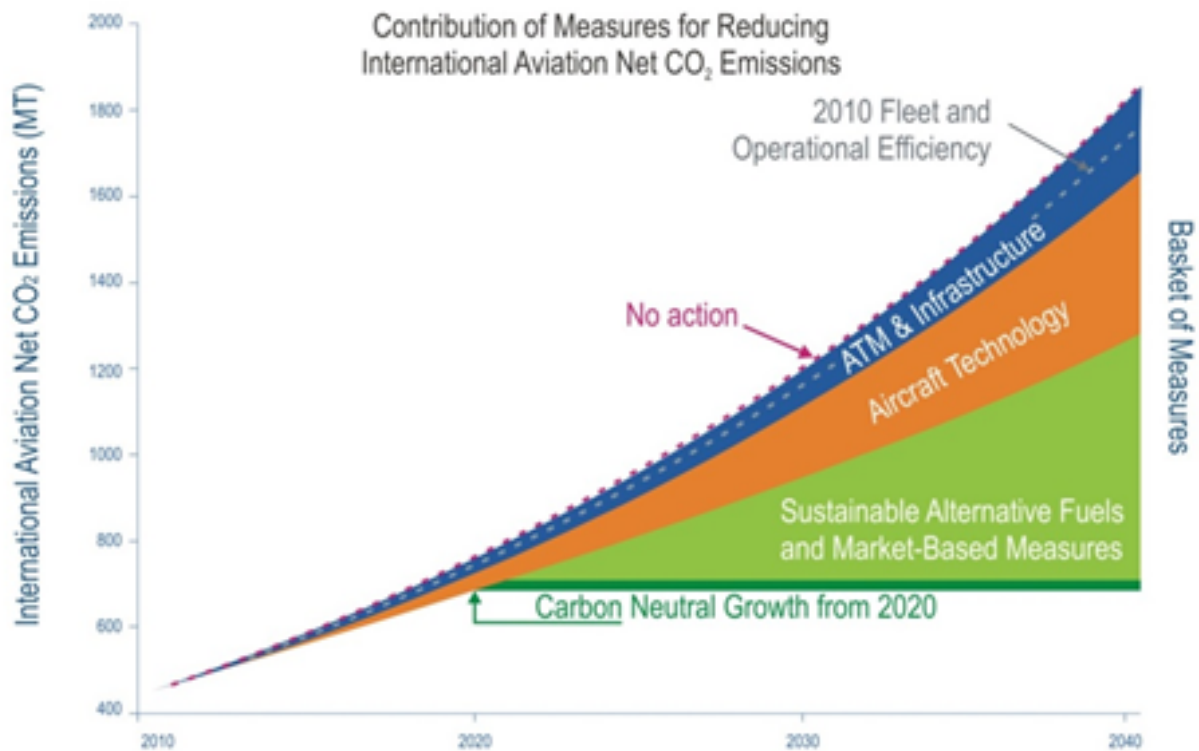
Figure 9: ICAO near-term scenarios / traffic development compared to business-as-usual



Source: ICAO (2020a)

In international civil aviation, Member States of ICAO agreed in 2013 on a global aspirational goal for the reduction of specific emissions by 2% per year and carbon-neutral aviation growth from 2020. As technical and operational efficiency improvements are smaller than traffic growth, carbon-neutral growth is unlikely to be achieved in the short term and not until low-carbon synthetic fuels become eligible by CORSIA (Carbon offsetting and reduction scheme for international aviation). CORSIA was agreed upon at the ICAO Assembly in 2016 (ICAO 2017b). From 2021 onwards, for emissions from international aviation exceeding the levels of 2019, offsets need to be purchased or measures have to be taken to reduce emissions. Should carbon-reduced or post-fossil fuels become available in the future in sufficient quantities, aviation obligations to reduce emissions could be fulfilled by using these fuels. Hence, the aviation sector should have a genuine interest in carbon-reduced or post-fossil fuels in case the price for CO₂ offsets becomes sufficiently high.

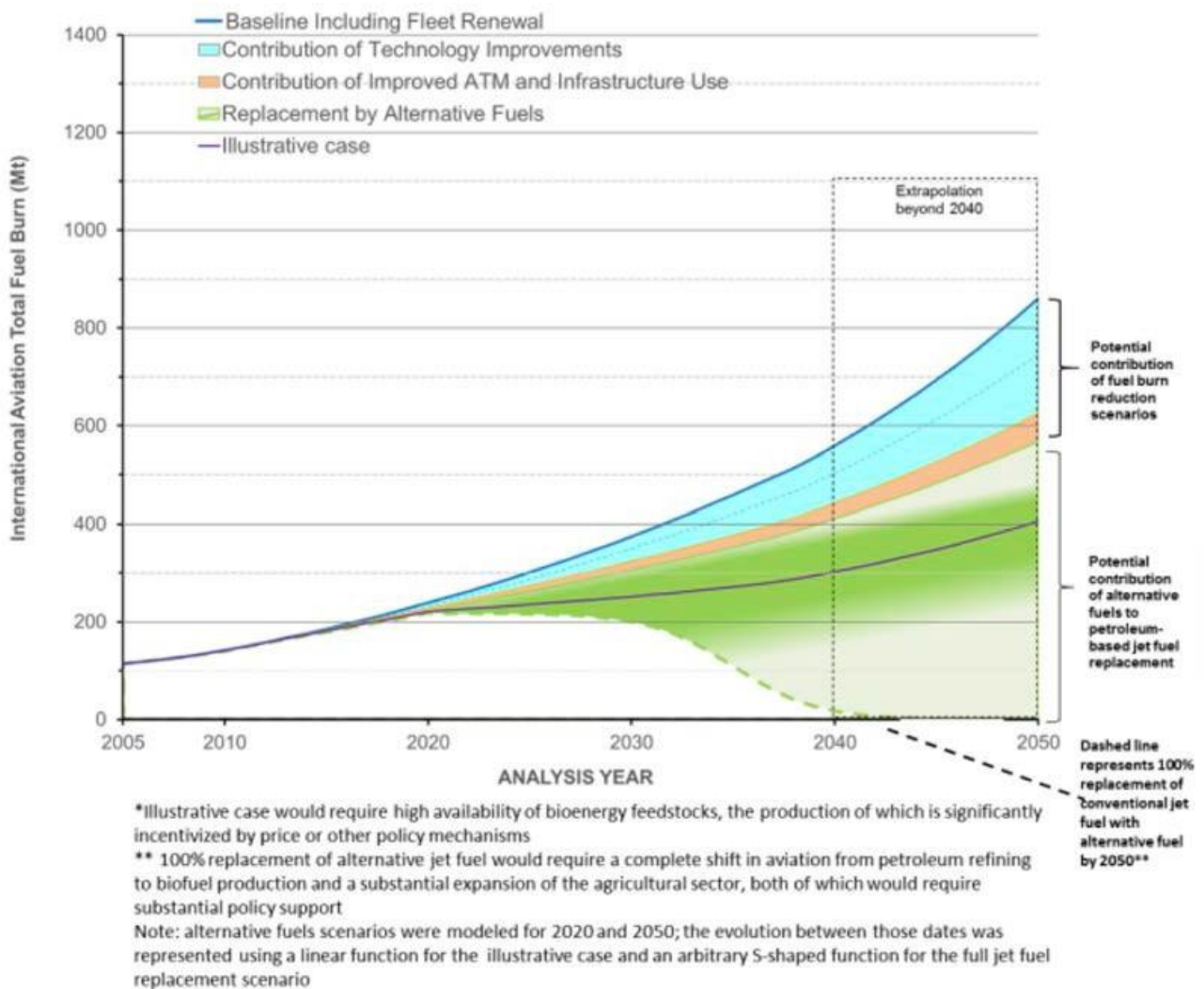
Figure 10: ICAO's basket of measures for the reduction of CO₂ from international aviation



Source: ICAO (2016)

In its 2016 environmental report, ICAO included a further scenario which highlighted the potential impacts of a replacement of conventional jet fuels by alternative fuels. At the time this scenario was developed, the focus was still on biofuels and less on e-fuels. Already the illustrative scenario shows the high potentials of alternative fuels – as technological, operational and infrastructural improvements are limited, alternative fuels have a high potential to contribute to a reduction in aviation's carbon emissions.

Figure 11: Fuel burn of international aviation and potential of alternative fuels



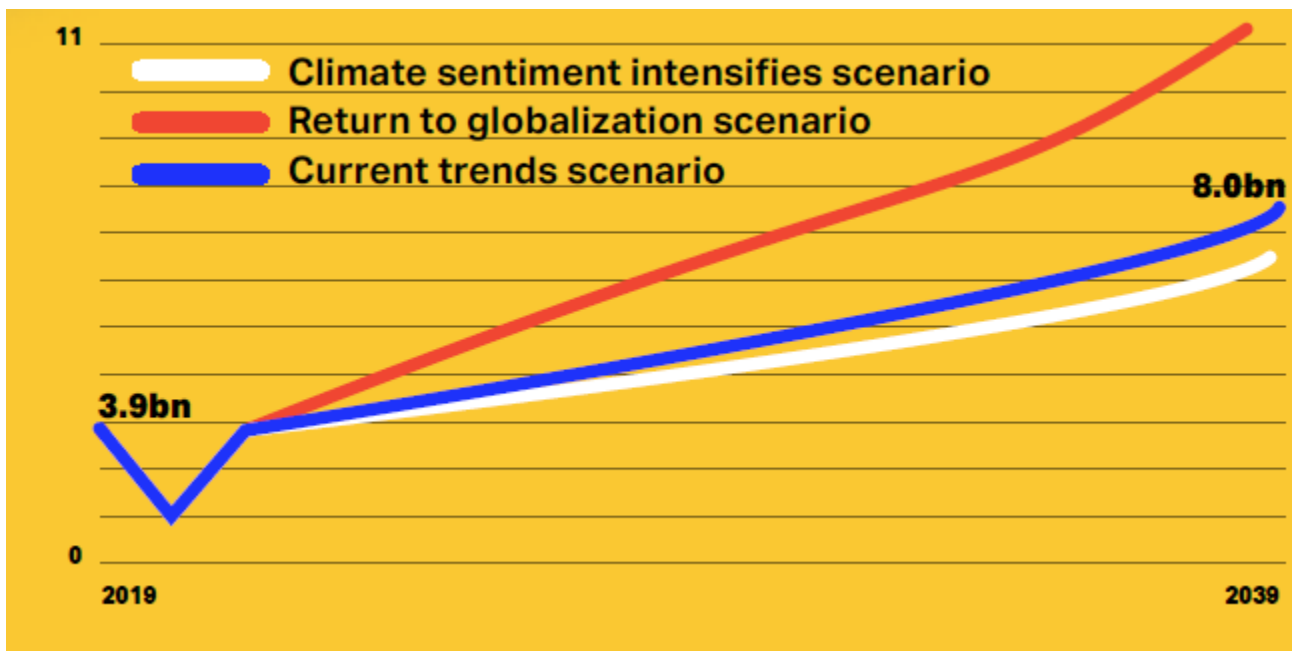
Source: ICAO (2016)

In addition to the previous work conducted within the scope of CAEP, ICAO plans to publish a reduced emissions scenario for 2019.

IATA 20-year passenger forecast

The International Air Transport Association (IATA) is the main industry body in global air transport. It publishes its own 20-year passenger forecast, which is updated bi-annually. The latest publicly available figures from 2020 reflect the impacts of the COVID-19 pandemic and show an increase in global passenger traffic of 3.2% ('Climate sentiment intensifies' scenario), 3.7% ('Current trends' scenario) and 5.3% ('Return to globalization' scenario), measured by the number of passengers. The scenarios depict a future that ranges between a situation in which more progress on carbon taxation and a sentiment of avoiding air travel will reduce demand growth rates and a situation in which liberal trade and air transport policies further promote traffic growth.

The 'current trends scenario' shows a growth rate of 3.7%, which is below the forecast of Boeing at a 4.6% growth rate, which also reflects the impacts of the COVID-19 pandemic. However, the latter mentioned forecast features revenue passenger kilometres as a main forecast parameter. Studies agree that passenger kilometres grow at a higher rate than the number of passengers, as the average distance travelled per passengers increases over time.

Figure 12: IATA passenger growth scenarios (billion passengers, segment basis)

Source: IATA (2020)

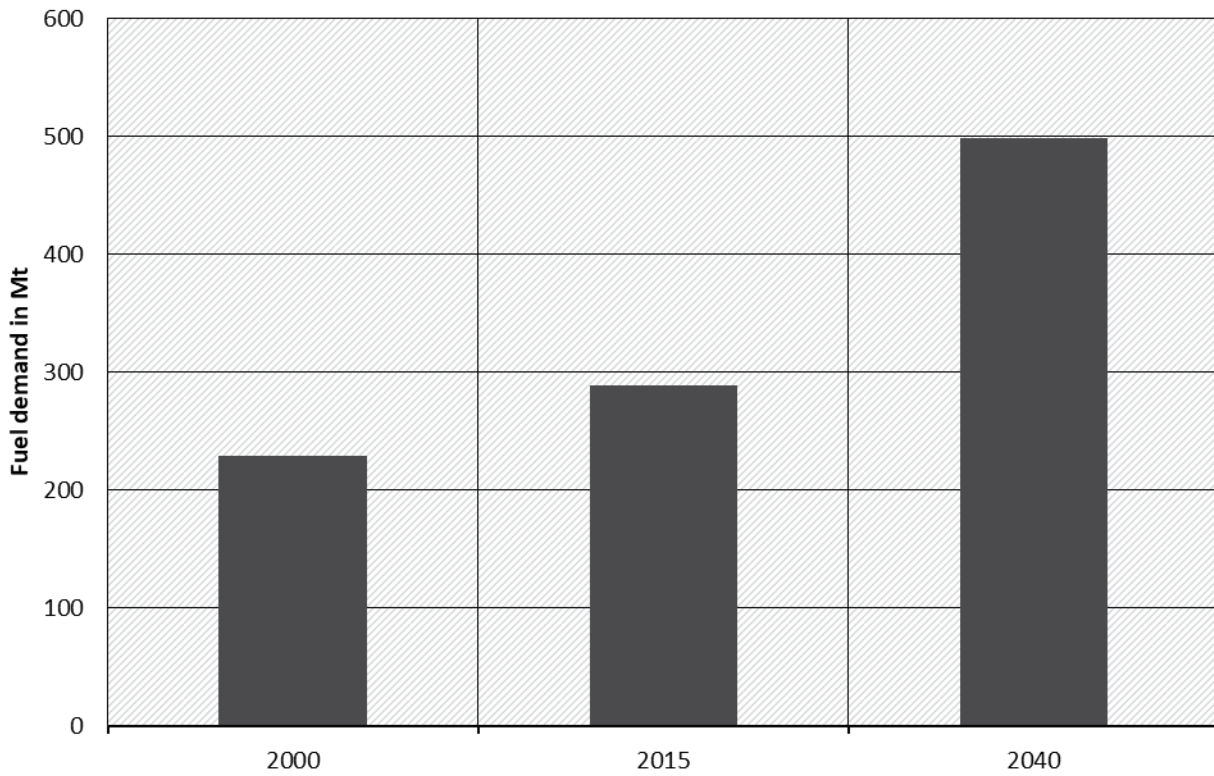
IEA World Energy Outlook 2018

In its World Energy Outlook 2018, the International Energy Agency has published three scenarios on future energy demand, entitled 'New Policies' scenario, 'Sustainable Development' scenario and 'Current Policies' scenario. The 'New Policies' scenario reflects the results of the COP21 in Paris 2015; the 'Current Policies' scenario reflects a failure to implement policies compliant with COP21 and the 'Sustainable Development' scenario which reflects a substantial reduction in global oil demand due to the introduction of greener technologies, e.g. in transport.

Oil demand in aviation in the 'New Policies' scenario is expected to grow by 50% from 2018 to 2040, with a demand volume of close to 500 Mt per year. This constitutes an increase of about 7.5% compared to previous IEA publications and is explained by a lower energy efficiency of new aircraft. A difference of 7.5% in fuel consumption in 2040 translates to a change in compound annual growth rate of initially 2.9% to 3.2%. IEA assumes an annual specific fuel efficiency improvement of 1.6% in contrast to the 2% aspirational goal of ICAO. IEA assumes in the 'New Policies' scenario a share of sustainable aviation fuel of 5% of the total fuel demand in 2040.

The fuel demand for aviation in the 'New Policies' scenario is shown in the following figure.

Figure 13: International Energy Agency – ‘New policies’ scenario – aviation fuel demand



Source: IEA (2018a), mb/d converted into Mt using factor of 49.8

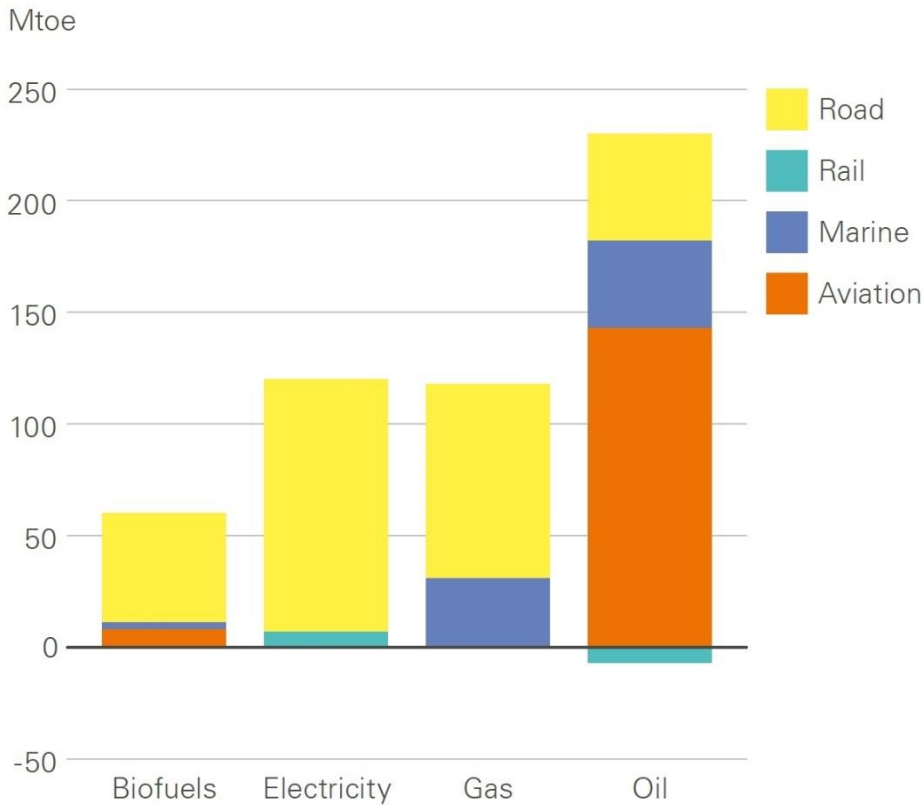
BP Energy Outlook 2019

In BP’s Energy Outlook 2019 edition, four different scenarios are discussed: one scenario with a high energy consumption growth (‘More energy’), two scenarios with stagnating energy consumption (‘Evolving transition’ and ‘Less globalization’) and one defossilization scenario (‘Rapid transition’).

For the ‘Evolving transition’ scenario, a more detailed breakdown of transport energy consumption is provided, as shown in the following figure. According to BP, aviation will be responsible for the majority of oil consumption growth in the transport sector.

Figure 14 shows that BP expects absolute energy demand in the aviation sector to increase by about 145 Mtoe in 2040 compared to 2017. While in all transport modes - with the exception of oil used for the railway sector - the demand of energy will be higher in 2040 than in 2017, absolute growth for oil in aviation is the highest by far for all transport modes and energy carriers.

Figure 14: BP Energy Outlook 2019 – ‘Evolving Transition’ scenario – final energy consumption in transport: growth by fuel and mode 2017-2040



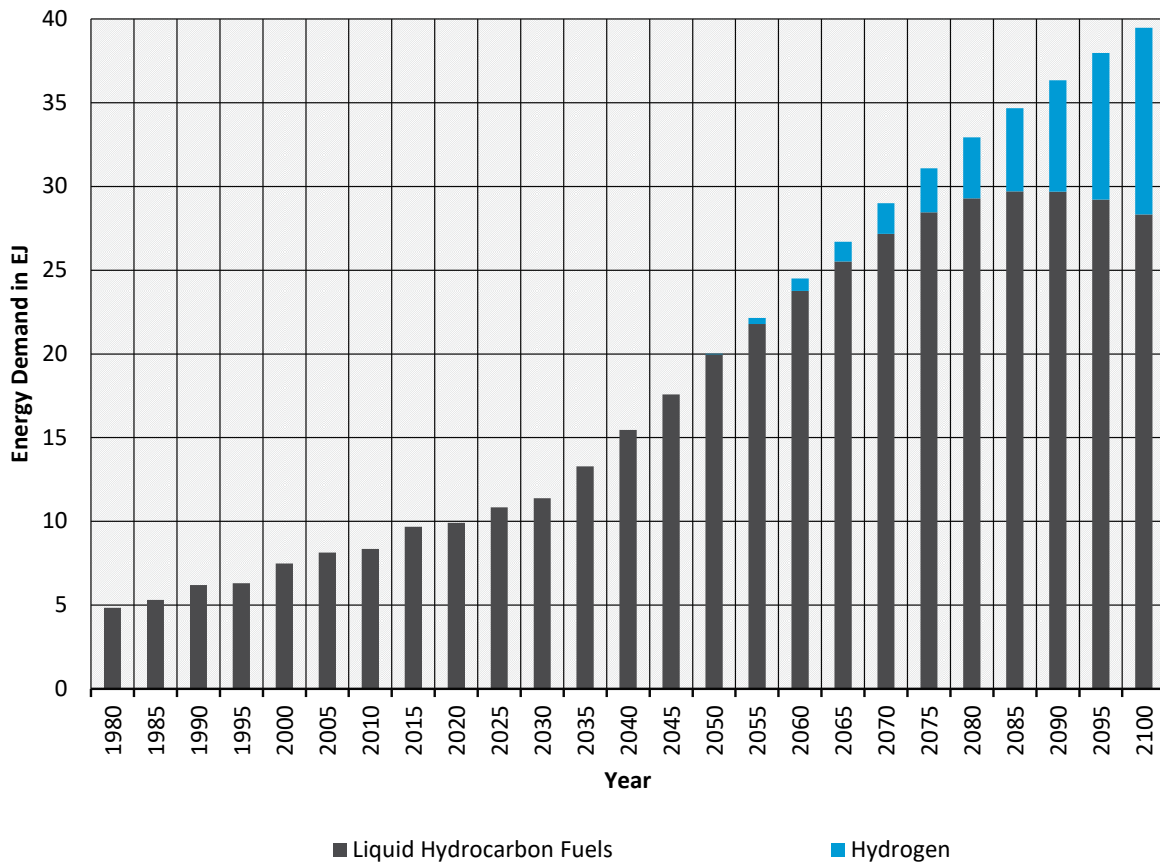
Source: BP (2019)

As in previous editions of the BP Energy Outlook, air transport is not shown as a separate sector in total energy consumption statistics for the scenarios considered.

Shell Sky Scenario

In 2018, Shell published a new scenario study entitled ‘Sky: Meeting the goals of the Paris Agreement’. In this scenario study, the authors outline the challenges associated with a transformation of the energy system to comply with the goals of the Paris Agreement. The forecasting horizon of the study is the year 2100. For each sector, the scenario study forecasts of energy demand and the share of different energy sources. The following figure shows the energy demand development for aviation from 1980 to 2100.

Figure 15: Energy consumption in air transport 1980-2100

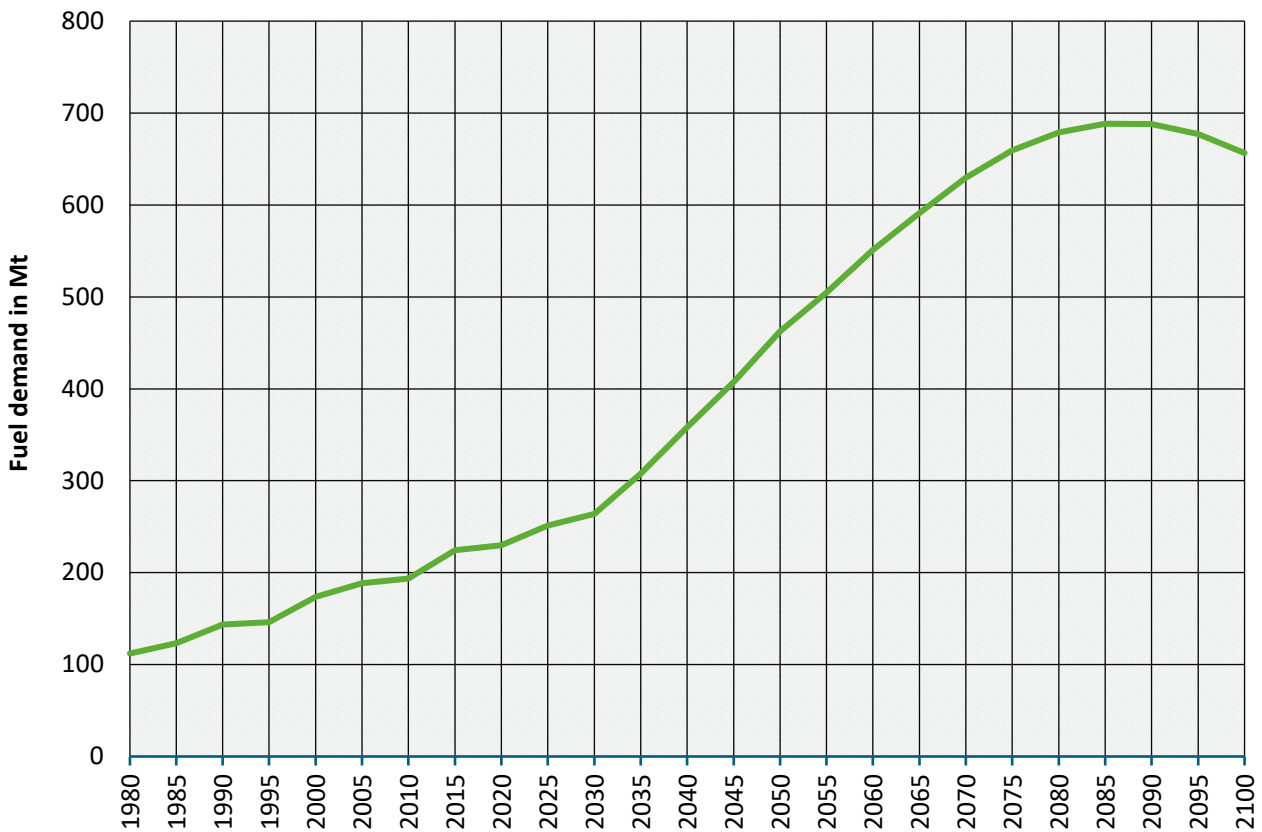


Source: Shell (2018)

Due to its long forecasting horizon, the Shell Sky scenario also includes hydrogen as an energy source in aviation. In the study it is expected that hydrogen aircraft will enter the market from 2050 onwards and will have a significant energy share of 28% in the year 2100.

When the energy demand for hydrocarbons is converted from EJ to Mt, a peak in demand around the year 2085 at less than 700 Mt can be observed.

Figure 16: Demand for hydrocarbon fuels in air transport 1980-2050



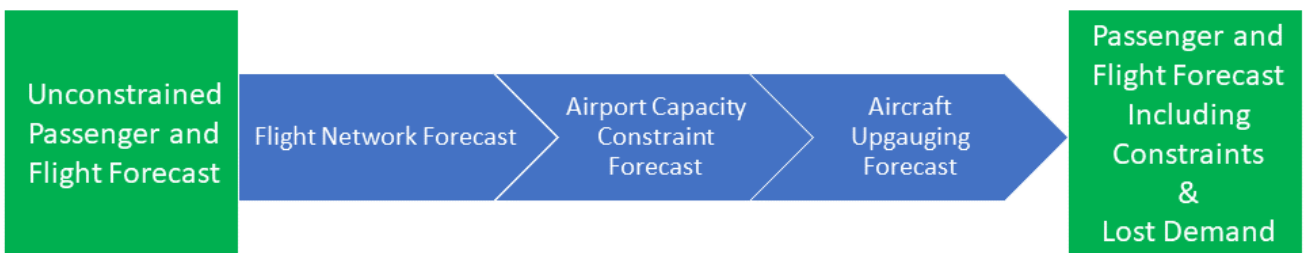
Source: Shell (2018), EJ converted into Mt using 43.15 MJ/kg jet fuel

DLR Capacity Constraint Forecast

The DLR Institute of Air Transport and Airport Research has a long history of forecasting air transport on national, regional and global levels. Previous studies have included the CONSAVE2050 scenario study conducted between 2002 and 2005 by DLR, NLR, IIASA, MVA, Lufthansa and QinetiQ. The most current forecasting study conducted by DLR is the Capacity Constraint Forecast, which explicitly includes current and future airport capacity limitations. Airport capacity limitations will have impacts on passenger growth rates, average aircraft sizes and ultimately also specific and absolute energy consumptions.

Forecasting passenger and flight volumes and the number of passengers per aircraft (‘aircraft size’) comprises several model steps which are described briefly for a better understanding of the model results.

Figure 17: Modelling overview of the DLR Capacity Constraint Forecast



Source: Gelhausen et al. (2019)

The first model step is to forecast passenger and flight volumes without consideration of airport capacity constraints ('Passenger & Flight Forecast ex Constraints').

The future flight network is established on this basis ('Flight Network Forecast'), i.e. this approach determines which airports are served by a non-stop connection and at what frequency. This is essentially dependent on the passenger volume potential for a direct service and route choice of passengers. If a non-stop flight is viable, it is established.

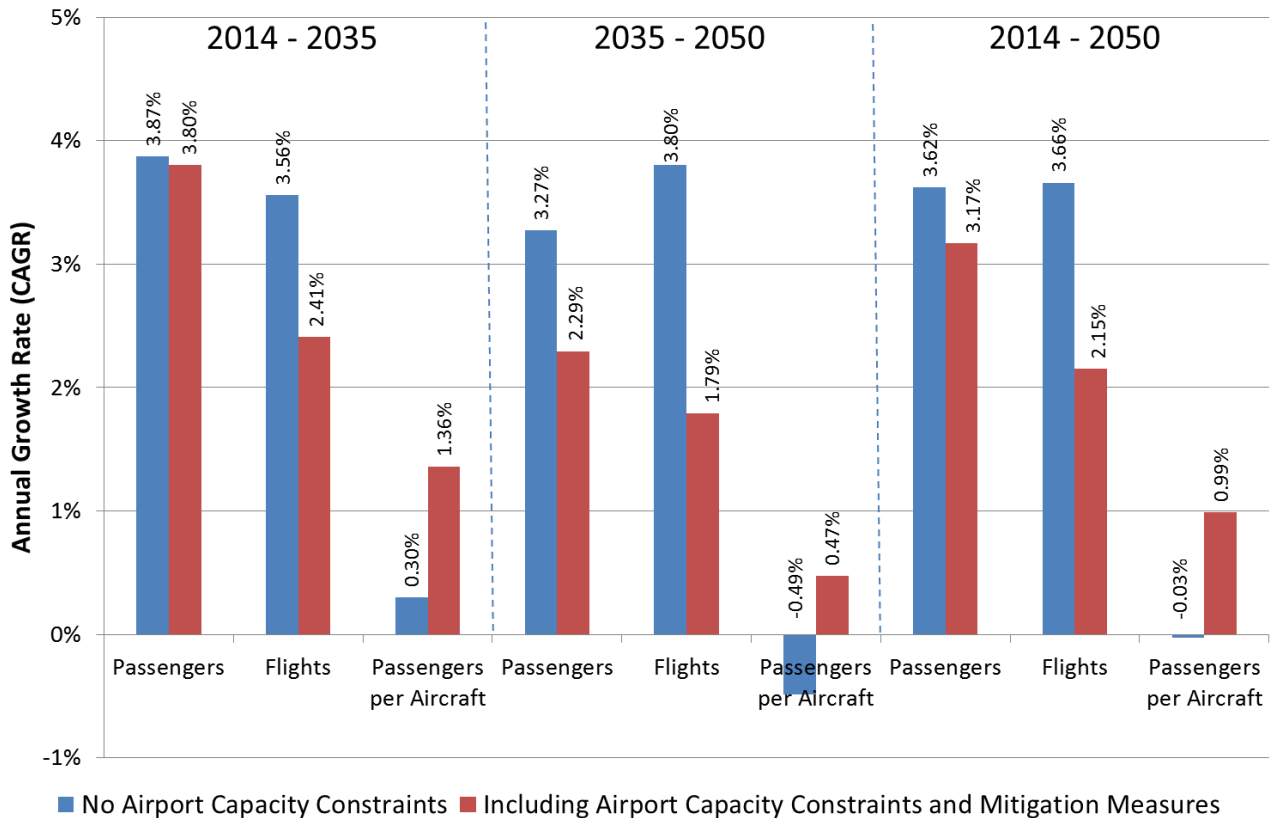
The third model step is to identify airport capacity constraints by comparing the demand for flights at an airport with actual or forecast airport capacity of that airport ('Airport Capacity Constraints Forecast'). If there is a capacity deficit, it is checked whether aircraft upgauging can mitigate the capacity deficit ('Aircraft Upgauging Forecast'). Here, airport capacity constraints refer to the runway system of an airport. Due to long planning procedures and the involvement of the public, especially in Western countries, the runway system is typically the crucial bottleneck in enlarging airport capacity, while airport systems like the terminal can be adjusted in the short term as part of the normal planning procedures. Therefore, for medium- to long-term forecasts of passengers and flights, we need to account for the capacity of the runway system of an airport.

As a result, a passenger and flight volume forecast which considers capacity constraints is obtained ('Passenger & Flight Forecast incl. Constraints'). Any passengers and flights that finally cannot be served due to a shortage of airport capacity are assigned to the lost demand category ('Lost Demand - Passengers & Flights'). The base year of the forecast is 2014 and the global flight plan has been retrieved from the Sabre Market Intelligence Database.² The growth rates are applied to the base flight plan to obtain absolute passenger and flight volume numbers.

The DLR forecast does not explicitly contain assumptions on a shift of short-haul traffic to high-speed rail. On a global level, the potentials for such a shift are relatively small and limited to individual corridors. Even in countries with a fast-growing, dense high-speed railway network like China, the shift to rail has not reduced aviation emissions significantly. At capacity-constrained airports, any airport capacity that becomes available through a shift of traffic to rail will be absorbed immediately by new flights to other destinations not connected by high-speed rail. Hence, the effects on energy consumption and emissions are typically smaller than anticipated; when short-haul flights are replaced by long-haul flights, the effects can even be negative.

² Global Distribution System Sabre provides a database tool with a highly detailed set of origin-destination passenger demand data, which is derived from computer reservation systems and additional modelling.

Figure 18: Forecast growth rates for passenger volumes, number of flights and passengers per aircraft until 2050



Source: Gelhausen et al. (2019)

The unconstrained forecast (blue bars in the figure above), which is basically a measure of market potential, shows a strong passenger volume growth of 3.9% p.a. up to 2035 and a lower value of 3.3% p.a. for the period of 2035 to 2050. This means a passenger volume growth of 3.6% p.a. for the period of 2014 to 2050. The number of flights increases at a rate of between 3.6% and 3.8%, i.e. 3.7% p.a. between 2014 and 2050. As a result, aircraft size, i.e. passengers per aircraft, remains more or less the same. Here, we see a slight increase of 0.3% p.a. up to 2035 and a small decrease of 0.5% p.a. thereafter. The main reason for this development is that over time, but especially after 2035, more and more nonstop connections are becoming viable. They are served mainly by rather small aircraft, as most of these routes are rather thin. Airport capacity constraints and their effects on aircraft size are excluded in the unconstrained forecast by definition.

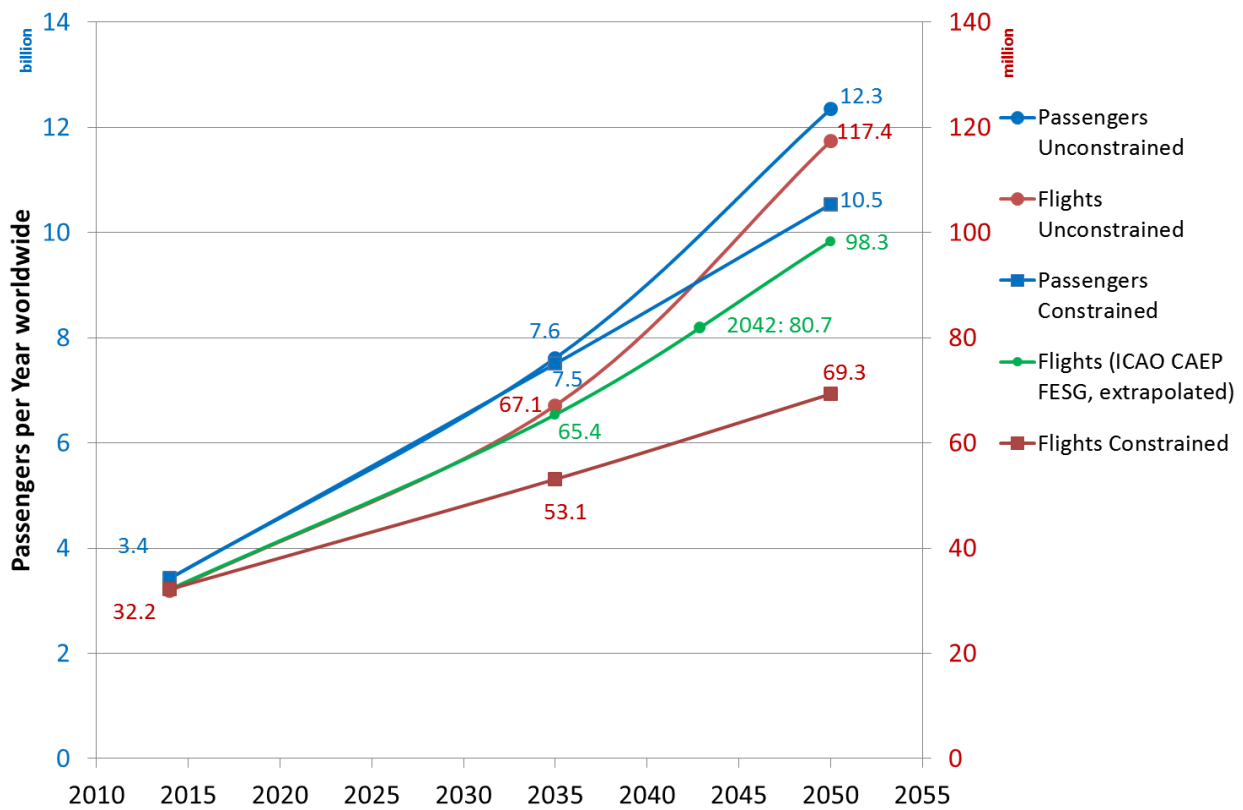
In the constrained forecast (red bars), limited airport capacity can almost completely be counterbalanced by increasing aircraft size up to 2035. Thus, the passenger volume growth rate is virtually the same as in the blue scenario. Nevertheless, flight volume growth drops to 2.4% p.a. and aircraft size growth increases to 1.4% p.a. However, after 2035 aircraft upgauging cannot fully mitigate the increasing effects of limited airport capacity. As a result, passenger and flight volume growth rates drop to 2.3% p.a. and 1.8% p.a. respectively, while aircraft size growth is at about 0.5% p.a. The decline in aircraft size growth is triggered by two factors:

- There is already a large increase in aircraft size between 2014 and 2035 and it is limited over a given time span. For a further increase of average aircraft size, early retirement of small aircraft is necessary or new aircraft need to be exceptionally large.

- More and more routes with rather small aircraft become viable. These routes are thin and cannot be viably served by larger aircraft because of a lack of demand for the time being.

Overall, passenger and flight volume grow at 3.2% p.a. and 2.2% p.a. respectively. Aircraft size increases at about 1.0% p.a. up to 2050 which means that the average aircraft carries 45% more passengers in 2050 than in 2014. As a result, average passengers per aircraft of all scheduled flights increases from 106 in 2014 to 141 in 2035 and 152 in 2050. The following figure shows the passenger and flight volume development in absolute numbers for both the constrained and unconstrained cases. Furthermore, the flight forecast of the ICAO CAEP FESG for 2042 is displayed as a reference.

Figure 19: Forecast passenger volume and number of flights for the years 2035 & 2050



Source: Gelhausen et al. (2019)

Passenger and flight volumes start at 3.4 billion passengers and 32 million flights for 2014 (based on the Sabre Market Intelligence Database, 2014). In the 2035 forecast, passenger and flight volume is 7.5 billion and 53 million respectively. In the 2050 forecast, passenger and flight volume equals 10.5 billion and 69 million respectively. 14 million flights (21%) in 2035 and 48 million flights (41%) in 2050 are lost because of limited airport capacity. Regarding passengers, 100 million passengers (1.5%) in 2035 and 1.8 billion passengers (15%) in 2050 cannot be served because of a lack of airport capacity. While virtually all passengers can be served up to 2035 due to increasing aircraft size, i.e. passengers per flight, there is a considerable gap of passenger volume of approx. 15% between the constrained and the unconstrained forecasts. The main reason for this gap is that it is increasingly difficult to enlarge airport capacity especially in the Western countries. Furthermore, aircraft upgauging cannot keep pace with demand growth after 2035. The following table summarizes the effects of limited airport capacity on the passenger and flight volume forecasts.

Table 3: Difference between the constrained and unconstrained forecast

	2014 - 2035	2035 – 2050
Lost Flights (without adaptation)	20.9%	41.0%
Lost Passengers (after adaptation through aircraft upgauging)	1.5%	14.7%
Aircraft Upgauging (size growth) per Year	1.7%	1.0%

Source: Gelhausen et al. (2019)

In comparison to the unconstrained forecast, 20.9% less flights can be operated between 2014 and 2035. This value increases to 41% between 2035 and 2050. However, airlines react with adaptation measures, first and foremost by using larger aircraft. Hence, the lost or unaccommodated demand expressed in passengers is significantly lower – approx. 1.5% between 2014 and 2035 and 14.7% between 2035 and 2050. On average, aircraft size increases by 1.7% per year until 2035 and by 1% per year up to 2050.

The DLR Capacity Constraint Model is under review in the CAEP/12 cycle (2019-2022) to become part of the ICAO Long Term Forecast. Furthermore, it is part of the Technology Evaluator of the European Union's Joint Technology Initiative CleanSky/CleanSky2, where the DLR forecast forms the basis for further environmental assessments of new aircraft technologies.

DIW Econ et al. – Forecast for the German Aviation Concept

In 2015, DIW econ et al. published a forecast on behalf of the German Federal Ministry of Transport, which was intended to lay the groundwork for the German aviation concept. In the forecast document, a BAU forecast without additional political measures and three scenarios which differ in terms of growth rates and applied political measures are shown:

- ▶ BAU Case – without any additional measures;
- ▶ Scenario 1 – Continuation of growth rates 2009 to 2015 at German airports;
- ▶ Scenario 2 – Growth rates in line with global aviation growth;
- ▶ Scenario 3 – Participation in global growth and additional measures for improving the acceptance of aviation.

Table 4: Passenger growth in international aviation, 2013-2030

Passenger Growth	Origin-Destination Traffic				Terminal Passengers				Transfer Passengers			
	BAU	S1	S2	S3	BAU	S1	S2	S3	BAU	S1	S2	S3
[%]												
Germany	54	59	63	58	66	71	80	76	112	117	143	140
Neighbouring Countries	62	65	66	62	72	75	75	71	108	113	109	105
EU28	56	59	60	56	62	64	66	62	95	99	103	100
Europe total	60	66	67	63	67	69	71	67	93	96	99	96

Source: DIW Econ et al. (2015)

The analysis by DIW Econ et al. (2015) shows that the growth of origin-destination traffic from and to Germany is assumed to be slightly lower than in neighbouring countries, but higher than in all Member States of the European Union. The average annual growth rate in origin-destination passengers is estimated to be between 2.6% and 2.9%, depending on the scenario. According to the model, Germany is estimated to be

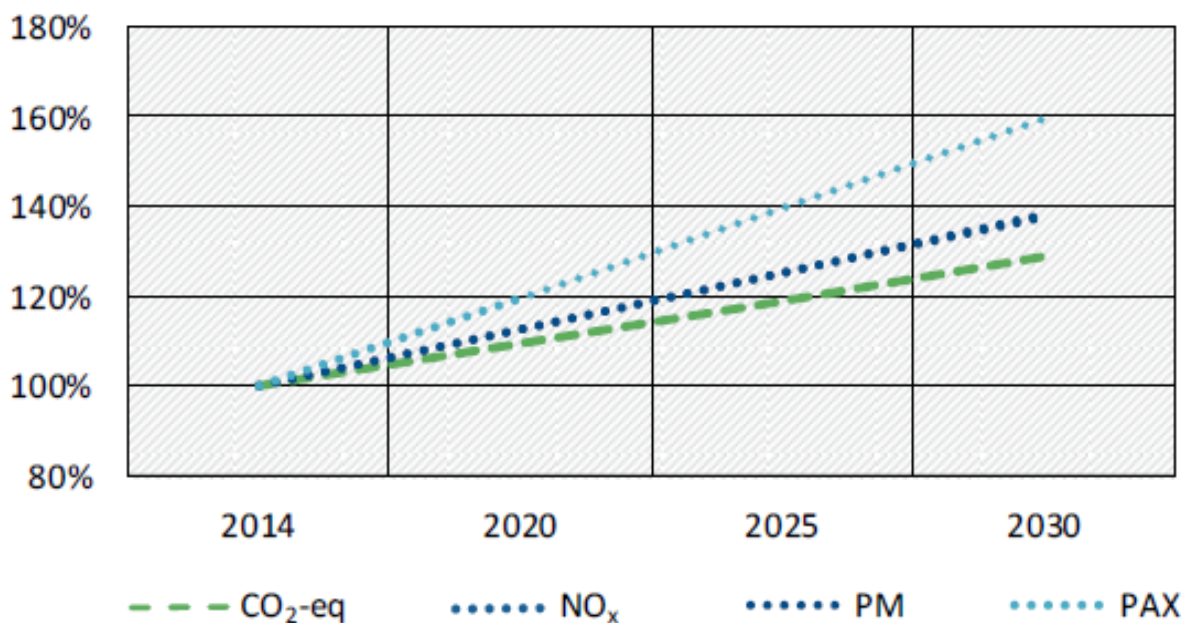
particularly attractive for transfer passengers as the average annual growth rate lies between 4.5% and 5.4%, depending on the scenario. The average annual growth rate of terminal passengers (i.e. total arriving and departing passengers) is estimated to be 3.0% to 3.5% between 2013 and 2030.

Emissions have not been modelled by DIW econ et al. and instruments addressing climate change have only been considered in scenario 1 (only EU-ETS in its current form) and scenarios 2 and 3 (global carbon offsetting as realized with CORSIA).

UBA Scenario Air Transport Germany under consideration of environmental aspects

The forecast published by DIW Econ et al. (2015) was extended by INFRAS in the environmental dimension (UBA 2018). Based on the forecast by DIW Econ et al. (2015), the development of emissions was calculated, taking into account assumptions on technological development of aircraft. The result is shown in the following figure – with a 60% growth in passengers up to the year 2030, the growth of emissions falls by 30%.

Figure 20: UBA's forecast of passengers and key emissions, 2014-2030



Source: UBA (2018)

Based on the forecast by DIW Econ et al. (2015), a positive scenario was developed, which included the internalization of climate costs, aviation tax and a shift to rail for flights over distances <600km.

The positive scenario with all its measures combined includes a forecast on the growth of passengers, which is 11% lower than the forecast by DIW Econ et al. (2015). The complete internalization of climate costs alone would result in an 8% reduction in passenger growth compared to the DIW forecast.

Nevertheless, even in the positive scenario, passengers at German airports grow by 50% between 2014 and 2030, which translates into an average annual growth rate of 2.7%.

The results for CO₂ emissions in the positive scenario show that with the instruments put into place (internalization of climate costs, shift to rail), about two thirds of the emissions growth between 2014 and 2030 could be reduced.

2.1.2 Analysis of scenarios

The projections presented in the previous chapters have in common that aviation is perceived to grow further at traffic growth rates of between 2.6% and 5.3%, measured in revenue passenger kilometres

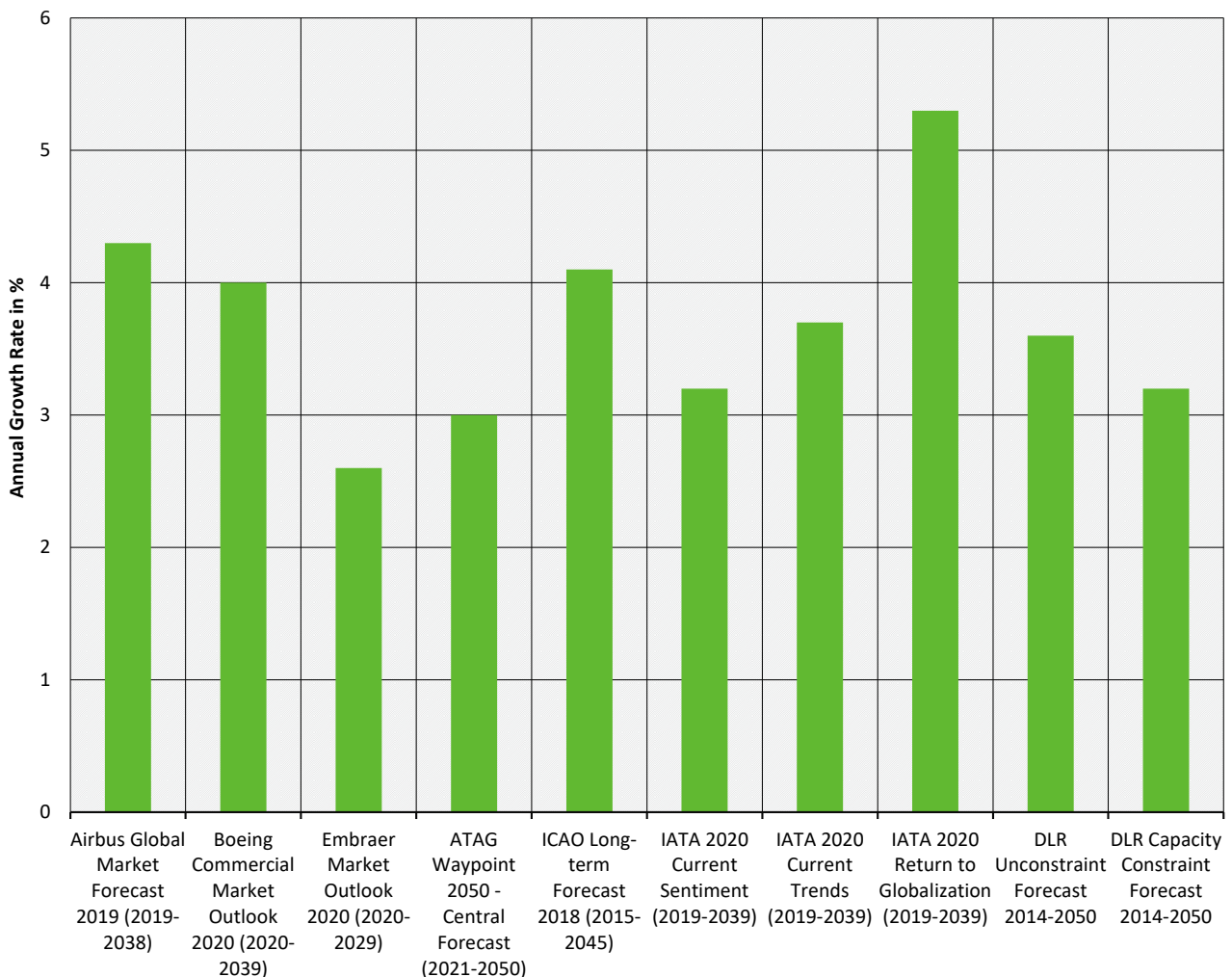
annually. The main contributing factors to this trend are a deeper integration of countries in globalized economic and logistic chains and a growth in disposable income. In the past, income has proved to be the major driver of air transport demand, as the propensity to travel by air increases and also more time-consuming ground transport modes are replaced by air travel.

More recent forecasts also deal with the long-term impacts of the COVID-19 pandemic. On average, long-term growth rates are smaller than in pre-COVID forecasts. Among aviation stakeholders, it is expected that global demand levels observed in 2019 are reached again within approx. 3-5 years.

A summary of global passenger traffic growth rates is provided in Figure 21. As the figure concentrates on passenger traffic growth, not all forecasts and scenario studies discussed above are included. For instance, both the Shell and BP studies do not include data on passenger growth.

While the first long-term forecasts published after the beginning of the COVID-19 pandemic show reduced traffic growth rates compared to the pre-COVID situation, it is still expected that aviation will recover, especially in the decade after 2030.

Figure 21: Comparison of annual growth rates in passenger traffic in selected forecasts



Source: Authors' own compilation

There is consensus among studies that technological and operational measures will further decouple energy demand from aviation growth. Nevertheless, aviation energy demand grows at a relatively high rate compared to other sectors. The challenges associated with aviation energy demand growth are manifold:

Firstly, compared to other sectors, it is relatively difficult to substitute liquid hydrocarbons in aviation with other energy carriers (like hydrogen or direct use of electricity). Research is currently being conducted on introducing hybrid-electric, full battery-electric or hydrogen-powered aircraft, but only for regional / short-haul aircraft, which have a share of only a very few percentage points in global carbon dioxide emissions from aviation. Hence, emission reduction potentials in this regard can be considered as rather small.

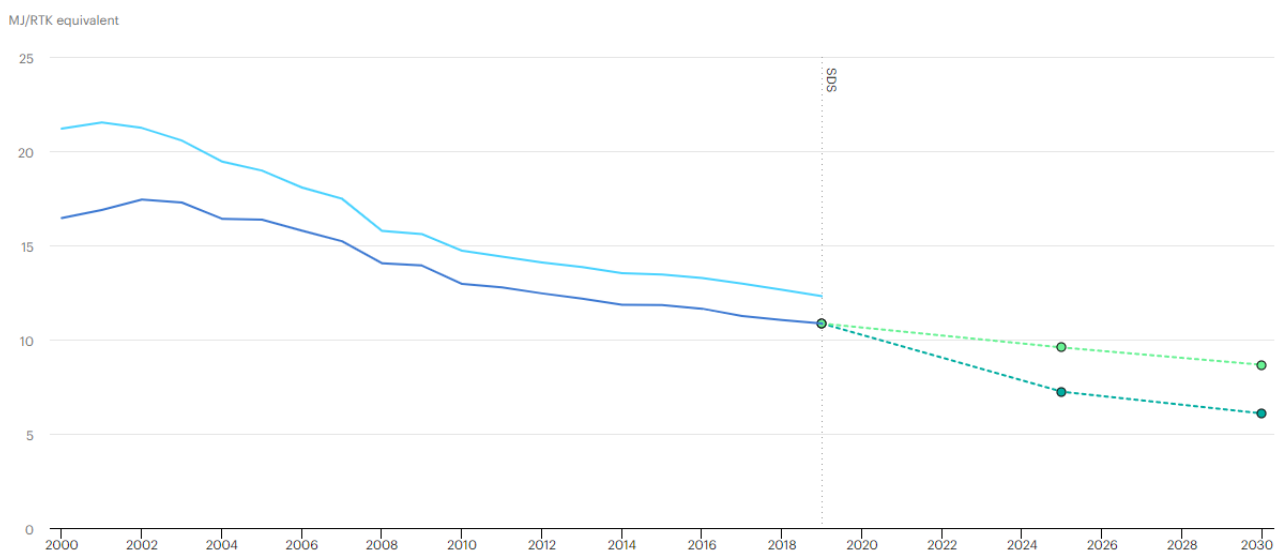
For most traffic segments, crude oil remains an important basis for energy supply in aviation until synthetic fuels will become available at large scale and affordable prices. As other sectors can more easily reduce their dependability on crude oil, the crude oil demand share of aviation is expected to rise from 6% currently to 9% in 2040 (IEA 2016).

Secondly, a consequence of aviation currently (and most likely in the future) depending on crude oil is that it is difficult - if not impossible - to fulfil the aspirational goal of carbon neutral growth based on aircraft technology and operational measures alone.

Thirdly, energy efficiency improvements in aviation pass slowly throughout the global fleet as aircraft are assets with a comparably long technical and economic lifespan. This applies to both individual aircraft, which have an average lifespan of more than 25 years, and aircraft types, which – once introduced into the market – remain in production for long time-frames. For instance, the Airbus A320 with conventional engines was first introduced in 1989 and remained in production until at least 2020 with relatively small optimizations and efficiency improvements. The main reasons why in-service aircraft types are not upgraded with more modern technologies introduced are complexity and costs for a re-certification and the desire of airlines to keep fleet variety as small as possible in order to reduce the costs of spare part stocks and engineers' training.

Various studies on the fleet-wide efficiency improvements have been conducted in the past. For instance, IEA (2020) has analyzed the energy efficiency improvement in aviation based on MJ/RTK. Since 2000, specific energy consumption has improved from 21.2 MJ/RTK to 12.3 MJ/RTK in 2019, which corresponds to an annual improvement of 2.8% per year. Under the assumption of the 2% aspirational goal of ICAO, energy consumption would decline to 8.7 MJ/RTK in 2030.

Figure 22: Energy efficiency of global passenger aviation

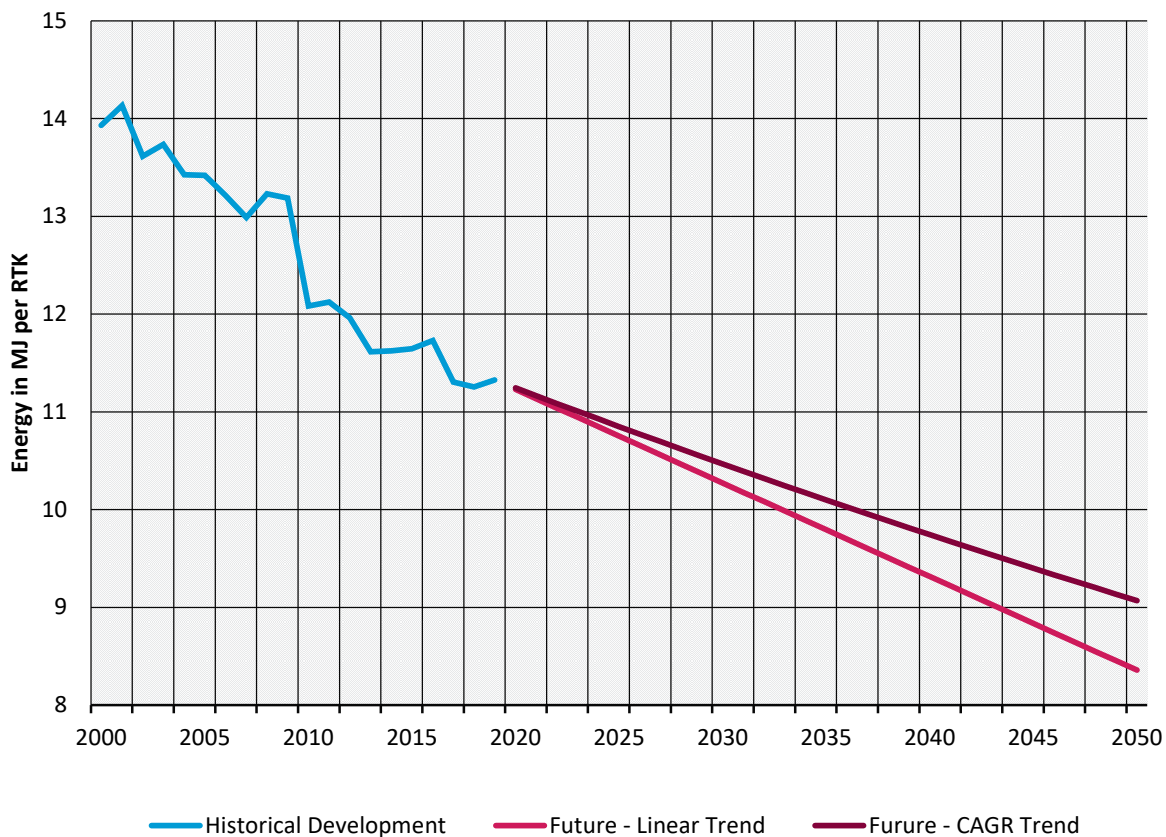


Source: IEA (2020c)

Other sources have concluded that historical efficiency improvements are significantly smaller than the values shown by IEA (2020c). For instance, ICCT (2020a) analyzed the long-term fuel efficiency improvement based on the entry of service of new commercial aircraft and finds annual efficiency improvements of 0.6% between 2000 and 2010 and of 1.5% in the decade after 2010. The latter is most probably due to the introduction of the Airbus A320neo, A350 and Boeing 737/787.

In addition to previous studies, DLR has conducted a new analysis which includes all flights departing from German airports. In 2019, energy consumption for all flights (passenger and cargo) departing from Germany is estimated at 11.3 MJ/RTK. Based on the linear trend of the last decade, specific energy consumption per RTK would decline to 8.4 MJ/RTK in 2050. Based on the annual improvement of 0.71% (CAGR) in the last decade, the value would decline to 9.1 MJ/RTK in 2050.

Figure 23: Energy efficiency of aviation, all flights from Germany



Source: DLR Calculations based on German Air Transport Statistics

Table 5 provides an overview of the efficiency improvements of various studies. Historically, fleet-wide efficiency improvements have been relatively high, amounting to more than 2% p.a. in the decade between 1990 and 2000. This has declined to 1.3%-1.9% between 2000 and 2010 and a further decrease to 0.8% to 0.9% is projected for the decade between 2010 and 2020. Due to the entry into service of more advanced aircraft in the upcoming years, this is expected to rise to approx. 1.4% for the decade of 2020 to 2030. The results calculated with the DLR model are based on the German air transport statistics (actual flights and payloads), while the results of Schaefer (2012) are based on flight schedules and assumed average load factors.

In addition to the empirically calculated annual improvement rates, ICAO has published an aspirational goal, which should be a contributing factor in the strategy for carbon neutral growth. The aspirational goal for the current decade is 2% p.a., which is substantially above the values that can be found empirically for the last 10-20 years.

Table 5: Historical aircraft fleet fuel efficiency improvements

Geographical scope	Timeframe	Annual fuel efficiency improvement	Data source
All flights departing Germany	1989-2016	1.61%	DLR model, Hepting et al. 2020
All flights departing Germany	1990-2000	2.36%	DLR model, Hepting et al. 2020
All flights departing Germany	2000-2010	1.27%	DLR model, Grimme and Jung 2018
All flights departing Germany	2010-2016	0.83%	DLR model, Grimme and Jung 2018
All flights departing Germany	2000-2010	1.41%	German Air Transport Statistics
All flights departing Germany	2010-2019	0.71%	German Air Transport Statistics
Global	2000-2010	1.86%	Schaefer 2012
Global	2010-2020	0.93%	Schaefer 2012
Global	2020-2030	1.39%	Schaefer 2012
Global	2000-2019	2.8%	IEA 2020
Global	2009-2019	2.0%* (avg.) 1.3% (CAGR)	ATAG 2020a
International Aviation	2000-2019	2.15%	IEA 2020
New aircraft entering service	1990-2000	0.80%	ICCT 2020
New aircraft entering service	2000-2010	0.60%	ICCT 2020
New aircraft entering service	2010-2019	1.50%	ICCT 2020

Note: *ATAG uses the term 'rolling improvement,' which is the average (avg.) of annual improvements; calculated as compound annual growth rate (CAGR), the improvement is equivalent to 1.3%.

Sources: Hepting et al. (2020), Grimme and Jung (2018), Schaefer (2012)

Most publicly available forecasting studies provide transport activity data (passengers, tons of cargo, RPKs, RTKs), but not the actual development of energy demand. Future energy demand depends on transport development as well as the efficiency of the air transport system (aircraft technology, operations and air traffic management). Hence, we combine the expectations on global traffic growth from Figure 21 with the efficiency improvements shown in Table 5. The resulting growth rates of both traffic and energy demand developments are shown in Table 6.

Table 6: Global aviation demand growth and estimation of energy demand growth

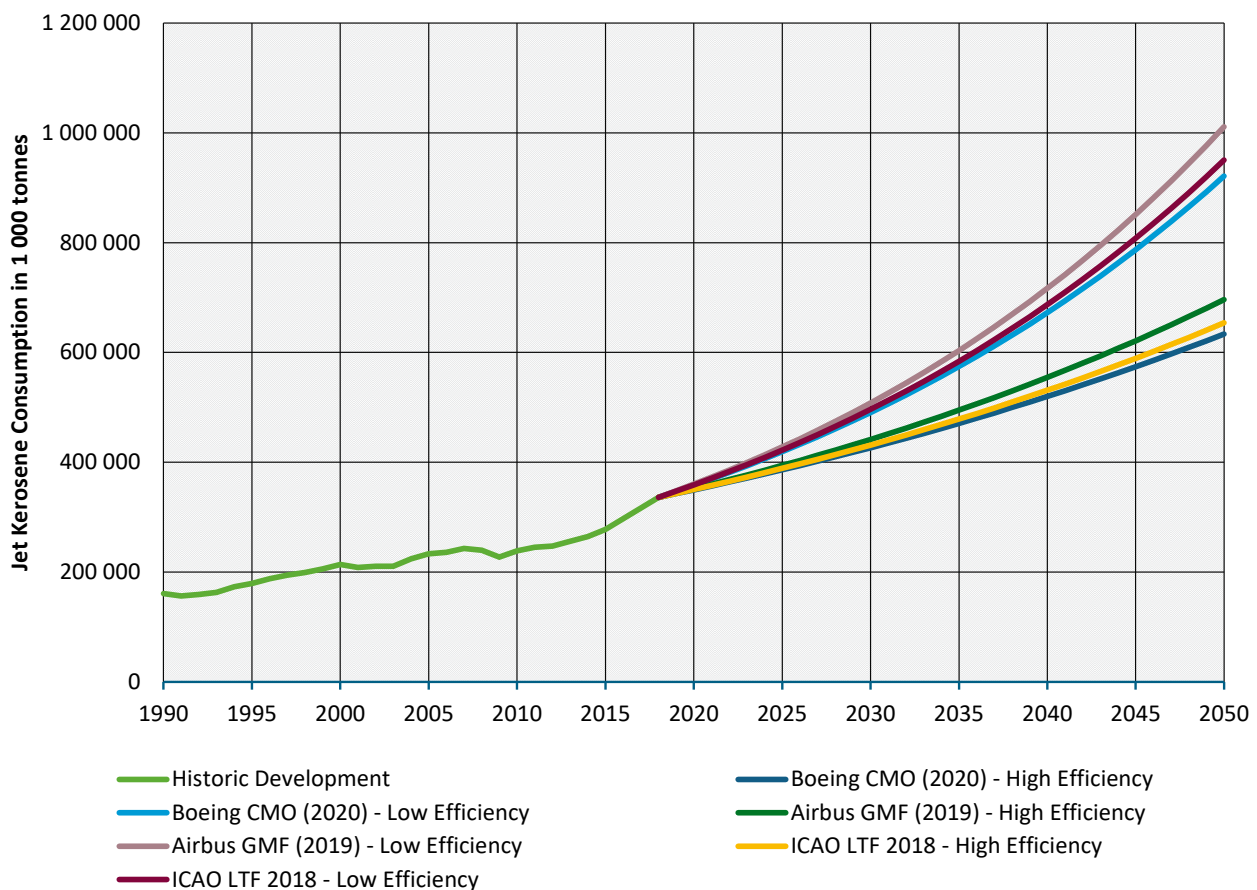
Forecast	Year of Publication	Time-frame	Aviation demand growth p.a. (CAGR)	Estimation of energy demand growth p.a. (CAGR)
ICAO Long-Term Forecast	2018	2015-2045	4.1%	2.1% - 3.3%
Airbus Global Market Forecast	2019	2019-2038	4.3%	2.3% - 3.5%
Boeing Commercial Market Outlook	2020	2020-2039	4.0%	2.0% - 3.2%

Source: Authors' own compilation

Based on the global historical development of energy demand and traffic as well as the above-mentioned forecasts and assumptions on future energy efficiency improvements, Figure 24 shows the development of global demand for jet kerosene. According to IEA (2018a), 336 Mtoe of jet kerosene were consumed in 2018. This figure, however, includes jet fuel consumed for all purposes such as passenger and cargo transport as well as military consumption. A small fraction of jet fuel is also used for non-aviation purposes as jet fuel can be used as substitute for other middle distillates such as diesel or kerosene.³

On the basis of the forecasts and assumptions on fuel efficiency improvements, the span for aviation fuel demand in 2050 ranges from 484 Mt (ICAO CAEP/11 Low Scenario in combination with a high efficiency improvement) to 1 096 Mt (ICAO CAEP/11 High Scenario with a low efficiency improvement; not depicted in Figure 24). In the ICAO CAEP/11 Most Likely Scenario, the demand for aviation fuel in 2050 ranges from 637 Mt to 958 Mt, i.e. 2 to 3 times above the 2015 level.

³ While in the German language the term 'Kerosin' is used synonymously with jet fuel, in American English 'kerosene' is used for the German 'Petroleum'.

Figure 24: Projection for global energy demand in aviation

Source: Authors' own compilation

2.1.3 Summary and conclusions

In this chapter, we have compiled various forecasts and scenarios on long-term aviation development globally, for Europe and for Germany. Most of the forecasts and scenarios include traffic-related indicators, such as growth rates of passengers, passenger-kilometres or cargo, but not forecasts on fuel demand. Most energy scenarios treat aviation only superficially as aviation has only a minor share in global oil or total energy consumption. In many cases, aviation is combined with other modes, with the result that no in-depth knowledge e.g. on regional distribution of aviation energy demand can be derived from these studies.

Therefore, we have combined the traffic forecasts and scenarios with assumptions on efficiency improvements for an estimation of future energy consumption in aviation. The key finding is that based on the assumptions, a decoupling of aviation demand growth and the growth of energy consumption will continue. While demand is expected to grow between 3% and 5% annually on a global level, the improvement in specific energy consumption (i.e. fuel per passenger kilometre) has been estimated to be in the range of 0.8% to 2% per year. However, one has to be careful when interpreting the different results of fuel efficiency studies. A simple arithmetic such as the mean of annual percentage values, as used, for example, in the ATAG (2020a) fuel efficiency paper, results in higher efficiency improvement figures than a calculation with the geometric mean (CAGR).

However, given the analysis of most recent empirical trends from 2000 to 2019, the industry objectives of an improvement of 2% per year until 2020 and carbon neutral growth from 2021 onwards can hardly be achieved on the basis of the regular fleet-rollover alone. The EU ETS and CORSIA also have only limited

utility in the long term as they do not directly address the defossilization of aviation since the emissions of aviation are only offset with emission reductions in other sectors. The availability of offsets and allowances for fulfilling commitments could be extremely challenging in the long run, when other sectors have been decarbonised and may not provide any excessive carbon credits any longer.

Depending on aviation demand growth and specific improvement, it can be expected that energy consumption and carbon dioxide emissions will rise two- to three-fold up to 2050, unless any radically new concepts in propulsion or energy provision are implemented. Technological improvements in the areas of aircraft, engines, operational procedures and air traffic management alone will not be able to offset growing aviation demand, which mainly comes from emerging economies where income is growing. Technically, e-fuels have the potential to address challenges for aviation both in energy provision and carbon reduction commitments.

The analysis has also shown that there is a need to conduct further research in the area of aviation scenarios, energy consumption and emissions. Only very few studies have focused so far on regionalised aviation energy consumption scenarios. Such scenarios, however, would be highly demanded in any further research on the implementation of e-fuels since it enables estimation of the production capacities needed and the locations where major demand will occur. Furthermore, scenario studies should also include concepts of radical change, such as electric propulsion and alternative energy carriers such as hydrogen. Such wildcards have the potential to lead to alternative futures.

2.2 Shipping

To date, GHG emissions of international maritime shipping have only been regulated to a small extent. Current international regulations require new ships to comply with a technical efficiency standard, whereas existing ships are required to have an energy efficiency management plan in place, but not to actually reduce their GHG emissions.

To enhance IMO's contribution to the global efforts by addressing GHG emissions from international shipping and to identify actions and measures to do so, the IMO adopted an Initial Strategy on Reduction of GHG Emissions from Ships (MEPC 72/17/Add.1) in April 2018, to be finalized in 2023.

In terms of level of ambition, IMO's Initial Strategy has specified two specific main targets. Firstly, GHG emissions from international shipping should peak as soon as possible and total annual GHG emissions should be reduced by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out in a way consistent with the Paris Agreement temperature goals. And secondly, the average sector's carbon intensity, defined as CO₂ per transport work, should be reduced by at least 40% by 2030 pursuing efforts towards 70% by 2050, compared to 2008. These levels of ambition are the result of negotiations in which EU Member States, including Germany, supported a 70% to 100% reduction on 2008 GHG emissions in 2050 in order to align the reduction targets for maritime shipping with the goals of the Paris Agreement.

Currently available technical and operational GHG reduction measures will, however, not be sufficient for phasing out total annual GHG emissions of international maritime shipping by 2050. And given that battery electric traction is – due to the long distances that are covered in the sector – not expected to be a large-scale option for the sector, the use of post-fossil fuels, which do not induce any direct or indirect fossil GHG emissions, will be required. These post-fossil fuels are, however, either still under development or are not yet available on a large scale.

To develop a roadmap that specifies the concrete steps that need to – and can – be taken on the different levels (global, EU, national) to enable sufficient supply and uptake of the most promising GHG-neutral energy options for international shipping to decarbonise, the project provides, in a first step, an overview and an analysis of the projections of the energy demand of international maritime shipping. This will allow

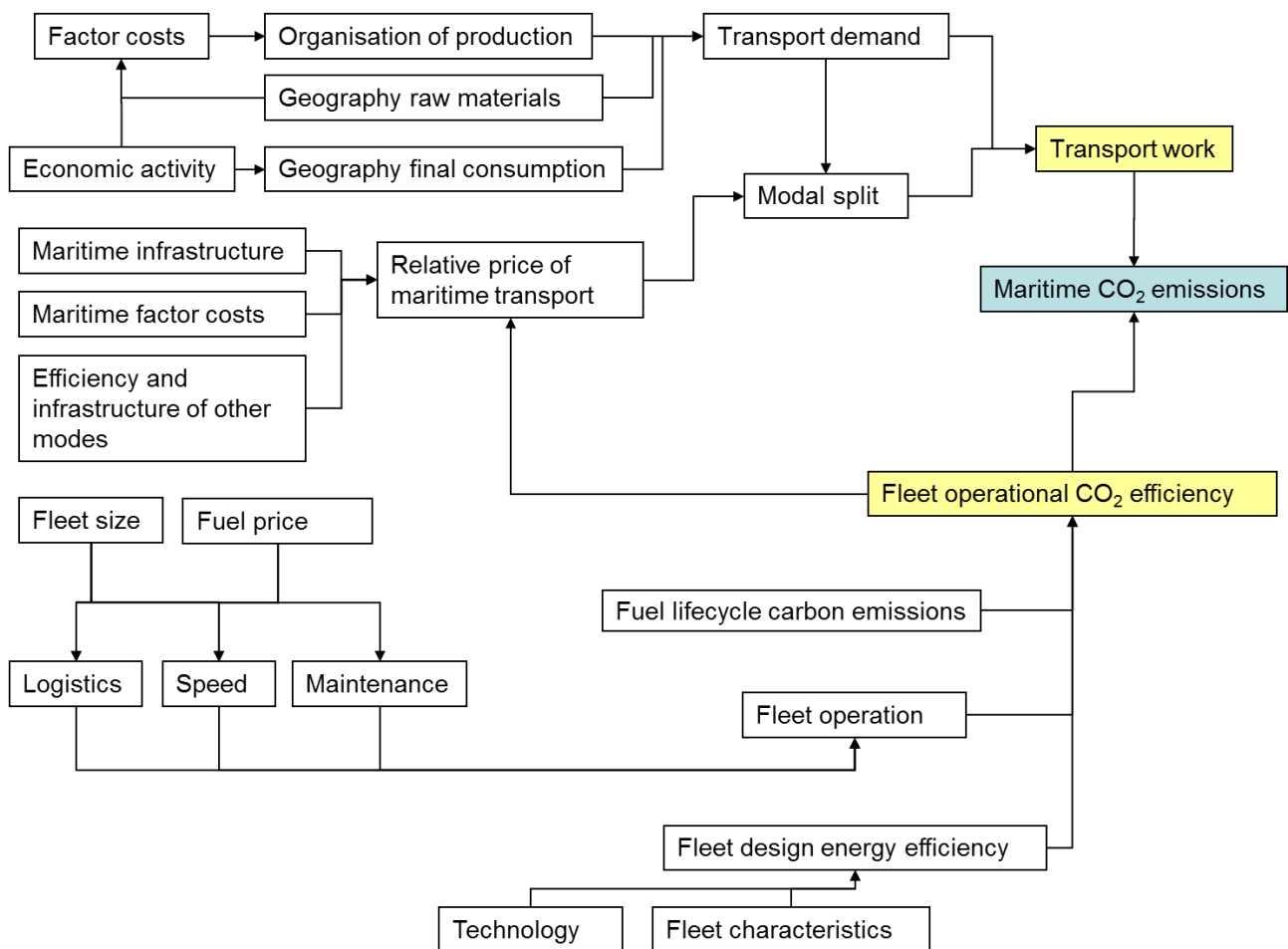
an estimation of the share of sector’s future demand that would have to be covered by GHG-neutral energy options if the sector had to decarbonise.

2.2.1 Energy demand and CO₂ emissions projections

2.2.1.1 Determinants of maritime CO₂ emissions

As illustrated by Figure 25, the CO₂ emissions of international maritime shipping are determined by many different factors, with the fleet’s operational CO₂ efficiency and its transport work being the two main direct determinants.

Figure 25: Stylized representation of factors determining maritime CO₂ emissions



Source: IMO (2009)

Accordingly, the two main direct determinants of the energy demand of maritime shipping are the fleet operational energy efficiency (a combination of the fleet design efficiency and the fleet operation as depicted in Figure 25) and the fleet’s transport work. Projections of the energy demand of the sector focus, therefore, on determining these two factors. Projections of the CO₂ emissions of the fleet consider in addition the carbon intensity of the energy demand.

Important underlying factors to determine the operational energy efficiency of the future fleet are the potential and costs of efficiency improvement measures, market barriers to the uptake of these measures, bunker fuel prices and energy efficiency regulations.

In studies on energy demand projections, the potential and costs of efficiency improvement measures are captured by means of marginal abatement cost curves, the market barriers by means of market barrier

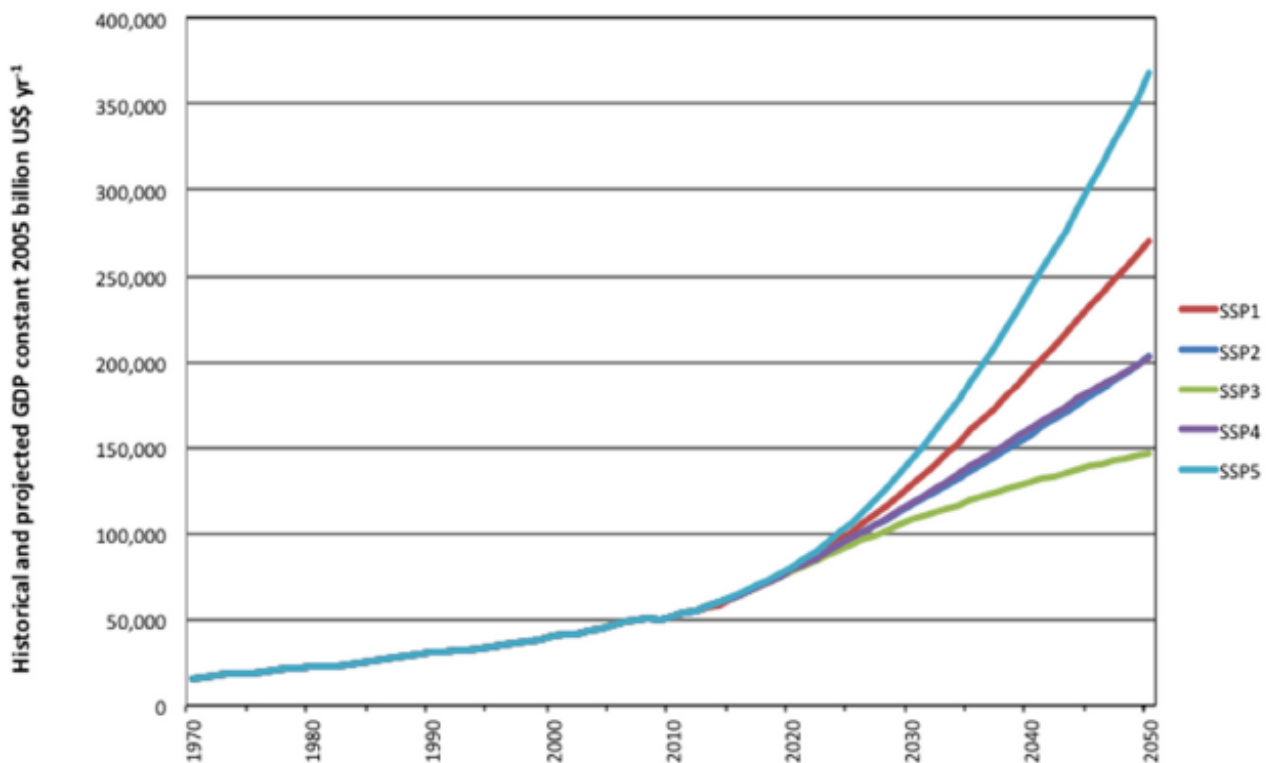
factors (specifying the share of cost-efficient measures not adopted due to the barrier), and bunker fuel prices by means of different price scenarios. In the Business-as-Usual (BAU) scenarios, the regulation currently in place is reflected; in the reduction scenarios the expected effects of current and additional future regulation are covered.

To determine the future volume of seaborne trade, one would ideally want to determine the expected future transport volume for the existing trades and determine additional trades that may arise due to global structural demand and supply changes. Since this is a rather complex analysis and associated with a high degree of uncertainty, most projections of the energy demand of maritime shipping scale the current fleet's transport work by means of projections of global GDP growth and projections of the demand for energy carriers (relevant for the activity of the tanker fleet and part of the bulker fleet), depending on the stringency of the climate policies.

Most of the recent projections of the GHG emissions and/or the energy demand of maritime shipping have thereby based the estimation of the global GDP growth on a so-called Shared Socioeconomic Pathway (SSP; see 2.2.1.2 for more details) and the estimation of the demand for energy carriers on a so-called Representative Concentration Pathway (RCP; see 2.2.1.2 for more details). There are, however, also recent projections (CE Delft und Lee 2019; IMO 2020a), which use more recent OECD GDP projections instead of a SSP projection. This GDP growth projection considers the impacts of the global 2007 to 2009 recession and therefore features lower future GDP growth rates.

In the Third IMO GHG Study (IMO 2014), for example, a set of GDP projections derived from the five SSPs (Figure 26) have been used for the projections of the transport work of ships related to the transport of goods other than fossil energy carriers. And four different RCPs and the related energy consumption projections have been used to project the transport work of ships related to the transport of fossil energy carriers like coal and liquid fuels.

Figure 26: GDP projections per SSP as used in the Third IMO GHG Study



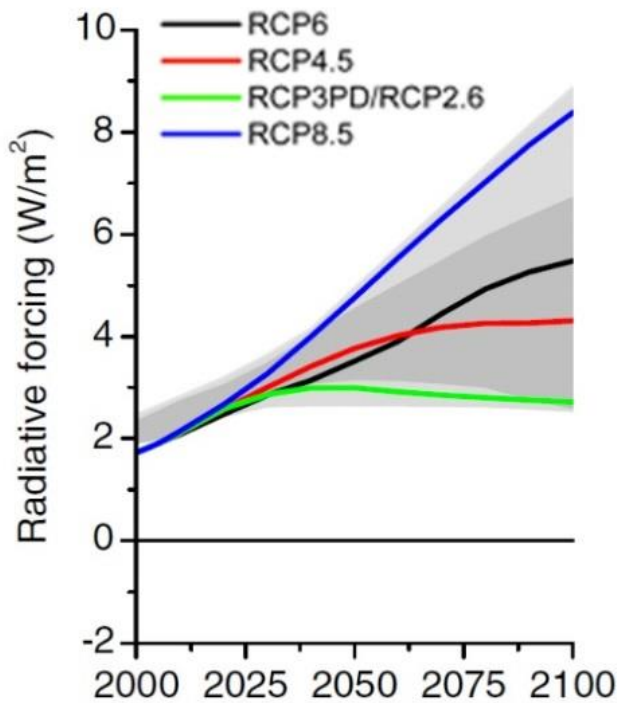
Source: IMO (2014)

Apart from different expectations regarding the future energy efficiency improvements of the fleet, the different projections presented in the following have used different combinations of RCP and SSP or alternative growth scenarios to derive the fleets' future activity. In the Annex (chapter 8), you can find an overview of the according combinations.

2.2.1.2 RCP, SSP and alternative growth scenarios

Four RCP scenarios (RCP2.6; RCP4.5; RCP6.0; RCP8.5), named according to their 2100 radiative forcing levels (Figure 27) have been selected to represent a broad range of climate outcomes as part of IPCC's Fifth Assessment Report.

Figure 27: Representative Concentration Pathways



Source: van Vuuren et al. (2011)

They have been derived with different models and under different scientific, economic, and technological assumptions (IIASA 2018).

Of the four RCPs, RCP2.6 is the only concentration pathway for which it is likely that the temperature increase stays below 2°C (IPCC 2014).⁴ In the next section, energy demand scenarios for the shipping sector that are based on RCP2.6 will therefore be considered in depth.

Five SSPs have been developed to complement the RCPs (Table 7). They describe potential major global developments including population development, urbanization and economic development (GDP) which will, in combination, lead to different challenges for mitigation and adaptation to climate change (Riahi et al. 2017). As long as the according climate policy can effectively be implemented, different SSPs can therefore be consistent with the same concentration pathway. In Table 7, the names and short descriptions of the

⁴ A temperature change of 1.5-1.7°C in 2100, not considering the carbon cycle and climate system uncertainties.

five SSPs are given; the names of some of the energy/emissions scenarios listed in Table 9 are thus based on the underlying SSP name.

Next to the SSP scenarios developed by the IPCC, alternative growth projections are also used in some of the emission projections for maritime shipping. As mentioned above, some projections of the Fourth IMO GHG Study are based, for example, on the OECD long-term baseline projection (OECD 2018).

Table 7: SSP scenarios

SSP	Name	Description
SSP1	Sustainability	World with relatively good progress towards sustainability, resource intensity reduction and fossil fuel dependency. Strong economic growth.
SSP2	Middle of the road	Some progress towards achieving development goals. Fossil fuel dependency is slowly decreasing. Development of low-income countries proceeds unevenly.
SSP3	Regional Rivalry	Fragmented regions characterised by uneven wealth and living standards.
SSP4	Inequality	A highly unequal world in which a relatively small, rich, global elite is responsible for most GHG emissions. Mitigation efforts are low.
SSP5	Fossil-Fuelled Development	Economic growth as a solution for social/economic problems. Energy system is dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation

Sources: IMO (2014), Riahi et al. (2017)

2.2.1.3 Alternative transport work projection models

Different models can be used for the projection of the transport work of maritime shipping.

To provide an example, the Fourth IMO GHG Study employs two alternative models for the projection of the transport work related to non-energy products (IMO 2020a). Both models start with an analysis of the historical relation between transport work and a driver of demand (for example total GDP). The models also have in common that they use long-term projections of these drivers. The main difference between these two models is that

- ▶ the logistic model presumes that the relation between transport work and its driver (total GDP) can be described by a logistic curve (sometimes called an S-curve), finds the curve that best resembles historical data and uses the curve to project transport work in the future, whereas
- ▶ the gravity model presumes that transport work is a function of per capita GDP and population of the trading countries and estimates the elasticity of transport work with respect to its drivers based on panel data of bilateral trade flows.
- ▶ Transport work projections that have been made with a gravity model typically have a lower elasticity with regards to GDP than projections made with a logistics model, leading to comparably lower gravity model transport work projections.

The abbreviations G and L in the scenario names in Table 9 of the Forth GHG study indicate whether the gravity or logistic model has been used for the according transport work projection.

2.2.2 Analysis of scenarios

2.2.2.1 Method and scope

This report presents energy demand and GHG emission projections for international maritime shipping as published in the literature. No additional projections have been carried out for the aim of this study.

Several studies have projected the sector's energy demand. This chapter provides an overview of some of these projections, focusing on projections from recent studies with a global scope,⁵ a 2050 time horizon and coverage of the world fleet rather than a subset of ship types.

The studies considered in this overview are listed in Table 8. As Table 8 also shows, not all of the studies considered actually provide an explicit energy demand projection. The focus of these studies lies on GHG emissions rather than energy demand, but they can still provide useful insights for the purpose of this study.

Table 8: Studies considered and available projections per study

Study	Energy demand projection	GHG/CO ₂ projection
IMO (2020a)	X	X
CE Delft und Lee (2019)	X	X
CE Delft and Lee (2017)	X	X
DNV GL (2017a)		X
DNV GL (2017c)	X*	X

Note: *The sector's energy demand in 2050 is estimated.

Source: Authors' own compilation, see also Table 43 to Table 45 (Annex)

The Fourth IMO GHG Study is the latest emissions inventory/projection published by the IMO (2020a).

In the following, projections for the future energy demand of the maritime shipping sector are presented, differentiating between business-as-usual (BAU) and reduction/high efficiency scenarios.

Business-as-usual scenarios assume that the current policies on energy efficiency and ship emissions remain in force and that no increased stringencies or additional policies will be introduced. Reduction scenarios include either greater efficiency improvements than BAU, additional emissions controls or both (IMO 2014). These actions have the possibility of mitigating the energy and CO₂ emission increase due to the expected growth in demand for transport services. High efficiency scenarios assume a relatively high uptake of energy efficiency measures independent of the implementation of further GHG reduction measures.

The specific scenarios per study that have been accounted for are specified in Table 9. In the Annex, Table 43 to Table 45 provide an overview of the main assumptions underlying the different projection scenarios, with the focus on the respective growth scenarios. Only those scenarios have been selected for further analysis which have been determined for a world in which at least the 2°C goal is likely to be met, i.e. scenarios that have been derived based on the RCP2.6 scenario.

⁵ The projections as published in LR; SCC (2016) does not cover the entire world fleet, which is why this study is not included in the analysis.

Table 9: Scenarios considered per study and alternative fuels considered in these scenarios

Study	Scenarios considered	Alternative fuel options
IMO (2020a)	BAU scenarios considered most realistic (Figure 26 in Fourth IMO GHG Study*): SSP2_RCP2.6_G SSP2_RCP2.6_L SSP4_RCP2.6_G SSP4_RCP2.6_L OECD_RCP2.6_G OECD_RCP2.6_L	LNG and fossil methanol
CE Delft und Lee (2019)	'1.6°C - Sustainability - high efficiency' '1.6°C - Middle of the Road - high efficiency' '1.6°C - Inequality - high efficiency' '1.6°C - OECD GDP projection - high efficiency'	LNG
DNV GL (2017a)	'Moderate and high growth' (BAU) 'Moderate and high growth'	LNG, LPG, methanol (from natural gas), biodiesel, bio methanol, liquefied biogas, electricity from renewables, hydrogen, nuclear power
DNV GL (2017c) ⁶	Baseline Scenario ('remaining')	LNG, LPG, biofuels, electricity; in the baseline carbon intensity is not improved

Notes: *The abbreviations G and L indicate whether gravity or logistic model is used for the transport work projections.

Source: Authors' own compilation

2.2.2.2 Energy demand projections

In the following, the range of the energy demand projection scenarios for the maritime shipping sector – as specified in Table 9 above – will be presented (Figure 28). The focus lies on those scenarios in which the maritime transport demand for fossil energy carriers has been determined for a world in which at least the 2°C goal is likely to be met, i.e. scenarios that have been derived based on the RCP2.6 scenario (section 2.2.1.2).⁷ The highest and lowest '2°C world'-scenario⁸ are indicated with red lines in Figure 28 and the corresponding energy demand is specified in Table 10. These two scenarios are referred to as the '2°C world' scenarios in the following.

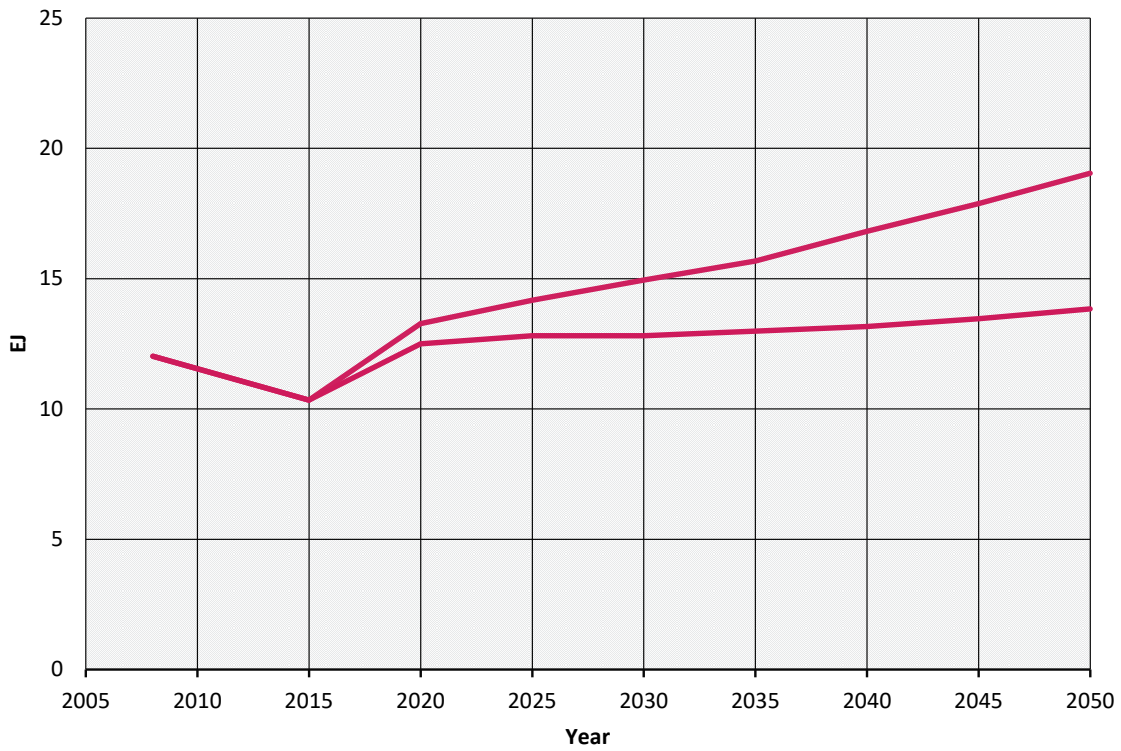
⁶ DNV GL (2020) also provides more recent CO₂ projections for maritime shipping. They differentiate thirty scenarios with three different ambition levels (no ambition/IMO ambition/defossilization by 2040), two different growth levels (low/high) and three fuel price scenarios (low biomass price/low electricity price/low blue and fossil price). The corresponding CO₂ projections are, however, only graphically presented and the sector's actual energy demand in absolute terms is not specified for the different scenarios and pathways; instead, a range of the 2050 energy demand for all low growth scenarios (10.5 to 11 EJ) and all high growth scenarios (23.5-24.6 EJ) is provided. Since we cannot allocate the energy demand to scenarios with specific ambition levels, we will not consider the study in the following.

⁷ In these scenarios, the demand for maritime transport of fossil energy carriers diminishes since the demand for fossil energy drops.

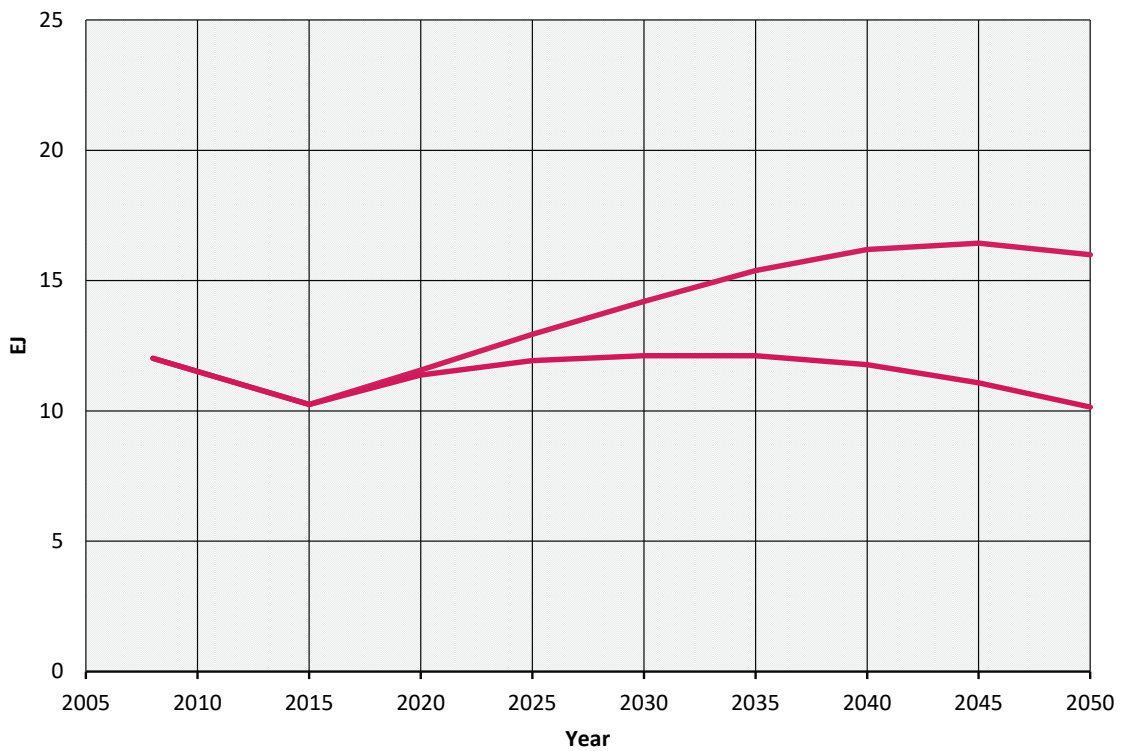
⁸ Highest and lowest scenario in terms of highest and lowest 2050 CO₂ emission levels.

Figure 28: Energy demand projections, highest and lowest '2°C-world'-scenarios

Energy demand BAU projections



Energy demand projections - high efficiency scenarios



Source: Authors' own compilation based on studies specified in Table 8

All BAU projections for the maritime shipping sector considered in the study expect the 2050 energy demand of the sector to be higher than the 2008⁹ and the current level, whereas the high efficiency scenario projections suggest that the 2050 energy demand of the sector is either higher or lower than the current and the 2008 level (Figure 28). For the BAU and high efficiency scenarios which see an increase of the 2050 energy demand compared to the current level, the expected increase of the energy demand varies greatly between the scenarios, with the spread increasing with the time horizon. The high efficiency scenario with the lowest 2050 energy demand level expects the 2050 energy demand to be approx. 16% below the 2008 level.

For the '2°C world' scenarios it holds (Table 10) that the maritime shipping sector is expected to consume between 14 and 19 EJ (BAU) and between 10 and 16 EJ (high efficiency scenario) in 2050, which corresponds to a change of the energy demand of between approx. +15% and +60% and between approximately -16% and +33% compared to the 2008 level.¹⁰

Table 10: Highest and lowest '2°C world' energy demand projections for maritime shipping

'2°C-world'-scenario	Unit	2008*	2020	2030	2040	2050
Highest Scenario BAU**	EJ	12.0	13.3	14.9	16.8	19.1
Lowest Scenario BAU**	EJ	12.0	12.5	12.8	13.2	13.8
Highest reduction/ high efficiency scenario***	EJ	12.0	11.6	14.2	16.2	16.0
Lowest reduction/ high efficiency scenario***	EJ	12.0	11.4	12.1	11.8	10.2
Highest Scenario BAU	%	0%	+10%	+24%	+40%	+59%
Lowest Scenario BAU	%	0%	+4%	+6%	+10%	+15%
Highest reduction/ high efficiency scenario	%	0%	-4%	+18%	+35%	+33%
Lowest reduction/ high efficiency scenario	%	0%	-5%	0%	-2%	-16%

Notes: *Authors' estimation based on 2008 CO₂ emissions and the 2012 CO₂/energy demand ratio provided in IMO (2014);

**As illustrated in the first graph of Figure 28;

***As illustrated in the second graph of Figure 28.

Source: Authors' own compilation

The energy demand in the *high efficiency* scenarios depends on several factors, with the assumed transport work development for ships and the ships' technical and operational efficiency improvements being two very important factors. As seen in Table 11, the highest '2°C world' reduction scenario is based on the RCP2.6 and the SSP1 scenario, resulting in a 430% increase of the transport work of the sector in 2050 compared to 2012, with an efficiency improvement of around 50% compared to 2012. The lowest '2°C world' reduction scenario on the other hand is characterised by a lower transport demand growth (in 2050 230% increase compared to 2012) and the same efficiency improvement (approx. 50% in 2050 compared to 2012).

⁹ The IMO GHG reduction target is related to 2008 emissions.

¹⁰ The lower bound 2050 level of the reduction scenarios is, at 14 EJ, higher than the lower-bound 2050 level of the BAU scenarios (13EJ). This can be explained by the use of different studies, some of which specify BAU scenarios only.

Table 11: Assumptions with regards to major determinants

'2°C world' scenario	Transport work development for ships		2050 efficiency improvements
Highest reduction/ high efficiency scenario	RCP2.6 SSP1	+430% in 2050 relative to 2012	48% relative to 2012
Lowest reduction/ high efficiency scenario	RCP2.6 OECD GDP projection	+230% in 2050 relative to 2012	48% relative to 2012

Source: Authors' own compilation

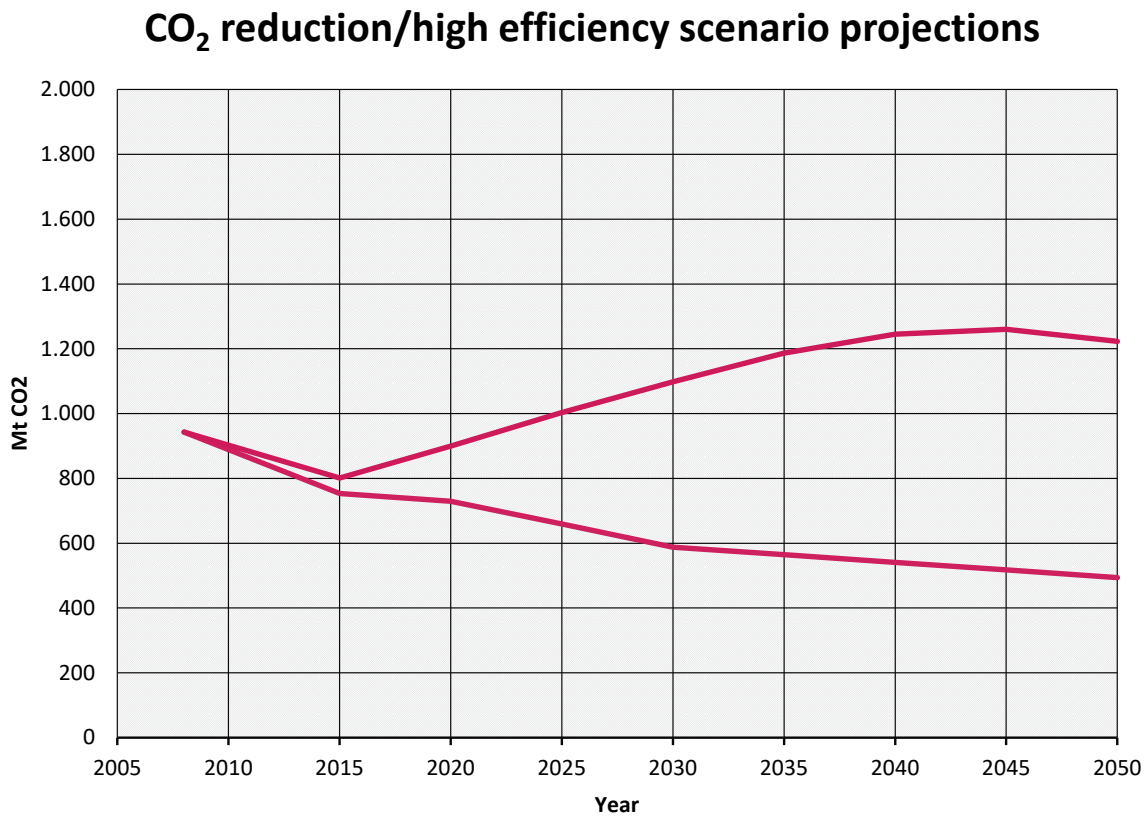
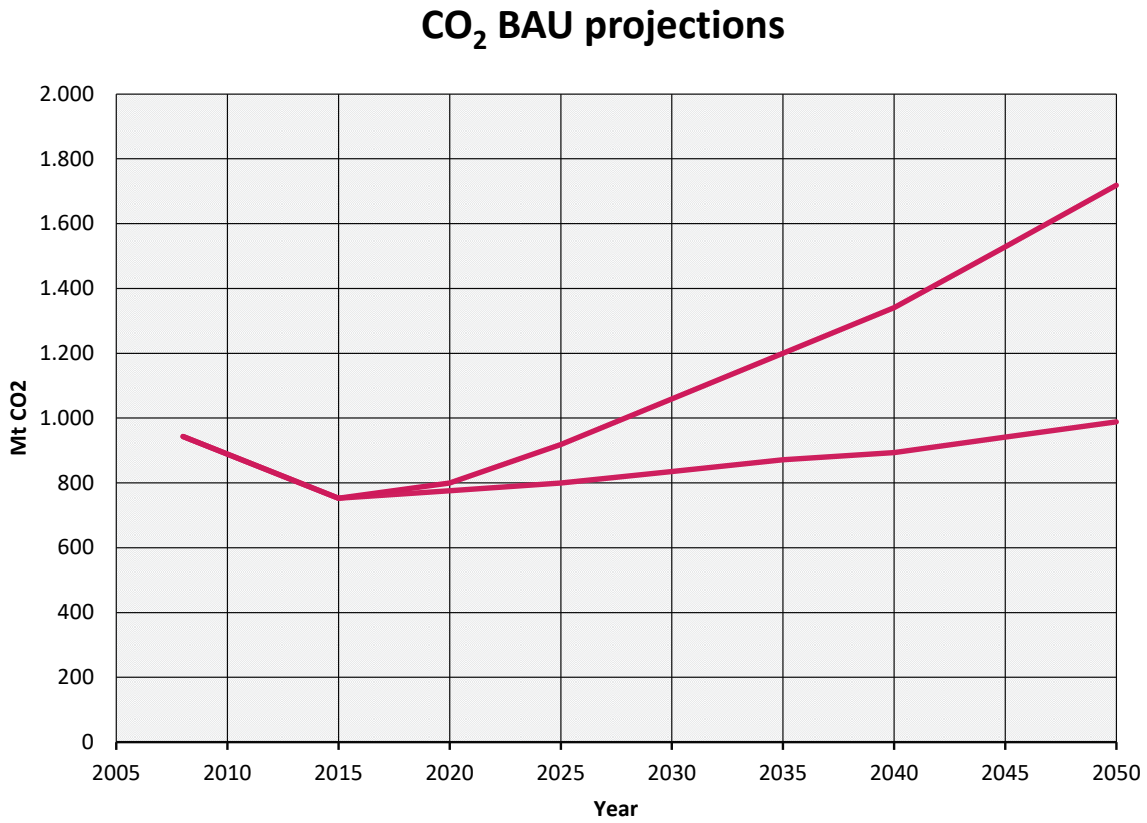
2.2.2.3 CO₂ emission projections

All of the studies considered include a GHG or CO₂ emission projection for maritime shipping, whereas only some energy demand projections (Table 8). The number of scenarios considered here is thus higher than in the previous section.

Compared to 2008 and current levels, all CO₂ BAU projections show an increase of the CO₂ emissions of maritime shipping up to 2050 (Figure 29). Some CO₂ reduction scenarios show a decrease of the CO₂ emissions of maritime shipping until 2050 if compared to 2008 and current emissions levels. For some scenarios, the emission reduction is higher than the energy demand reduction which can be explained by the scenarios' assumptions with regards to the availability and costs of low carbon fuels (Table 9).

The figure consists of two graphs. They show CO₂ emissions projection scenarios for the maritime shipping sector.

Figure 29: CO₂ emissions projections [highest and lowest '2°C world' scenarios]



Source: Authors' own compilation based on studies specified in Table 8

The highest '2°C world' *reduction* scenario (Table 12) expects the CO₂ emissions of maritime shipping to amount to approx. 1 220 Mt in 2050, which would be an increase of about 30% compared to 2008. The lowest '2°C world' *reduction* scenario expect the CO₂ emissions of maritime shipping to amount to approx. 490 Mt, which would constitute a decrease of about 48% compared to 2008 emissions.¹¹

Table 12: Highest and lowest '2°C world' CO₂ emission scenarios for maritime shipping

'2°C-world'-scenario	Unit	2008*	2020	2030	2040	2050
Highest BAU**	Mt	945	800	1 059	1 340	1 720
Lowest BAU**	Mt	945	775	835	895	990
Highest reduction/ high efficiency scenario***	Mt	945	900	1 100	1 245	1 220
Lowest reduction/ high efficiency scenario***	Mt	945	730	590	540	490
Highest BAU	%	0%	-15%	+12%	+42%	+82%
Lowest BAU	%	0%	-18%	-12%	-5%	+5%
Highest reduction/ high efficiency scenario	%	0%	-5%	+16%	+32%	+30%
Lowest reduction/ high efficiency scenario	%	0%	-23%	-38%	-43%	-48%

Notes: *IMO (2014);

**As illustrated in the first graph of Figure 29;

***As illustrated in the second graph of Figure 29.

Source: Authors' own compilation

Since the highest '2°C world' CO₂ reduction scenario is the same as the highest '2°C world' energy demand reduction scenario, the major underlying assumptions (Table 13) are the same. For the lowest '2°C world' CO₂ reduction scenario, which is the moderate growth scenario as presented in DNV GL (2017a), growth rates are assumed to be equal to or lower than the growth rates as used in DNV GL's high growth (RCP2.6; SSP3) scenario and it is assumed that transport work increases by 31% between 2016 and 2050. Compared to the base year 2016, the efficiency of ships is assumed to improve by approx. 50% in 2050, considering speed reduction and other energy efficiency measures. Compared to the 2050 BAU emissions, 22% of the emissions reductions can be attributed to efficiency improvements, whereas almost 30% of the emissions reductions can be attributed to speed reduction and 16% to alternative fuels.

The question of whether or not post-fossil fuels are expected to be used naturally has an impact on the expected CO₂ emissions of the sector (see Table 9 for the corresponding assumptions per study). To a large extent, this explains the relatively high CO₂ emissions in the BAU scenarios and in the highest reduction/high efficiency scenario as well as the relatively low CO₂ emissions in the lowest reduction/high efficiency scenario. There are recent projections available in the literature that expect the sector to decarbonize by 2050. The focus of these studies lies on the expected mix of post-fossil fuels in 2050 rather than on the sector's CO₂ emissions.

¹¹ Note that in the underlying studies, the 2012 values deviate from each other.

Table 13: Assumptions relating to major determinants

'2°C world' scenario	Transport work development for ships		2050 efficiency improvements
Highest reduction/ high efficiency scenario	RCP2.6 SSP1	+430% in 2050 relative to 2012	48% relative to 2012
Lowest reduction/ high efficiency scenario	Equal or lower growth compared to High Growth (RCP2.6; SSP3) scenario	+31% in 2050 relative to 2016*	50% relative to 2016

Notes: *The carbon intensity is assumed not to change over time in the baseline– the growth of the transport demand thus corresponds to the gross growth of the emissions as specified in Figure 6 in DNV GL (2017b).

Source: Authors' own compilation

2.2.3 Summary and conclusions

This report presents and analyzes energy demand and GHG emission projections for international maritime shipping as published in the literature. The main focus lies on '2°C world' scenarios, in which the future transport demand of maritime shipping is determined under the assumption that the global 2°C goal is likely to be met.

For these 2°C world' scenarios we find that the 2050 energy demand is expected to range from 14 to 19 EJ in the BAU scenario and from 10 to 16 EJ in the reduction scenario (Table 14). This constitutes an increase of 15% to 59% compared to 2008 in the BAU case and constitutes, compared to 2008, either a 16% decrease or a 33% increase of the energy demand in 2050 in the reduction scenario.

Table 14: Summary of the energy demand and CO₂ emission projections for shipping

'2°C world' scenarios	BAU scenarios	Reduction scenarios
2050 energy demand projections	14-19 EJ (+15 - +59% compared to 2008)	10-16 EJ (-16 - +33% compared to 2008)
2050 CO ₂ emissions projections	990 – 1 720 Mt (+5 - +82% compared to 2008)	490 – 1 220 Mt (-48 - +30% compared to 2008)

Source: Authors' own compilation

The CO₂ emissions projections deviate from the energy demand projections for two reasons. Firstly, more CO₂ emissions projections than energy demand projections have been published, with the consequence that the results are not directly comparable. Secondly, some scenarios assume that the carbon intensity of the sector in terms of CO₂ emissions per unit of energy demand improves over time, e.g. by the use of alternative fuels. The CO₂ emission increase up to 2050 compared to 2008 levels might therefore be lower than the 2050 energy demand increase.

For these 2°C world' scenarios we find that the 2050 CO₂ emissions of international maritime shipping is expected to range from 990 to 1 720 Mt in the BAU scenarios and from 490 to 1 220 Mt in the reduction scenario (Table 14). This represents an increase of 5 to 82% compared to 2008 in the BAU case and constitutes, compared to 2008, either a 48% decrease or a 30% increase of the CO₂ emissions in 2050 in the reduction scenario.

It can thus be concluded that in the most optimistic scenario, total annual GHG emissions are nearly reduced by 50% by 2050 compared to 2008. However, in this scenario the possibility of using alternative fuels has already been considered (DNV GL 2017c, Table 9). The most optimistic '2°C world' scenario in which the use of alternative fuels has not been considered results in a decrease of CO₂ emissions in 2050 of approx. 18% compared to 2008. The remaining 32% reduction (approx. 305 Mt) would need to be achieved

by means of innovative measures, including post-fossil fuels. If the remaining reduction was, in this most optimistic reduction scenario, to be achieved by means of post-fossil fuels only, approx. 4 EJ of post-fossil fuels would be required to meet the 50% emissions reduction target. To meet the 70–100% emission reduction target, 6.5 to 10.2 EJ of post-fossil fuels would be required.

To put this in perspective for Germany: for nationally-induced international shipping, it has been estimated that if Germany followed a development path towards a resource-efficient and greenhouse-gas-neutral Germany by 2050, approx. 0.036-0.054 EJ of power-to-liquids (PtL) fuels would be required by the sector (UBA 2019a).

2.3 Aggregate projections

Table 15 provides a summary of the global demand projections of various studies for global aviation and shipping. Since the analyses of these projections were conducted before the outbreak of the Covid-19 pandemic, they do not take into account the pandemic's impact (chapter 0).

Table 15: Projected final energy demand of aviation and shipping

	Unit	2020	2025	2030	2035	2040	2045	2050
Aviation & shipping								
High	EJ	27.4	31.5	36.1	41.0	46.5	51.7	57.9
Low	EJ	26.9	28.9	31.1	33.1	35.2	37.0	39.0
Aviation (Figure 22)								
ICAO LTF 2018 - Low Efficiency	EJ	15.8	18.6	21.9	25.8	30.3	35.6	41.9
ICAO LTF 2018 - High Efficiency	EJ	15.5	17.1	19.0	21.1	23.4	26.0	28.8
Shipping (Figure 26, Table 26)								
Highest red scenario	EJ	11.6	12.9	14.2	15.2	16.2	16.1	16.0
Lowest red scenario	EJ	11.4	11.8	12.1	12.0	11.8	11.0	10.2

Source: Author's own compilation

In 2020, aviation and maritime shipping currently consume about 27 EJ combined. Depending on which 'additional policies' projections materialize, the combined demand of both sectors could grow by 45% (low scenario) or by more than double by 2050 (high scenario).

GHG emission projections depend on many assumptions, particularly in terms of mitigation policies and their stringency. They cannot, therefore, be compared directly. However, we can estimate how much CO₂ would be emitted when the fuel demand provided in Table 15 would, as in the past, be fully supplied by fossil fuels.

Table 16: Projected CO₂ emissions of aviation and shipping from fossil fuels

	Unit	2020	2025	2030	2035	2040	2045	2050
Aviation & shipping								
High	Mt	2 018	2 316	2 650	3 003	3 404	3 778	4 219
Low	Mt	1 976	2 124	2 285	2 423	2 576	2 699	2 841
Aviation								
ICAO LTF 2018 - Low Efficiency	Mt	1 131	1 331	1 565	1 841	2 166	2 547	2 996
ICAO LTF 2018 - High Efficiency	Mt	1 105	1 226	1 360	1 509	1 675	1 858	2 062
Shipping								
Highest red scenario	Mt	886	986	1 085	1 161	1 238	1 230	1 223
Lowest red scenario	Mt	871	898	925	913	902	841	779

Source: Author's own compilation

In 2020, CO₂ emissions of aviation and shipping account for approx. 6% of global CO₂ emissions from fuel combustion in 2018 (IEA 2021a). Aviation and shipping emissions projected for 2050 would account for 8.5% to 12.6% of global CO₂ emissions in 2018.

3 Political action fields

The aim of this chapter is to identify existing policy tools that will enable a climate-neutral, post-fossil energy supply for shipping and aviation and to analyze which actors can implement these policies.

As a first step, the key barriers to the uptake of post-fossil fuels in shipping and aviation are identified and analyzed (section 3.1). This assessment is a basis for the development of policies to overcome the identified hurdles and to allow for a quicker market uptake of such fuels. A transition can only be achieved after all relevant obstacles will have been overcome.

In a second step, we identify policy instruments that can help these barriers to be overcome (section 3.2). In a third step, we analyze which actors could implement such instruments (section 3.3). As a last step, we draw conclusions from the previous analyses (section 3.4).

3.1 Barriers to the uptake of post-fossil fuels

3.1.1 Aviation

3.1.1.1 Introduction

Compared to, for example, rail or road traffic, air transport is more difficult to decarbonize (e.g. ICCT 2019). According to a number of studies (e.g. Schmidt et al. 2016; ICCT 2019), an increasing use of e-fuels can, however, be regarded as a promising long(er)-term strategy for significantly reducing carbon emissions in the aviation sector. This requires the availability of electricity from renewable sources.

Due to the long lifecycles of existing infrastructures, aircraft types and (engine) technologies, combined with a (still) very limited range of applications for new technologies (like the direct use of renewable electricity for electric propulsion) and a need for globally uniform technical and operational standards and procedures, it would be too costly to achieve a significant transition to post-fossil forms of energy supply like hydrogen in the foreseeable future. In addition, given the time span to introduce entirely new aircraft designs based on hydrogen into commercial operation of at least 20 years and the limited remaining carbon emissions budget available for the aviation sector, focusing on a hydrogen path rather than a drop-in fuel path would most likely result in significant "waste" of this carbon budget. In other words, even though post-carbon e-fuels are still quite expensive today, they are more likely to provide aviation's contributions to global efforts to reduce CO₂ emissions much earlier than any that arise from a hydrogen path.

Moreover, it is difficult to find an energy carrier that has similar characteristics to jet fuel with regards to energy content, usability and technical viability. In this regard, the aviation system differs from ground transport, where even at today's technological level the direct use of electricity as an energy carrier can be regarded as a proven concept. Finally, these technological challenges have to be tackled against the background of high long-term demand growth (section 2.1), which can be assumed even for a post-COVID-19 world.

The need for a market-based measure, which had been acknowledged even at ICAO level where it had led to the genesis of CORSIA, underline that other measures (like new technologies and operational improvements) are insufficient to keep annual carbon emissions at constant levels (CNG 2020 goal), let alone to really achieve a net decrease in emissions. Even the European aviation industry considers the need for alternative fuels as the only way to reducing climate impacts of aviation, as advances in aircraft technology alone will not be able to reach a sustainable aviation system. This position was outlined in a letter by the European Advanced Biofuels Flightpath Initiative, which consists of Air France/KLM, IAG Group, Lufthansa, Airbus and others, to the stakeholders of the EU RED II Trialogue in March 2018 (Flightpath 2020 2018).

Similar to biofuels, e-fuels have the advantage that existing infrastructures, vehicles and engines can be used further – at least up to certain drop-in levels (e.g. Schmidt et al. 2016). Furthermore, a transition towards e-fuels can take place gradually as blending with conventional jet fuel is possible. As more e-fuel

quantities become available in the future, the fuel blends actually used could have higher synthetic shares as time progresses.

Against this background, this chapter will focus on barriers to the use of e-fuels in aviation, and on potential policies to overcome such barriers, while alternative technology options are not further investigated. However, as hydrogen is needed to produce synthetic e-fuels, any increasing use of synthetic fuels is on a similar technological pathway as the direct use of hydrogen. There will likely be synergies between the e-fuels and hydrogen pathways in a way that parts of the process chain could later be used for the direct use of hydrogen as well. In other words, both technology pathways are going in similar rather than in opposite directions, with the result that a bifurcation at a later stage would still be possible. Based on these considerations, we focus on the e-fuels pathway and do not further discuss at this stage the hydrogen pathway (on the prospects of hydrogen-powered aircraft, see e.g. Khandelwal et al. 2013).

The structure of this chapter is as follows: The analysis starts with a review and mapping of the main barriers to the use of e-fuels in aviation. This is followed by a discussion of potential policies to overcome such barriers. This discussion includes a brief review of each policy we have identified, along with a discussion of its pros and cons. Finally, the chapter concludes with a stakeholder analysis, which discusses the potential and suggested role of each stakeholder group in setting up a roadmap for the increasing use of e-fuels in aviation.

3.1.1.2 Barriers to the use of e-fuels in aviation

Based on data and literature analyses as well as views collected from stakeholders,¹² we have compiled a number of key barriers to the use of synthetic e-fuels in the air transport sector: high costs and the lack of a political roadmap or strategy which collide with established technologies and associated path dependencies. Figure 30 provides an overview of the main barriers.

Figure 30: Barriers to the introduction of e-fuels in air transport



Source: Author's own compilation

¹² On 04/12/2018, we were able to collect views from the following stakeholders during the BDL Forum 'Luftverkehr und Umweltschutz' in Berlin: Lufthansa Group, Mineralölwirtschaftsverband and atmosfair, a non-profit climate protection organization providing offsetting solutions to the air transport and travel trade industries.

Technological issues

In general, any provision of other jet fuel types which do not meet the globally relevant fuel standards would raise the question of compatibility and probably require a costly, ubiquitous duplication of fuel provision infrastructures. The same applies to the introduction of engines that would require other types of fuel. Based on this, we can preliminarily conclude that a successful market entry of new fuel types can only be achieved in the case of full compatibility with existing Jet A/Jet A-1 fuels, to allow for blending.

Like the global air transport system as a whole, energy supply to aviation is a well-tailored running system characterized by the ubiquitous availability of jet fuel compliant with international standards (mainly Jet A in the US, Jet A-1 outside the US, and TS-1 in the former Soviet states) for gas-turbine-powered aircraft. These fuel types were first established at the end of World War II, while details of specifications were adjusted subsequently. The above standards mainly differ with regard to their flash point minima and/or freeze point maxima but are compatible with virtually all current and historic turbofan and turboprop aircraft. In contrast, piston engines (spark ignited internal combustion engines to propel aircraft), which are commonly found in historic and light aircraft but are barely used in commercial air transport, make use of avgas, which is a variety of gasoline with high octane number and contains tetraethyl lead. Due to the small market volume,¹³ avgas will not be considered further in this study.

The characteristics of Jet A, as supplied in the USA, must reach ASTM International (2019a) specification D1655, while the characteristics of Jet A-1, supplied mostly outside the USA, are additionally specified in British specification DEF STAN (UK Defence Standardization) 91-91 and IATA Guidance Material (Kerosene Type), NATO Code F-35 standards (e.g. ASTM International 2019a; Aviation Jet Fuel Information 2019).

ASTM D7566 provides standards for the manufacture of aviation turbine fuel, consisting of conventional and synthetic blending components (ASTM International 2019b). Its annexes contain specifications for the different pathways that have been approved as shown in the following table.

Table 17: ASTM D7566 approved sustainable jet fuels

Process	ASTM D7566 Annex	Max. blending Level	Publication
Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene (FT SPK)	Annex A1	50%	2009
Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids (HEFA SPK)	Annex A2	50%	2011
Synthesized Iso-Paraffins from Hydroprocessed Fermented Sugars (HFS SIP)	Annex A3	10%	2014
Fischer-Tropsch Synthesized Paraffinic Kerosene with Aromatics (FT SPK/A)	Annex A4	50%	2015
Alcohol-to-jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Annex A5	50%	2016
Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	Annex A6	50%	2020
Synthesized Paraffinic Kerosene from Hydrocarbon-hydroprocessed Esters and Fatty Acids (HC-HEFA-SPK)	Annex A7	10%	2020

Source: ICAO 2020b

¹³ Sales of 7 543 t of avgas compared to 10.2 million t of jet fuel in Germany in 2019 according to the official mineral oil data (BAFA 2019).

Sustainable aviation fuels (SAF) have to be blended with conventional jet fuel to meet the requirements of a minimum aromatics content as outlined in ASTM D7566, whereby the blending of FT SPK, HEFA SPK, SPK/A and ATJ-SPK is currently allowed up to 50% with conventional jet fuel and 10% for SIP SPK (IATA 2015). Jet fuel specifications prescribe an aromatics content of between 8% and 25%. The aromatics, which are included in kerosene, are not required for the combustion process but for the fuel system. Currently used O-Rings are guaranteed to seal properly with a sufficient share of aromatics only. Previous studies have come to the conclusion that without a sufficient exposure to aromatics, they might, for example, shrink, harden or fail (Liu et al. 2011; Graham et al. 2013). However, there are ambiguous opinions in the aviation industry on this requirement. While Airbus started flight-tests with 100% sustainable aviation fuel based on the HEFA production process in March 2021,¹⁴ Boeing has announced that the full range of aircrafts of the American manufacturer will only be able to operate on 100% sustainable aviation fuels from 2030 onwards.¹⁵

Based on this literature-based information, we conclude that – technologically – there is already enough scope for a significant and ubiquitous drop-in use of e-fuels in international air transport – at least through blending. As a result, hardly any duplication of infrastructures at the airport level or changes to the operational routines at the airline levels would become necessary.

In the long(er) term, there shall even be sufficient scope for the use of pure e-fuels, without any blending. We talked to experts within DLR about this. Apparently, the above-mentioned problem with the O-Rings in the context of the use of aromatic-free fuels occurred during a measurement campaign conducted by NASA, followed by tests in which O-Ring materials reacted differently to aromatic-free fuels (Liu et al. 2011). DLR, however, also got feedback from Airbus and Boeing who could not confirm the NASA-observations – which also stem from an old DC-8 aircraft – and who believe that a higher-than-50% blending quota could easily be adopted once there is sufficient demand for such fuels. This was demonstrated by Airbus with the above-mentioned flight tests in March 2021.

Apart from this, however, Searle et al. (2019) point to the fact that certification can be a barrier for novel fuels, as ASTM requires “up to 235 000 gallons of new jet fuels to be tested”, which may be a too large amount of new fuel to be produced just for R&D purposes. If new fuels are produced in similar or very similar ways compared to fuels which are already approved, this hurdle is, however, reduced to only some 10k or 100 gallons of fuel to be tested respectively (Searle 2019), based on data from the Commercial Aviation Alternative Fuels Initiative (2013).

In the current certification situation, FT SPK is probably the most suitable route for PtL production. Although ATJ-SPK is also theoretically feasible with feedstock coming from power-based production processes, the currently-certified inputs isobutanol and ethanol are more complicated to produce. A much more efficient route would require methanol as input, but currently, a major challenge in the context of PtL fuel production is that jet fuels produced via the methanol route are still not yet covered by ASTM D7566.

¹⁴ Airbus, 18/03/2021, Aviation leaders launch first in-flight 100% sustainable aviation fuel emissions study on commercial passenger jet, <https://www.airbus.com/newsroom/press-releases/en/2021/03/aviation-leaders-launch-first-inflight-100-sustainable-aviation-fuel-emissions-study-on-commercial-passenger-jet.html>.

¹⁵ Boeing, 22/01/2021, Boeing Commits to Deliver Commercial Airplanes Ready to Fly on 100% Sustainable Fuels, <https://boeing.mediaroom.com/2021-01-22-Boeing-Commits-to-Deliver-Commercial-Airplanes-Ready-to-Fly-on-100-Sustainable-Fuels>.

High relative cost of e-fuels

Fuel costs are among the main cost items for most airlines, if not the largest one. Cost share averages reported by some 28 IATA airlines for 2012, provided by IATA, indicate that fuel made about one third of total airline input costs (Ferjan 2013), while other sources name ranges of between 15% and 40% (e.g. Terwel et al. 2019). The actual impact of the fuel costs – in proportion e.g. to airline revenues, can vary immensely between airlines: For the Lufthansa network airlines (Lufthansa German Airlines, Swiss, Austrian Airlines), fuel costs in 2017 (4.172 billion EUR) reached some 18% of the revenues (23.3 billion EUR) (Lufthansa Group 2018), while this share amount to, for example, 27% in the case of Ryanair (Ryanair 2018).

This starting point already leads to the main barriers to the use of PtL fuels and other sustainable aviation fuels: in an unregulated market, fuel suppliers and airlines are unlikely to blend conventional fuels with more environmentally-friendly fuel types, unless the latter were available at similar or lower costs, and in existing distribution channels.

Hence, in a free market, to be attractive for suppliers and users, the cost of synthetic fuels would have to be roughly equal to or lower than those for conventional fuels – at least if identical performance levels are assumed; in cases in which synthetic fuels show a higher performance level, e.g. stemming from higher energy density, less pollutant emissions¹⁶ etc., small price premiums could still be accepted by the market. Existing regulatory costs would also have to be considered, e.g. the obligation to offset certain shares of CO₂ emissions from conventional fuel under the CORSIA¹⁷ scheme. If the EU ETS were extended to non-CO₂ effects, the relative advantage of PtL fuels would further increase.

However, as we will also illustrate below, due to a more complicated, multi-stage production process, required feedstock and (input) energy, and a lack of large-scale plants, e-fuels come at significantly higher cost than conventional fuels. Also, they are expected to remain more expensive in the future despite efforts to lower unit costs by increasing economies of scale and introducing advanced technologies:

Neste's MY Renewable Jet Fuel, produced in a HEFA/HVO production process, is considered to be 3-4 times more expensive than traditional jet fuel (Berti 2018). Several studies expect considerable reductions in production costs for e-fuels in the medium and long term. However, the spans of current and expected production costs are relatively wide and range from some 4.00 to 1.75 €/l today and 3.50 to 0.85 €/l in 2050 (Figure 37). This compares to an average of 0.38 €/l for conventional jet fuel on average between 2015 and 2019 (Figure 35).

For the competitive position of PtL fuels in 2050, the future price of conventional fuel must be considered, which is a difficult endeavour, given various factors which will determine the fuel price for end users. Taxation of petroleum-based fuels could have an impact as well as emissions trading, but also the general market situation, when many other sectors will have converted from petroleum-based fuels to direct use of electricity, e-fuels or hydrogen. As a result, potential demand can be considered too low or even zero, and any e-fuel market would struggle to develop. Moreover, the relative competitiveness of e-fuels could be affected in the long term by the development of global demand for mineral oil-based fuels. With defossilization as a political objective in all areas where liquid hydrocarbons are currently being used, demand for

¹⁶ It is understood that the combustion of synthetic fuels will result in less soot particle emissions than conventional fuel, but largely unchanged emissions of CO and NO_x (Braun-Unkloff et al. 2017). However, soot emissions are not yet part of any environmental pricing scheme at airports, hence there is no direct commercial benefit for aircraft operators in using synthetic fuels in this regard.

¹⁷ From 2021 onwards, CORSIA only tackles any additional emissions – exceeding 2019 levels – from operations on international routes between participating states, but not the annual baseline of emissions achieved by 2019. As a consequence, the environmental effectiveness of CORSIA will be rather limited (Scheelhaase et al. (2018)), or – due to Covid-19 – even zero in the initial years in which global air transport volumes remain below 2019 levels.

mineral oil could drop significantly. Hence, the market price for oil could come under severe pressure and therefore widening the price gap between mineral oil-based fuels and e-fuels.

Institutional and legal barriers

Another burden is the lack of a global or at least regional strategy towards the implementation and promotion of e-fuels in air transport and elsewhere, along with required institutional frameworks in the form of regulations and clarification of potential legal issues. As explained in more detail in the following section, such strategic and political decisions would have to tackle issues such as incentives to produce and use e-fuels, carbon pricing, (blending) quotas, R&D and investment funding, and mandatory timing. Also, possible legal burdens regarding the use of e-fuels would have to be sorted out.

To reduce barriers for the use of e-fuels, various incentives or regulations would need to be applied to address the different issues and provide the required levers:

- ▶ Policies that directly raise the use of e-fuels in aviation, such as mandatory blending shares for e-fuels in jet fuel, as in Germany.
- ▶ Policies that would lower the net production costs (price) for e-fuels, and associated risks (e.g. potential ‘first mover disadvantage’) like R&D subsidies or investment aids.
- ▶ Policies that would improve the relative competitiveness of e-fuels in increasing the cost for conventional fuels, like different forms of carbon pricing for CO₂ internalization.

While this report cannot provide a deeper analysis of the **potential legal issues** associated with the introduction of synthetic fuels in the aviation sector, we assume that legal challenges will play a major role when policies would intervene with existing bilateral air service agreements governing international commercial aviation. This would particularly concern any policy involving a cross-subsidisation of e-fuel research, distribution or production in the form of surcharges, taxes or duties, which generally would need to be accepted by both parties that have concluded such a bilateral air service agreement. While it would be generally possible to design policies only addressing domestic or intra-EU flights, where a consensus might be reached more easily, for environmental and organizational reasons it would be preferable to find a solution which addresses all aspects of commercial aviation.

In order to avoid challenges to any policy promoting e-fuel development, use and production by other parties, it seems to be advisable to design policies that exert an influence on other levels, e.g. on technical specifications of fuels or fuel production, import or distribution.

While important steps have been made towards the general use of – at least – blended e-fuels (which is now possible according to ASTM and other certifications), the focus should be on the following questions:

- ▶ Can, for example, EU Member States, the legislative bodies of the EU or EASA regulate technical specifications of fuels produced or distributed in a Member State or in the EU as a whole and being used in aviation?
- ▶ To what extent could, for example, compulsory blending quotas for e-fuels, or other policies, be introduced at the national or e.g. European level(s)?
- ▶ Can, for example, EU Member States, the legislative bodies of the EU or EASA regulate fuel supply in such a way that mandatory blending quotas can be introduced, and can all airlines, also from third countries, be forced to use such fuels?

The RED II (Renewable Energy Directive, EU 2019) requires national implementation and includes aviation. Subject to more detailed legal assessments, this could be a basis for a national solution if no progress is made at the EU level.

3.1.2 Shipping

3.1.2.1 Introduction

In contrast to aviation, the use of *various* post-fossil fuels is conceivable for maritime shipping. This can be explained by two main reasons: Firstly, the maritime shipping fleet is much more heterogeneous in terms of vessel types- and sizes as well as their operational profiles. Secondly, due to air quality regulation and the heterogeneity of the sector, different bunker fuel types are currently being used (HFO, MGO, LNG, methanol, LPG, ethane) and further bunker fuel types (DME, ethanol) are being tested/considered. This has led to a variety of engines that are being used or are under development as well as to the development of engines that allow for fuel flexibility. In principle, all these bunker fuel types could thus be produced and used as e-fuels in order to decarbonize the maritime shipping sector. In addition, the use of hydrogen and other hydrogen carriers like ammonia as well as the use of fuel cells are also considered as options to decarbonize the sector.

No superior post-fossil fuel type has emerged to date and due to the heterogeneity of the sector, it can also be assumed that not just one single fuel type will prevail.

The fuel types, which are all not available as e-fuel for shipping yet, basically differ in terms of the following:

1. expected bunker prices of the e-fuels (incl. production and distribution costs) which can be expected to fundamentally deviate from their fossil counterparts;
2. costs (CAPEX and OPEX) and level of development/availability of the according systems on board the ships;
3. costs (CAPEX and OPEX) and level of development/availability of onshore distribution infrastructure;
4. degree to which the fuels have so far been embedded in rules, guidelines and standards;
5. volumetric energy carrier density.

In the context of this study, it is not possible to assess the different fuel types from the perspective of the different ship operators and this is also not the aim of the project. The goal is to rather develop a roadmap that specifies how to best promote the use of post-fossil fuels in maritime transport. To this end it is, on the one hand, important to analyse which barriers to the use of the various fuels currently exist in order to be able to establish starting points for a targeted advancement. On the other hand, it is important to discuss whether the fuel types might be associated with negative external effects which could be a reason for not encouraging the use of these fuel types.

In subsections 3.1.2.3 to 3.1.2.5, the barriers to the use of different e-fuels in maritime shipping are analyzed. A literature review has been carried out to this end.

The analysis focuses on the value chain starting with the transportation of the fuel to the ports, i.e.:

1. The transportation of the fuels to the ports;
2. the bunkering (port infrastructure and handling) and
3. the use of fuels on board ships.

The analysis is structured in the reverse order. The barriers to the production of the post-fossil fuels are analyzed in chapter 4.

It should be noted that the same barriers can play a role in different links of the value chain. For example, the barriers to the development of vessels that can transport post-fossil fuels (first link in the chain analyzed) could also play a role in the development of the according bunkering vessels (second link in the chain analyzed). In this case we will not reiterate the barrier but refer to the preceding analysis instead.

The following types of barriers are differentiated in the analysis:

- ▶ technological barriers;
- ▶ economic barriers;
- ▶ institutional and legal barriers.

In section 2.2.5, the barrier analysis is summarized and major barriers to the use of the post-fossil fuels which could be addressed are specified.

Prior to the analysis of the barriers, section 3.1.2.2 presents and explains the selection of fuels considered in the barrier analysis and discusses potential negative external effects associated with the fuel types discussed.

3.1.2.2 Fuels considered and their potential negative external effects

Fuels considered

The following post-fossil fuels are considered in the barrier analysis for the shipping sector:

1. e-diesel;
2. hydrogen (H₂);
3. ammonia (NH₃);
4. methanol/methyl alcohol (CH₃OH);
5. methane (CH₄);
6. liquefied Petroleum Gas (LPG)/propane (C₃H₈);¹⁸
7. dimethyl ether (DME; C₂H₆O).

Ammonia is an inorganic compound, containing no carbon. Methanol is an alcohol, i.e. an organic compound characterized by one or more hydroxyl (-OH) groups attached to a carbon atom of a hydrocarbon chain, with methanol being the simplest alcohol. Methane and propane are alkanes which are saturated hydrocarbons, i.e. simple organic compounds which are composed of carbon and hydrogen atoms only and molecules that have no carbon-to-carbon double bonds (Chemistry 2020). Methane is the simplest alkane, followed by ethane and propane. DME is a symmetric ether, i.e. an organic compound where an oxygen atom is connected to two alkyl groups; DME can be produced by dehydration of methanol.

Most of the selected fuels are gaseous at ambient temperature (hydrogen, propane, methane, ammonia, DME) whilst e-diesel, methanol and ethanol are liquid.

In this study, all the fuels are assumed to be neither fossil- nor bio-based; they are assumed to be based on hydrogen produced by means of renewable electricity and water electrolysis. To produce the hydrocarbons and alcohols as e-fuel, carbon would have to be captured whereas for ammonia, nitrogen would have to be

¹⁸ LPG is by definition any mixture of propane and butane in liquid form. In the USA, the term LPG is generally associated with propane. Since the boiling point of butane prevents the use of pure butane in colder climates, it can be expected that propane or propane-rich mixtures of propane and butane is used as fuel for ships DNV GL (2017b).

captured (see chapter 4 for a detailed presentation of the production of the fuel types). The CO₂ released when using hydrocarbons and alcohols as bunker fuels would thus be recycled.

As mentioned in the introduction, some of these fuel types (4.-7.)¹⁹ are already being used or are regarded as being used in shipping due to air pollution regulation. Corresponding internal and external combustion engines (ICEs/ECEs) have been or are being developed.

Since e-fuels are expected to be relatively expensive, it makes sense to consider their use in fuel cells, which are more efficient than ICE, too. The selected fuels are hydrogen carriers and could thus potentially be used in fuel cells.

Since they are hydrogen-based, the production costs of the e-fuels other than H₂ will naturally be higher than for H₂, but the fuels might have advantages compared to H₂ in terms of e.g. technology readiness of the infrastructure, liquefaction costs or lower storage space requirement per MJ/per MJ H₂. Ammonia, for example, has been advanced as a carbon-free alternative with a relatively high hydrogen content per volume unit and relatively low liquefaction costs.

Ammonia and hydrogen could, however, be used in marine ICE in the near future too, which would allow a bunkering logistic and bunkering infrastructure to be established independently of the availability of marine fuel cells.

At this point it should be noted that most studies related to post-fossil fuels in maritime shipping focus on the first four fuel types as listed above (hydrogen, ammonia, methanol, and methane). However, since engines are (readily) available that allow the use of LPG and DME and class rules have been developed, we consider the latter two fuel types relevant options too.

E-diesel, whose applicability in shipping is proven, is also less discussed in the maritime shipping literature, but must be considered as a reference point. Production costs of e-diesel are relatively high, and it remains to be seen whether the cost advantage due to the usability of the existing infrastructure is sufficient to make e-diesel a relatively cheaper solution. Apart from potential barriers related to the production of e-diesel, we only identified a regulatory barrier to the use of low-flashpoint e-diesel, like automotive diesel, in shipping, which will be discussed in section 3.1.2.3 (p. 101).

It should be noted, finally, that next to methanol, ethanol is being discussed as an alternative fuel for shipping. However, the analyses in the literature are mainly focused on the production of bioethanol and to our knowledge, no projects have been carried out to test ethanol in large marine engines. Ethanol shares many attributes with methanol, particularly in combustion systems²⁰ and they are fully mixable in the vessel's bunker tanks.²¹ This indicates that a methanol engine/system can use ethanol directly or with limited modifications which still has to be proven in practice. Due to the limited information available and due to the similar combustion properties of methanol and ethanol, we decided not to further investigate ethanol in the following.

¹⁹ The use of fossil-based methane (LNG) has already been established in maritime shipping and a small number of maritime ships are methanol-fuelled.

²⁰ Ethanol and methanol have similar octane numbers, very high heats of vaporization and low stoichiometric air-fuel ratios, with the latter two differing more than the former, see Verhelst et al. (2019).

²¹ <https://www.maersk.com/news/articles/2019/10/24/alcohol-biomethane-and-ammonia-are-the-best-positioned-fuels-to-reach-zero-net-emissions>.

Potential negative externalities

In order to assess whether the promotion of the use of specific fuels is desirable from a societal perspective, the possible negative external effects that could be associated with the use of the fuels should be taken into account. Potential risks for humans and nature are relevant in this context.

In principle, only those fuels and systems should be used whose use is associated with manageable risks. Appropriate regulations and procedures must then ensure that the risks are minimized. The according costs can be expected to vary for the different types of fuel.

In addition, the GHG emissions associated with the post-fossil fuels should effectively be zero in a decarbonized world – at least if Carbon Capture and Storage (CCS) is not considered – and their production and use should not have an adverse effect on health and/or environment.

In the following, we describe the fuels in terms of their flammability and explosion risk, in terms of their toxicity and in terms of the emissions associated with them.

It should be noted in this context that LNG-, methanol- and LPG-fuelled ships are in operation and the health and safety risks associated with these fuels can, therefore, be expected to be controllable, at least on ships with ICE engines. The same holds for ethanol, DME and ammonia in the sense that these are cargos that are transported by ships. Since there is no hydrogen-fuelled ship in operation yet and hydrogen is not shipped as cargo, the uncertainty with regards to health and safety risks are the highest here.

The risks associated with using these fuels in fuel cells have to be assessed too. DNV GL (DNV GL 2017d) has carried out a safety assessment for three different types of fuel cells (PEMFC, HT-PEMFC, SOFC) and for three different fuel types (methane, methanol, hydrogen), considering in total 148 failure scenarios for a RoPax vessel and a gas carrier. As a result, for some of the failure scenarios, further actions were recommended. For a total of 100 scenarios, additional mitigation actions were recommended. Taking these recommendations into account, the analysis team recognized that tolerable risk levels (ALARP) could be reached with respect to operational and human safety.

Regarding flammability, hydrogen, methane, propane and DME are considered *extremely* flammable gases, whereas methanol and ethanol are *highly* flammable liquid and vapour, and ammonia and diesel a flammable gas/liquid.

The auto-ignition temperature of hydrogen is relatively high, but it has much wider flammability limits (4 to 75 volume percent in air) and very little energy is required for ignition (Table 18). Hydrogen has a nearly invisible flame and is prone to detonation. Hydrogen also escapes relatively easily, increasing the likelihood for an explosion. It has been demonstrated that it spontaneously ignites on sudden release from pressurized containers. A number of incidents have been attributed to spontaneous ignition, but the mechanism responsible for these ignitions is not fully understood (HSE 2010). Ammonia has a relatively high auto-ignition temperature and its minimum ignition energy is high (Table 18). It can form explosive mixtures with air, but the lower flammability limit is relatively high, too. However, if ammonia is partially cracked to obtain a hydrogen-ammonia mixture in order to improve the combustion properties in an ICE, the flammability risk of hydrogen is given in the fuel system. DME has a relatively low auto-ignition temperature. High temperatures of some fuel cells are also associated with higher safety risks, at least if directly operated with hydrogen. Since DME has a relatively low auto-ignition temperature, this could be an issue there too. Propane, DME, vaporized methanol and ethanol are heavier than air and will thus flow along floors and tend to settle in low spots. Such accumulations can cause explosion hazards. This holds especially for LPG which has a relatively low explosion limit of about 2% (DNV GL 2017b).

Table 18: Characteristics of the fuels relevant for a safety assessment

	HFO	Methanol	Ethanol	DME	Propane	Methane	Hydrogen	Ammonia
Auto-ignition temperature [°C]	>400	440	400	240	470	595	560	630
Flammability limits, mixture with air [% by volume]	1.5-6 (typical)	6 -50	3.1-27.7	3.4-26.7	2.1-9.5	5-15	4-75	15-33.6
Flash point [°C] ²²	>60 (65-80)	9	12	(-42.2)	(-104)	(-188)	(<-253)	(<-33)
Minimum ignition energy of gas/vapour [MJ]		0.14	0.23	0.15	0.25	0.21	0.016	680
Explosion group*	IIA	IIA	IIB	IIB	IIA	IIA	IIC	IIA

Notes: *Hazard increases from IIA to IIC.

Sources: IFA 2021; WHO 2021; Dow 2020; TRIS 2015

For cryogenic stored fuel there is fire possibility as a result of having pure oxygen forming around the pipes (EEIT 2018) and risks associated with boil-off gas. In addition, there is a risk of cold burns and injuries; oxygen and nitrogen might also be frozen or condensed out of the ambient air.

Methanol, ethanol and ammonia are toxic, with ethanol being the least toxic. Methanol is toxic if swallowed, is toxic in contact with skin, is toxic if inhaled and causes damage to organs (ECHA 2018c), whereas ethanol has a low order of acute toxicity to humans by all routes of exposure (EMSA 2017). Both methanol and ethanol dissolve readily in water, are biodegradable and do not bioaccumulate. They are not rated as toxic to aquatic organisms (EMSA 2017). Ammonia causes severe skin burns and eye damage, is toxic if inhaled (ECHA 2018a) and can be lethal to humans at 2 700 ppm when exposed for a duration of 10 minutes (DUT 2019); it is also very toxic to aquatic life (ECHA 2018a). The advantage of ammonia is that it can easily be detected by its strong odour.

For comparison: residual fuel oil, currently used in shipping, is very toxic to aquatic life, is harmful if inhaled, is suspected of damaging fertility and unborn children and may cause damage to organs through prolonged or repeated exposure (ECHA 2018b). Diesel is considered toxic to aquatic life, may be harmful in contact with skin, may be harmful if inhaled, is suspected of causing cancer and may cause damage to organs through prolonged or repeated exposure (DUT 2019).

Carbon monoxide (CO) can form in (internal) reforming units of specific fuel cells (PAFC, MCFC, SOFC, HT-PEMFC) (DNV GL 2017d). CO is a poisonous, colourless, odourless and tasteless gas and is extremely flammable.

For both methane and methanol it holds that, if used in an Otto cycle combustion engine,²³ formaldehyde might be emitted (DNV GL 2016a; SINTEF 2017). Formaldehyde can be toxic, allergenic, and carcinogenic (SINTEF 2017). According to CIMAC (2014), however, aftertreatment systems for formaldehyde-oxidation are proven technology for natural gas and already in use in the gas engine market.

²² The flashpoint is defined as the temperature at which the fuel produces enough vapours to form an ignitable mixture with air at its surface. The flashpoint is always lower than the boiling point.

²³ In the Otto cycle combustion process, fuel gas is injected in the cylinder at low pressure via gas admission valves at the cylinder liner mid stroke. The lean fuel gas/air premixture is then ignited by pilot fuel. In the Diesel cycle combustion process, the fuel-gas is injected at very high pressure via the cylinder cover and burned in a gas-jet flame ignited by pilot fuel (WIN GD (2020)).

With the combustion of ammonia, NO_x emissions can occur, but could be mitigated by means of DeNO_x system. If carbon fuel is used in certain fuel cells (PAFC, MCFC, HT-PEMFC) low level of NO_x are emitted too.

For methane it holds that unburned methane can slip, especially from Otto cycle combustion engines, as well as in the supply chain, which is of concern because of the relatively high global warming potential of methane. Aftertreatment systems with catalysts to oxidize the residuals of unburned methane are not yet available for ship applications. According to MAN (2020), an oxidation catalyst is not an option for two-stroke engines because of unsuitably low exhaust gas temperatures. Exhaust gas temperatures of four-stroke spark ignition and dual fuel engines can be sufficient, but the oxidation catalyst for these engines are still under development (see, for example, IMOKAT and MariGreen projects).

Hydrogen has an indirect contribution to climate change through increasing the growth rates of methane and tropospheric ozone. It is very likely that it has a small, warming effect, but there is still a high level of uncertainty regarding the exact global warming potential of hydrogen (BEIS 2018). This means, however, that hydrogen slip – just like methane slip – would have to be minimized.

Ammonia is known to have an indirect impact on ozone depletion through the formation of nitrous compounds in the atmosphere. These are currently considered a negligible contribution to ozone depletion, but will need to be considered for large scale ammonia utilization (Valera-Medina et al. 2018).

The combustion of fuels leads to the formation of nitrous oxide (N₂O), which is a greenhouse gas as well as an ozone depleting gas. As a GHG, N₂O has a very high global warming potential and engines should, therefore, be optimized to minimize N₂O emissions. Due to the higher combustion temperature, the diesel-cycle process is probably better suited than the Otto cycle process to preventing N₂O generation. For the ammonia internal combustion engines that are under development, N₂O seems to be a major challenge and the technology to clean the exhaust gas accordingly is not proven yet.²⁴

3.1.2.3 Barriers to the use of e-fuels on board ships

Technological barriers

In this subsection the technological barriers that might prevent the use of post-fossil fuels on board ships are analyzed. This analysis is divided into two parts.

The first part focuses on the use of the post-fossil fuels in ICE/ECE. The ICE/ECE in which the fuels can be used in principle and the level of development of these engines are analyzed. Per fuel type the technical issues are discussed.

The second part focuses on the use of the post-fossil fuels in fuel cells. The fuel cells in which these fuels can be used in principle are analyzed and, in addition, the degree of development and the technical issues of the different fuel cells are discussed.

In both sections, the focus of the analysis is on the use of post-fossil fuels for propulsion purposes and thus on main engines rather than on auxiliary engines. Concepts are probably transferable, but auxiliary engines can also be more easily powered with the help of batteries and renewable energy sources such as wind and solar.

Internal/external combustion engines

²⁴ DGV, 08/05/2020, The role of combustion engines in decarbonization – seeking fuel solutions, <https://www.dnv.com/expert-story/maritime-impact/The-role-of-combustion-engines-in-decarbonization-seeking-fuel-solutions.html>.

Two main types of marine propulsion engines are currently used in the maritime industry, namely internal combustion engines (ICE) and external combustion engines (ECE).

Liquid fuels are used in ICE compression ignition engines, whereas gaseous fuel in ICE spark ignition engines.²⁵ Dual fuel engines are compression ignition engines that can run on both liquefied gaseous fuels and liquid fuels, but if they run on liquefied gaseous fuels like LNG, they require a pilot fuel to start the combustion process.

Two- and four-stroke ICE compression ignition engines have been the dominant engines in the sector for a long period of time. Dual fuel ICE engines, which give fuel flexibility, have gained popularity with stricter air pollution regulation.²⁶ The dual fuel engines are available as two-stroke, diesel cycle engine and as two- and four-stroke, Otto cycle engine. If fuelled by LNG, methane slips from the Otto cycle engines.

Diesel electric engines are comprised of diesel generators that produce electricity to be fed to run an electric motor, which in turn runs the propeller via a gearbox. Diesel electric engines have gained popularity since they are energy-efficient engines for ships with flexible power demand as it provides the right amount of power and torque to the propeller in different operational loads.²⁷ For ships sailing at fixed operation load (SMCR), diesel electric engines are less energy-efficient and not per se more efficient compared to diesel mechanical engines.

Gas turbines are ICEs while steam turbines and Stirling engines ECEs. Gas turbines are used by jet aircraft but can also be used by ships. Currently, gas turbines and Stirling engines are mainly used by Navy ships. There are some commercial ships that use a combined gas and steam (COGES) system, e.g. cruise ships and fast ferries (Packalén und Nord 2017); moreover, a recently designed LNG carrier to be powered by such a system using LPG has received its Approval in Principle,²⁸ but total numbers are negligible. Ships with steam turbines are specialist vessels such as nuclear-powered vessels and certain merchant vessels, mainly LNG carriers, where the cargo can be used as bunker fuel. Indeed, most LNG carriers have historically burned boil-off gas in steam turbines (ICCT 2020d) and approx. 230 steam-turbine-driven LNG carriers are in operation. Nowadays, ships have other options to using LNG, including marine diesel engines which are more efficient (ICCT 2020d). Gas turbines are currently also less efficient than their equivalent diesel engines and expensive to operate due to the higher distillate fuel prices and poor part load performance (Sayma 2017). However, fuel flexibility may offer new opportunities for gas turbines (Sayma 2017).

Table 19 provides an overview of the (expected) engine availability for the different post-fossil fuels.

²⁵ Gaseous fuels cannot be used in compression ignition engines because compression ignition engines need a compression ratio above 18, whereas spark ignition engines can work with fuels such as gasoline (petrol), which has a compression ratio of 8-10.

²⁶ Dual fuel engines give ship owners the flexibility to operate a ship on two alternative fuels, e.g. HFO and LNG. This is, for example, relevant for ships that are partly operating in Emission Control Areas (ECAs) and want to switch fuel when entering an ECA.

²⁷ The power efficiency of generators is usually considered to be approx. 96% and the power efficiency of the electric motor is also considered to be 96% (under the assumption that the generator is running at the optimal load of 80-85% SMCR). This leads to lower specific fuel oil consumption compared to diesel mechanical engines.

²⁸ Approval in Principle (AIP) is a framework used to review and approve innovative and novel concepts not covered by traditional classification prescriptive rules, with the result that a level of safety in line with the current marine industry practice is provided. The AIP concept is a risk-based approach to classification, which allows for new designs and novel concepts to be validated with safety equivalencies (RINA (2017)).

Table 19: (Expected) engine availability for the different post-fossil fuel types

Combustion methodology	Main engine types	Mechanically compatible with	Engine availability
ICE - Compression ignition	Mono fuel engine	Diesel	Available (2-stroke slow speed, 4-stroke medium and high speed)
		DME	Not available, but should be possible
	Dual fuel pilot fuel ignition (pilot fuel/2 nd fuel options not specified)	Diesel	Available (2- and 4-stroke); use of low-flashpoint diesel might require minor adjustment.
		Methane	Available (2- and 4-stroke)
		Ethane	Available (2-stroke)
		Methanol	Available (2-stroke; retrofit: 4-stroke)
		Propane	Available (2-stroke)
		Ethanol DME	In principle available (2-stroke), but not applied
		Ammonia	Not available; announced to be developed (2-stroke)
Hydrogen	Under development (4-stroke; for smaller ships)		
ICE - Spark ignition (SI)	Gas engine (4-stroke)	Methane	Available
		Propane	Not available, but should be possible
		DME	Not available, but should be possible
		Methanol	Has been tested
		Ammonia	Not available, but should be possible
		Hydrogen	Under development (for smaller ships)
ICE	Gas turbines	Distillate conventional bunker fuel	Available
		Methane	Available
		Propane	Design with approval in principle (COGES)
		Hydrogen	Not available, but should be possible for up to 85% of hydrogen
ECE	Steam turbines	Diesel	Available
		Methane	Available

Sources: Austin 2017; Brown 2019; Lipton 2018; MAN 2014; MAN 2018; Penjic 2018

As Table 19 shows, there are specific engines available for diesel, methane, ethane, propane, and methanol or engines can be retrofitted accordingly. There are, however, no ammonia-fuelled ICE or ECE engines for ships available yet. MAN aims to have a two-stroke ammonia engine commercially available by 2024.²⁹ Wärtsilä (2020) announced that in the first quarter of 2021, a consortium will commence a long-term, full-scale laboratory test using ammonia as a fuel in a marine four-stroke combustion engine and will begin

²⁹ Nils Lindstrand, MAN Energy Solutions is developing a fuel-flexible, two-stroke ammonia engine as a key technology in the maritime energy transition, <https://www.man-es.com/discover/two-stroke-ammonia-engine>.

working with ship owners on field tests in 2022.³⁰ For hydrogen, the first marine ICEs (dual fuel and spark ignition, four-stroke) have been developed³¹ aimed at tugs, ferries and other small commercial crafts.³² For larger ships, an application as auxiliary engines is also conceivable.

In the following, the characteristics and technical issues associated with the different post-fossil fuels are discussed. Methane is considered an established fuel in the sector and is not considered here.

Methanol

A small number of maritime ships are currently methanol-fuelled (Table 20). A RoPax Ferry (Stena Germanica) has successfully been converted to run on methanol and eleven new-build chemical tankers (methanol-fuelled methanol carriers) are active in the market, with another eight on order. Three bulk carriers are also on order (StenaBulk 2020) and A.P. Møller - Mærsk has expressed the ambition to operate a container feeder on e-or bio-methanol from 2023 onwards.³³ In China, a first methanol-fuelled cargo barge has been built for testing purposes; several projects have also been, and are being, carried out in which either ships are converted to run on methanol or methanol-fuelled new-builds are being developed (Table 20). In addition, the China Waterborne Transportation Research Institute is performing a comprehensive study on methanol as marine fuel, recently joined by the Methanol Institute (Offshore Energy 2020) and different ICE engines are being tested as part of the Green Maritime Methanol project (GMM 2020).

The conversion of the Stena Germanica comprised:

- ▶ Installation of an injector that comprises four separate hydraulic circuits for methanol, marine gas oil (MGO), a sealing oil to prevent methanol leaks and a cooling system.
- ▶ Engine-related conversions: Exchange of cylinder heads, fuel injectors and fuel plungers in existing fuel pumps. A common rail system for methanol injection has been added to the engine.
- ▶ For the storage of methanol, a ballast tank in the double bottom has been converted into a double-walled methanol tank.

³⁰ Wärtsilä, 01/07/2020, Wärtsilä's recent experiments with the fuel, which releases no CO₂ when it burns, show its potential for maritime applications, <https://www.wartsila.com/insights/article/successful-tests-pave-the-way-for-ammonia-as-a-future-marine-fuel>.

³¹ BeHydro is the joint venture between two Belgian companies, namely Company Maritime Belge (CMB) and Anglo Belgian, <https://www.behydro.be/en/home.html>.

³² Maritime Journal, 21/10/2019, A new joint venture aims to commercialise dual fuel diesel/ hydrogen engines as well as mono-fuel hydrogen engines for vessel propulsion, <https://www.maritimejournal.com/news101/power-and-propulsion/hydrogen-fuelled-engines>.

³³ Mærsk, 17/02/2021, A.P. Møller - Mærsk will operate the world's first carbon neutral liner vessel by 2023 – seven years ahead of schedule, <https://www.maersk.com/news/articles/2021/02/17/maersk-first-carbon-neutral-liner-vessel-by-2023>.

Table 20: Methanol ICE applications and projects

Company/vessel name/project	Vessel type	Engine type	Status	Installation type
A.P. Møller - Mærsk	Container feeder	Dual fuel engine	Ambition to operate on e-methanol/bio-methanol from 2023 onwards	New-build
Waterfront Shipping Co (Charterer)	Chemical tanker (methanol carriers) (11 in fleet, 8 on order)	Liquid gas injection dual fuel engine	Vessels in operation / on order	New-build
Stena Bulk/Proman Shipping	Bulk carrier (Stena ProMare, Stena ProPatricia, Stena Prosperous)	Liquid gas injection dual fuel engine	Vessels on order	New-build
Stena Line	RoPax Ferry (Stena Germanica)	Dual fuel engine	Vessel in operation	Retrofit
Project of Jianglong Shipbuilding	Cargo barge (Jianglong)	Dual fuel engine	Vessel in (test) operation	New-build
Uthörn II	Coastal research ship	Two 300 kW, 1 500 rpm engines modified for methanol operation	Vessel on order	New-build
FASTWATER project	Harbour tug, pilot boat, coast guard vessel	Medium- and high speed (dual fuel) demonstration engines; dual fuel retrofit kit	Project launched in June 2020	Retrofit
Sustainable Marine Methanol (SUMMETH) project	Inland and coastal ferry	Dual fuel engine (project demonstrated applicability of methanol engine concept in the range of 250 to 1 200 kW)	Project completed in 2018	Retrofit
GreenPilot project	Pilot boat 729 SE	Two spark ignition engines have been installed and tested on pilot boat using (bio-) methanol	(Demonstration) project completed in 2018	Retrofit

Source: Author's own compilation

Methanol has some disadvantages in comparison to conventional bunker fuel; overall, however, most of the technological barriers can be considered surpassed for methanol-based engines.

Disadvantages:

1. Methanol is corrosive towards some metals; it is a solvent that also attacks some plastics, resins, and fiberglass compounds (Methanol Institut 2017). The use of methanol thus requires the use of methanol compatible materials; MAN (2014) considers the corrosiveness of methanol not to be a problem for the combustion chambers of current standard engines.
2. The cetane number³⁴ of methanol is much lower than that of diesel and its auto-ignition temperature is twice as high as that of diesel (Grahn und Sprei 2015), which is why a conventional marine diesel engine cannot run on methanol without modifications. Either a dual-fuel engine or a spark ignition engine is thus required.³⁵ Several other engine models can be retrofitted, but this does not apply to all older marine diesel engines (FCBI energy 2015). The application of spark-ignited methanol injection technology can be performed on existing engines without structural modifications to the engine design and structure (MKC et al. 2017). Blending methanol with ignition improvers is also being tested.
3. Methanol has a very low viscosity compared with conventional HFO and diesel. Special efforts are therefore needed to prevent leaks in seals (FCBI energy 2015).
4. Methanol has poor lubrication; this might increase the abrasion of engine components (Grahn und Sprei 2015). More/other types of lube oils are needed when ships are fuelled with methanol.
5. As specified in the Interim Guidelines for the safety of ships using methyl/ethyl alcohol as fuel (MSC.1/Circ.1621), specific design requirements have to be fulfilled by ships using methanol as fuel.
6. Double-walled high pressure fuel pipes should be installed for safety purposes due to the low flash point quality.
7. If methanol is used in internal combustion engines, NO_x Tier III levels might not be met. This can, however, be solved by mixing methanol with water. Methanol and water are easily mixed, and the mixtures will stay stable.

DME

DME can be produced by dehydration of methanol. DME has been studied as an alternative fuel since ship/engine conversion is expected to be less complex compared to methanol, due to the absence of SO_x and an expected NO_x reduction:

- ▶ According to the Japan DME association, a few DME-fuelled road vehicles (light/medium trucks, buses) have been built/tested.
- ▶ A marine engine (dual-fuel, two-stroke, high-pressure injection/diesel cycle) that can be operated on DME or other low-flashpoint liquid fuels like methanol, ethanol, LPG is already commercially available, but during the time of the study there has been no evidence of this engine actually being operated on DME.
- ▶ Retrofitting of two-stroke/low speed engines is possible, too.

³⁴ Cetane number is an indicator of the combustion speed of fuel and compression needed for ignition.

³⁵ Methanol has a higher octane number than gasoline and is therefore suitable for Spark Ignition (SI) engines with a higher compression ratio without the occurrence of knock. This enables higher efficiencies in SI engines compared to gasoline (MKC et al. (2017)).

- ▶ Daihatsu Diesel and JFE engineering compared DME and MGO under lab conditions when used to run a 4-stroke diesel engine (TNO et al. 2013). They concluded that the combusting pressure of the two fuels is nearly identical, that DME scores better at low loads in terms of black smoke and CO production.

Technical challenges of DME:

- ▶ Poor lubrication is a major disadvantage since feed pumps, high pressure fuel pumps and injectors will experience more wear (TNO et al. 2013). According to TNO et al. (2013), lubricity additives have been tested to compensate, but the results were unsatisfying and pumps still had premature wearing. A separate lubrication system is then required to compensate for the low lubricity of DME (TNO et al. 2013).
- ▶ DME shows corrosive action in most elastomers, damaging sealing elements and other components of fuel systems made of elastomers (Kruczynski et al. 2017).
- ▶ If not stored fully refrigerated, DME must be pressurized at 5-6 bars to ensure that it is liquidized (TNO et al. 2013). However, back pressure is experienced, when pressurized DME is injected into the chamber. This backpressure affects the needle motion in the injector resulting in a negative influence on the efficiency of the engine (TNO et al. 2013).
- ▶ Lower viscosity than that of diesel fuel may cause leakage within the fuel supply system which relies on small clearances for sealing (Kropiwnicki et al. 2017)
- ▶ Low modulus of elasticity: The compressibility of DME is four to six time higher than that of diesel in a closed system which means that the compression work of the high pressure fuel pump is 3.2 times greater and the compression work of the low pressure fuel pump for DME is greater by up to 10% in an open system (Kropiwnicki et al. 2017).

DME-methanol mix

Tests have been carried out on using the fuel mixture resulting from the methanol to DME conversion process: A process unit for dehydrating methanol to a fuel mix of DME (60% by weight), water (25% by weight), and methanol (15% by weight) was designed, installed, and operated on-board the Stena Scanrail, a RoPax ferry operating between Gothenburg and Frederikshavn.³⁶ An auxiliary engine was modified to run on the fuel mix and installed on board the ship. The process unit successfully produced fuel of the desired quality. There were some difficulties with fuel ignition in the auxiliary engines, but once combustion was established it was quite similar to diesel. Use of ignition improver and preheating improved starting, but further testing and engine development is recommended.

Engine modification was necessary because of the lower cetane ranking of the fuel mixture, lower fuel density, and reduced lubricity of the fuel as compared to normal diesel fuel.

Propane

³⁶ By doing the conversion of methanol into DME on board the ship, the storage is more efficient since DME is gaseous at normal temperature (Maritiem (2018)).

The auto ignition temperature of propane is relatively high which is why compression temperature is not sufficient for ignition in a conventional mono fuel CI engine. There are three main approaches that can be applied in order to use LPG as a fuel (DNV GL 2017b):

- ▶ A diesel cycle two-stroke engine with pilot fuel oil injection is already available on the market. Ships with conventional two-stroke diesel engines can be retrofitted accordingly.
- ▶ In an Otto cycle, lean-burn, four-stroke medium speed, spark plug or pilot fuel ignited gas engine; this is currently, however, only available for stationary power plants. To maintain a safe knock³⁷ margin when operating on LPG (and not on LNG), the engine output might have to be reduced.
- ▶ An alternative option to utilize LPG for propulsion is the installation of a gas reformer to turn LPG and steam into methane in a mixture with CO₂ and some hydrogen. In this case, the energy content of the gas produced in the reformer is sufficient for a regular gas or dual fuel engine to be used with no need for derating. A reformer will, however, lower the efficiency.
- ▶ In a gas turbine, possibly in combination with a steam turbine³⁸ or CO₂ turbine.

The technology is thus currently available for large ships with two-stroke engines and turbines and can be developed for smaller ships with four-stroke engines if there is a demand for this (DNV GL 2017b). In fact, 4 LPG tankers have been retrofitted and another 11 LPG tankers have been announced to be retrofitted with an LPG dual fuel two-stroke propulsion engine (BW LPG 2021).³⁹ More than 60 LPG tankers are currently on order which will be equipped with an LPG dual fuel two-stroke engine.⁴⁰ According to ClassNK (2018), several projects with Approval in Principle from major classification societies are currently ongoing. In 2020 for example, ClassNK granted an Approval in Principle to a concept design of LPG dual fuelled bulk carrier.⁴¹

Hydrogen

In principle, internal combustion engines and turbines can also be used for combustion of hydrogen (DNV GL 2015). A hydrogen-fuelled demonstrator ICE for trucks is currently under development (ULEMCo 2018a). As part of the HYLANTIC project, a demonstration marine engine modified to run on hydrogen is being developed (ULEMCo 2018b). Recently, the first marine ICEs for commercial use (medium speed, dual fuel and spark ignition) have been developed by the Belgium companies ABC and CMB.⁴² The Port of Antwerp has

³⁷ Knocking refers to unintended ignition.

³⁸ A COGES propulsion system is based on electric propulsion motors and alternators driven by both gas turbines and steam turbine(s). Heat recovery steam generators are fitted in the gas turbine exhaust lines and generated superheated steam (at approximately 30 bar) is led to a steam turbo-alternator.

³⁹ Offshore Energy, 26/01/2021, BW LPG's fourth retrofit set for sea trials, <https://www.offshore-energy.biz/bw-lpgs-fourth-retrofit-set-for-sea-trials/>.

⁴⁰ Clarksons Research, <https://clarksonsresearch.wordpress.com/>

⁴¹ ClassNK, 27/04/2020, ClassNK grants world-first AiP to Imabari Shipbuilding for their concept design of a 180,000 DWT LPG dual fuelled bulk carrier, https://www.classnk.or.jp/hp/en/hp_news.aspx?id=4925&type=press_release&layout=5.

⁴² BeHydro is the joint venture between two Belgian companies, namely Company Maritime Belge (CMB) and Anglo Belgian, <https://www.behydro.be/en/home.html>.

ordered a tugboat which will be equipped with the dual fuel engine type (85% hydrogen, 15% diesel)⁴³ and Lloyd's Register has awarded Approval in Principle to the dual fuel engine with a capacity of 1 megawatt.⁴⁴

Ammonia

The technology to use ammonia in internal combustion engines exists, but has so far not been applied in large engines with modern techniques (C-job 2018).

A consortium in the Netherlands (C-job naval architects, Proton Ventures and Enivu) recently announced its intention to research and demonstrate in a two-year project “the technical feasibility and cost effectiveness of an ammonia tanker fuelled by its own cargo” (Brown 2018).

MAN aims to have a two-stroke ammonia engine commercially available by 2024.⁴⁵ Wärtsilä (2020) announced that in the first quarter of 2021, a consortium will commence a long-term, full-scale laboratory test using ammonia as a fuel in a marine four-stroke combustion engine and that they will begin working with ship owners on field tests in 2022.⁴⁶

The technical disadvantages related to ammonia as a fuel for an internal combustion engine are (CUT 2014):

- ▶ very high auto-ignition temperature;
- ▶ low flame speed;
- ▶ high heat of vaporization;
- ▶ narrow flammability limits.

There are solutions to these disadvantages, both for Compression Ignition (CI) and Spark Ignition (SI) engines:

- ▶ It is not possible to solely use ammonia in a CI-engine due to the high compression ratios needed for ignition/combustion. However, in a dual fuel constellation, ammonia could be used together with a combustion promoter fuel with a higher cetane number, such as diesel or DME (CUT 2014). Since hydrogen could be used as the stronger igniter, a reformer could also be used with a catalyst breaking down a sufficient amount of ammonia into hydrogen and nitrogen. The pure hydrogen will ignite and burn with ammonia, forming water, nitrogen and some NO_x (C-job 2018). Industrial research has shown that a volume ratio of 3% hydrogen and 97% ammonia would work (MVO Nederland 2017), but this process has been neither validated nor demonstrated on vessels under sailing conditions during the study. The challenge is that the amount of hydrogen required varies with the engine load and speed, which can cause control issues. For the start-up, CUT (2014) suggests that this can be solved by having a

⁴³ Port of Antwerp, 24/09/2019, Hydrogen-powered tug is world first for Port of Antwerp, <https://www.portofantwerp.com/en/news/hydrogen-powered-tug-world-first-port-antwerp>.

⁴⁴ Lloyd's Register, 18/09/2020, BeHydro dual fuel hydrogen engine awarded Approval in Principle by LR, <https://www.lr.org/en/latest-news/behydro-dual-fuel-hydrogen-engine-awarded-approval-in-principle/>.

⁴⁵ Nils Lindstrand, MAN Energy Solutions is developing a fuel-flexible, two-stroke ammonia engine as a key technology in the maritime energy transition, <https://www.man-es.com/discover/two-stroke-ammonia-engine>.

⁴⁶ Wärtsilä, 01/07/2020, Wärtsilä's recent experiments with the fuel, which releases no CO₂ when it burns, show its potential for maritime applications, <https://www.wartsila.com/insights/article/successful-tests-pave-the-way-for-ammonia-as-a-future-marine-fuel>.

small tank that stores extra hydrogen when the engine is running and uses it if necessary, i.e. if the exhaust is not hot enough to decompose ammonia. A premix of ammonia with DME might also be a solution to this problem.

- Combustion of ammonia in an SI-engine can be facilitated by having stronger igniters, compacted combustion chamber and longer spark plugs to overcome ammonia's reluctance to combustion. An improved combustion can also be achieved by supercharging (CUT 2014). The design of an SI engine using ammonia as single fuel has been patented by Toyota. They suggest that several plasma jet igniters arranged inside the combustion chamber or plural spark plugs that ignite the ammonia at several points will facilitate ammonia combustion (CUT 2014). If used with an additional fuel, gaseous fuels are more preferred for use in SI-engines since they can be introduced into the engine together with the gaseous ammonia (CUT 2014).

Ammonia is corrosive to copper, copper alloys, nickel and plastics and independent of the engine used these materials have to be avoided in an ammonia-fuelled engine (CUT 2014).

In addition, steel is sensitive to ammonia stress corrosion cracking. This can be controlled by adding a small amount of water (0.2%) to the ammonia (Royal Academy of Engineering 2013). This requires, however, modifications in the fuel supply lines.

If ammonia is used in internal combustion engines, NO_x emissions are relatively high. This is a problem that has not yet been solved. However, there are aftertreatment technologies available, e.g. selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) systems that could be used to reduce the NO_x emissions. There are SCR systems that make use of ammonia which might lend themselves for ammonia-fuelled ships. For the ammonia internal combustion engines that are under development, N₂O seems to be a major challenge and the technology to clean the exhaust gas accordingly is not proven yet.⁴⁷

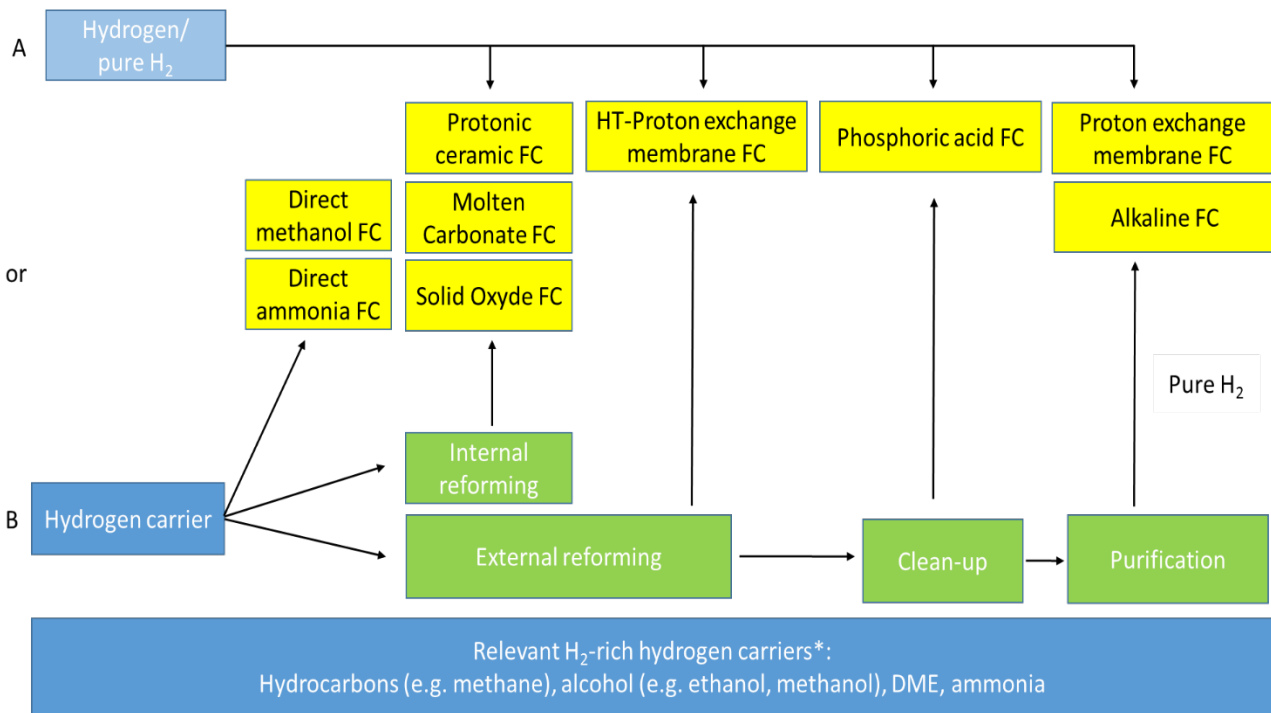
Fuel cells

Apart from using ECE or ICE, an electric engine in combination with fuel cells, providing the electricity for the engine could be applied for the propulsion of maritime ships. Fuel cells need an energy storage device, like batteries, to cover peak load creating the necessity for a hybrid energy system.

Fuel cells can either be operated on hydrogen or different other hydrogen carriers, e.g. the post-fossil fuels mentioned above. The use of other hydrogen carriers (especially hydrogen-rich fuels) could be more attractive for reasons of costs, storage volume, availability, etc.

There are different fuel cells which require different pre-processing steps, depending on the hydrogen carrier used (Figure 31).

⁴⁷ DGV, 08/05/2020, The role of combustion engines in decarbonization – seeking fuel solutions, <https://www.dnv.com/expert-story/maritime-impact/The-role-of-combustion-engines-in-decarbonization-seeking-fuel-solutions.html>.

Figure 31: Post-fossil fuels and fuel cell technologies

Notes: *Liquid fuel would need to be evaporated in the first instance.

Sources: Authors' own illustration based on Van Biert et al. (2016) and Ganley (2006)

Some fuel cells (e.g. solid oxide, molten, protonic FC) do not require external reforming of the hydrogen carrier, whereas the other fuel cells require at least external reforming (hydrocarbons are, for example, converted by means of steam reforming and water-gas-shift). Depending on their sensitivity to impurities in the fuel (e.g. CO_x or sulphur), additional clean-up and purification of the fuel may be needed.

Table 21 provides an overview of the main characteristics, advantages and technical challenges of the different fuel cell types. DNV GL (2017d) have ranked the different fuel types using multiple criteria and came to the conclusion that the PEMFC, the HT-PEMFC and the SOFC are the three most promising technologies. They did not consider the PCFC in their analysis.

Table 21: Fuel cell types – their characteristics, advantages and technical challenges

Fuel cell type	Fuel	Efficiency*	Operation temperatures	Advantages	Technical challenges
Alkaline (AFC)	High purity H ₂	50-60%	Low/medium (0 – 230°C)	High maturity; size; relatively high power levels per module; good tolerance for cyclic operation	High sensitivity to fuel impurities; rel. low efficiency (no WHR); moderate lifetime
Proton Exchange Membrane (PEMFC)	Pure Hydrogen	50-60%	Low (50-100°C)	High maturity; size; low operation temperature allows flexible operation and less stringent material requirements; good tolerance for cyclic operation	Medium sensitivity to fuel impurities; hydrocarbons need to be reformed in separate stage; rel. low efficiency (no WHR); moderate lifetime

Fuel cell type	Fuel	Efficiency*	Operation temperatures	Advantages	Technical challenges
Direct Methanol (DMFC)	Methanol	20%	Low (ambient – 110°C)	Good tolerance for cyclic operation; size; low sensitivity to fuel impurities	Very low efficiency; moderate lifetime; low level of maturity; very low power levels per module (up to 5 kW)
Phosphoric Acid (PAFC) ⁴⁸	Flexibility towards fuels	40% (up to 80% with WHR)	Medium (150 – 220°C)	Lifetime; high maturity; heat recovery feasible; relatively high power levels per module possible	Medium sensitivity to fuel impurities; Safety challenges (temperature; CO and H ₂ in reforming unit); moderate tolerance for cyclic operation; size.
High temperature Proton Exchange Membrane (HT-PEMFC)	Flexibility towards fuels	50-60% without WHR	Medium (up to 200°C)	Size; low sensitivity to fuel impurities: no clean-up reactor after reformer is needed; good tolerance for cyclic operation	Safety challenges (temperature; CO and H ₂ in reforming unit); relatively low efficiency (no WHR); low maturity; rel. low power levels per module
Protonic Ceramic (PCFC)	High flexibility towards fuels	Potentially more than 50%	Medium/high (300 – 600 °C)	Low sensitivity to fuel impurities	
Molten Carbonate (MCFC)	High flexibility towards fuels	50% (up to 85% with WHR)	High (600 – 700°C)	Lifetime; high maturity; low sensitivity to fuel impurities; reforming unit is not needed - reforming occurs in FC itself; relatively high power levels per module	Safety challenges (temperature; CO and H ₂ in cell from internal reforming); low tolerance for cyclic operation; size
Solid Oxide (SOFC)	High flexibility towards fuels	60% (up to 85% with WHR)	High (500 – 1000°C)	Moderately sized; low sensitivity to fuel impurities	Moderate maturity; safety challenges (temperature; CO and H ₂ in cell from internal reforming); low tolerance for cyclic operation; moderate lifetime; rel. low power levels per module

Notes: *Electric efficiency if not specified otherwise.

Source: DNV GL 2017d

As a general rule, it holds that the higher the operating temperature of the fuel cell, the less sensitive it is to fuel impurities. A higher temperature also allows for waste heat recovery (WHR)⁴⁹, increasing the efficiency of a fuel cell. However, high temperatures are also associated with higher safety risks, at least if directly operated with hydrogen. If the high temperatures fuel cells are operated with hydrogen carriers and

⁴⁸ Note that according to the Royal Academy of Engineering (2013) the phosphoric acid fuel cell is not suitable for marine applications due to the nature of its electrolyte.

⁴⁹ On a conventional ship equipped with an ICE or ECE, waste heat recovery systems recover the thermal energy from the exhaust gas and convert it into electrical energy, while the residual heat can further be used for ship services such as hot water and steam GloMeep (2018). Waste heat from fuel cells released to cooling system and exhaust gas could be recovered to be used for fuel reforming processes, if necessary or could be transformed to electricity by means of a gas turbine (Lin et al. (2010)).

not directly with H₂, H₂ will form in the internal reformer only, reducing the safety risk. The high-temperature PEMFC⁵⁰ and the PAFC are operated at a much lower temperature (up to 200°C) compared to the higher temperature fuel cells PCFC, MCFC and the SOFC (600-700°C); the PEMFC and the AFC are considered low-temperature fuel cells.

Compared to the ICE/ECE, most fuel cells have a higher energy efficiency, but the efficiency of some fuel cells is relatively low (DMFC). Fuel cells that do not allow for WHR, have a low efficiency in comparison with other fuel cells.

Van Biert et al. (2016) point to the complexity of using low temperature fuel cells with non-hydrogen fuels. The overall efficiency would be limited by the need to generate high temperature heat and steam for reforming and losses in clean-up and purification equipment.

The fuel cells feature different tolerances to cyclic operation, including endurance against start/stops as well as transients during operation caused by load changes. To extend the service life of the fuel cells, a storage device, e.g. a battery thus has to be used in parallel to allow for a power output that is as constant as possible. Since a ship that is powered by a fuel cell will most probably be equipped with a battery anyway to improve the efficiency, the intolerance for cycling of specific fuel cells might thus not be a major technological barrier.

Nevertheless, one of the biggest challenges is to increase the lifetime of the fuel cells to suit the lifetime of the ships. The lifetime of fuel cells in non-stationary applications is lower than that for stationary applications. Recent independent data on the actual expected lifetime of the different fuel cells in non-stationary is scarce, but from the available data it can be concluded that none of the fuel cell types has an expected lifetime comparable to that of a ship (25-30).

In the *Evaluation of the National Innovation Program Hydrogen and Fuel Cell Technology Phase 1* carried out on behalf of the German Federal Ministry of Transport and Digital Infrastructure and the German Federal Ministry for Economic Affairs in 2017, it is stated: Since 2011, the median lifetime of fuel cells in stationary applications has doubled to approximately 25 000 hours for PEMFCs. For SOFCs, it has increased four times, reaching about 40 000 hours. At the same time, leading Japanese fuel cells already reach lifetimes of 70 000 hours (for PEMFCs) and 90 000 hours (for SOFCs) today. Funding recipients continue to see fuel cell lifetime as an ongoing barrier to commercialization. In mobile applications, service life for HT and LT-PEMFCs increased from 1 000 hours in 2011 to about 5 000 hours today (McKinsey 2017).

As Table 21 shows, the technical maturity of some of the fuel cell types, especially of the direct methanol fuel cell is still rather low. All present fuel cell systems in shipping are actually non-commercial prototype installations. Table 22 provides an overview of recent projects in field per fuel applied. Mainly PEMFCs operated on hydrogen seem to have been applied in the projects, but also HT-PEMFCs and SOFC operated on methanol have been tested and an inland ferry (MS Innogy) still operates on e-methanol.

⁵⁰ The *high-temperature* PEMFC thus operates at a higher temperature than the PEMFC, but at a significant lower temperature than the PCFC, MCFC and the SOFC.

Table 22: Overview of current fuel cell projects

Project name or vessel or shipping company	Vessel type	Fuel cell type	Project status	Installation type
Hydrogen				
Energy observer	Catamaran	PEM fuel cell (plus solar panels, wind turbines, onboard hydrogen production system from seawater)	The sailing commenced on end of 2017	New-build
NEMO H ₂	Small passenger inland ferry	PEM fuel cells	Operation had to be stopped due to H ₂ -logistical problems	New-build
Zemship	Passenger inland ferry (FCS Alsterwasser)	PEM fuel cells; battery	Since 2013 the ferry is laid up; bunkering facility was closed for economic reasons	Retrofit
Maranda project	Research vessel Aranda	PEM fuel cells (165kW to power dynamic positioning and electrical equipment during research activities)	Ongoing project; Aim: Demonstrate a marine capable PEM fuel cell and test it for 18 months in arctic conditions	Retrofit
Royal Caribbean	Cruise	PEM pure hydrogen fuel cells	Pilot installation	
ABB and Ballard systems	Vessels with power requirement of 3 MW; initial focus on cruise ships	PEM fuel cells	MoU has been signed	New-build
HySeas III	Seagoing passenger ferry	PEM fuel cells (six 100 kW modules) using renewable hydrogen	Demonstration in operational service planned for 2022	New-build
FLAGSHIPS (MF Hidle)	Car and passenger ferry	PEM fuel cells (3 x 200kW)	Under construction, expected to be delivered to Norway in March 2021	New-build
MF Hydra	Car and passenger ferry	PEM fuel cells (2 x 200kW)	Under construction	New-build; liquid hydrogen storage
Pilot-E project (operator Havila Kystruten)	Coastal cruise ferry (operating in Norwegian Fjords)	PEM fuel cells (3.2 MW system; several fuel cell modules connected in parallel)	Fuel cell system has been developed, vessel to be retrofitted by 2023	Retrofit; liquid hydrogen storage
Ludwig Prandtl II	Research vessel	Fuel cells in combination with metal hydride storage and membrane modules will be tested also as part of the vessel's energy system	Design phase	New-build

Project name or vessel or shipping company	Vessel type	Fuel cell type	Project status	Installation type
Methanol				
MS Innogy	Inland passenger ferry	HT-PEM fuel cells, batteries (back up diesel motor)	Ferry in operation	Retrofit
e4ship (Pa-X-ell2)	Cruise ship (AIDAnova)	PEM fuel cell	Test operation (installation and testing planned for 2021)	Retrofit
e4ship (RiverCell2)	River cruise vessel	Hybrid system with modularised HT-PEM fuel cell system will be developed and tested onboard a river cruise vessel	Ongoing project (until end of 2021)	Retrofit
e4ship (Pa-X-ell)	RoPax Ferry (Viking Line MS Mariella)	HT-PEM fuel cell prototype; 90kW system (three racks of six 5kW modules)	Demonstration project (project completed)	Retrofit
METHAPU project	Undine car carrier	Solid oxide fuel cell for auxiliary power	Trial (project completed)	Retrofit
Ammonia				
ShipFC project (Viking Energy)	Offshore vessel	Solid oxide fuel cell (scale up of a 100kW fuel cell to a 2MW fuel cell system is part of project)	Installation of fuel cell system scheduled for late 2023	Retrofit
Methane				
FellowSHIP (Viking Lady)	Offshore supply vessel	Molten carbonate fuel cell (320 kW) for auxiliary power	Fuel cell system was integrated in 2009 and project was completed end of 2018	Retrofit
Diesel				
Schibz	General cargo	Integrated hybrid SOFC fuel cell system for sea going ships	Development of scalable, integrated hybrid fuel cell system for sea going ships having a power capacity of 50 to 500 kW with the use of low sulphur diesel which can be adapted to a natural gas system as a mid-term goal. Phase 2 of the project will be completed by 2022	Retrofit

Source: Author's own compilation

The power level of the modules of some fuel cells is still rather low for certain ship types, whilst others are rather bulky (Table 21).

Fuel cell modules can be stacked to provide higher power output, but the space requirement of the fuel cells does not currently allow fuel cells to be applied to large ships. As an example: a consortium is currently

developing a fuel cell for the shipping industry with an electrical generating capacity of 3 MW. This fuel cell within a single module is said to be of similar in size to a conventional diesel engine. The largest container ships had an average installed power of 80 MW in 2012.

Retrofitting of ships to operate on fuel cells is technically possible, but ships have to afford the deck space and the design and stability implications and should be equipped with an electric propulsion engine.

Economic barriers

Ship owners/operators will refrain from using post-fossil fuels if the use of post-fossil fuels is associated with higher costs.

Using post-fossil fuels might be associated with higher capital and operational expenditures and higher opportunity costs.

Capital expenditures for the ship and its systems including not only the engines and or fuel cells but also their complementary components such as reformers, batteries or additional air pollution reduction measures, considering the corresponding safety requirements, might be higher for ships powered by a post-fossil fuel.

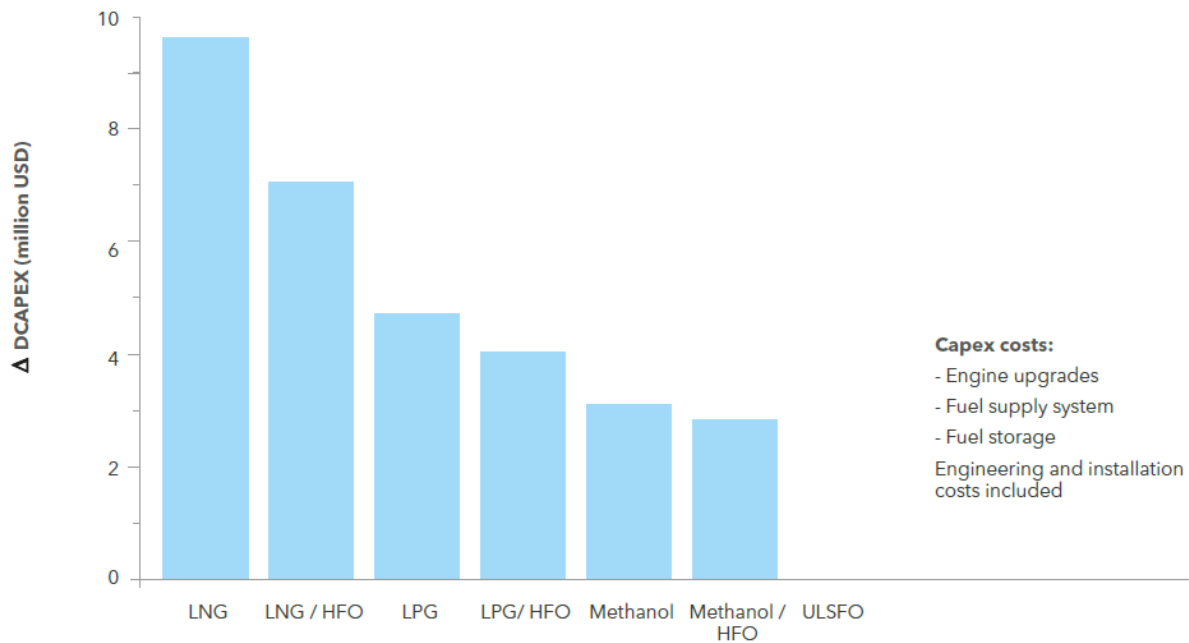
The fuel expenditures might be higher and the operational expenditures might also increase due to higher expenditures for minimising health and safety risks (e.g. for crew training and a sufficient high number of crew members) and due to a higher insurance premium.

Finally, opportunity costs might accrue when using post-fossil fuels, since the system space requirements, especially the fuel storage space requirements, might lead to a loss of cargo/passenger space and corresponding revenues. If ships, due to the volumetric density of the fuels, chose to refuel more often, they might lose revenues too.

Capital expenditures

Internal combustion engine

DNV GL (2017b) have analyzed the capital expenditures for a new build ship of 75 000 dwt equipped with an ICE for various fuel options. Expenditures for engine upgrades, fuel supply system, fuel storage and the corresponding engineering and installation costs have been considered and the costs are compared to the LSFO option. They find that the incremental costs are with nearly 10 million US\$ the highest for LNG (methane), followed by LPG (almost 5 million US\$). The additional CAPEX costs are assessed to be lowest for methanol (approx. 3 million US\$).

Figure 32: CAPEX for ship with ICE by post-fossil fuel type

Source: DNV GL 2017b

Comparing an LNG-fuelled ship with a hydrogen-fuelled ship, the hydrogen-fuelled ship would be associated with higher capital expenditures for two reasons. Firstly, the hydrogen-fuelled ship needs different components such as valves, hoses and piping since hydrogen is a smaller molecule which can escape through joints or seals that would retain LNG. Secondly, a hydrogen-fuelled ship would require tanks with a much higher grade of insulation to achieve the same boil-off rate as for LNG (Knight 2018).

MAN Diesel & Turbo has examined hydrogen fuel through dedicated projects, but realized that the cost of the whole onboard arrangement was too high (Austin 2017). Given the experience with LNG, for which the cost of storage tanks has not decreased in ten years, hydrogen storage costs would likely remain as high as those for LNG – if not higher – for the foreseeable future (Austin 2017).

Fuel cells

Fuel cell systems are expensive compared with diesel engines. According to DNV GL (2018), a fuel cell system costs 5 000 \$/kW with CAPEX of diesel engine amounting to approx. 400 \$/kW (DNV GL 2018b).

There are, however, CAPEX differences between the fuel cells. DNV GL (2017d) rank the fuel cells according to their relative costs as follows:

- ▶ high: MCFC, SOFC;
- ▶ moderate: PAFC, HT-PEMFC, DMFC;
- ▶ low: AFC, PEMFC.

If hydrogen carriers other than H₂ were used, the costs for reformer, clean up and purification might also have to be accounted for.

Operational Expenditures

Fuel expenditures

Ships using post-fossil fuel will probably have higher fuel expenditures than ships using conventional bunker fuel.

If post-fossil fuel was used in ICE/ECE, the fuel expenditures can be expected to be higher, since the price of the post-fossil fuel is expected to be higher than the price of conventional.

If post-fossil fuel was used in fuel cells, fuel expenditures might, depending on the fuel used, also be higher. The combination of fuel cell and electric engine has, at least for some fuel cells, a higher efficiency than an ICE/ECE. However, depending on the fuel used, the energy efficiency of the ship, considering the entire propulsion system, including for example external reformers, freshwater generators, and purifiers might still be lower.

The price of post-fossil fuel can be higher due to higher production costs, but also due to higher transportation costs. The costs of transporting LPG is, for example, roughly 2 to 2.5 times the price of transporting diesel, which is mostly due to different densities and different safety standards each require (SGC 2012).⁵¹

Expenditures to manage health/safety/environmental risks

Safety, health and environmental issues related to the post-fossil fuels and their use in either ICE/ECE or in fuel cells can be a barrier to the use of these fuels in maritime shipping since higher expenditures for minimising health and safety risks might have to be incurred.⁵²

Loss of revenue

Loss of space for cargo or passengers

Fuel cells, reformers, batteries and storage tanks all require space onboard a ship and might overall require more space if compared to a conventional ship, even though other devices like a scrubber may become redundant. This might lead to a loss of space for cargo or passengers leading to income losses. It may not be possible to use these in relatively small ships due to a lack of space.

The storage tank space requirement depends on

- ▶ the efficiency of the propulsion system;
- ▶ the energy density of the fuels; and
- ▶ the storage method, depending on the fuel characteristics.

The storage method might vary between fuels:

- ▶ It is plausible to assume that containment systems which store fuel on board of ships will follow the design principles known from the corresponding carrier (e.g. LNG or LPG carrier).
- ▶ Cryogenic storage⁵³ is applied on LNG vessels.
- ▶ There are fully-pressurized, semi-pressurized and fully-refrigerated LPG tankers in place, with larger volumes being shipped by means of fully-refrigerated tankers. Propane, ammonia and DME can be

⁵¹ The production costs of the different post-fossil fuels are discussed in chapter 4.

⁵² Potential negative externalities associated with the different post-fossil fuels are discussed in section 3.1.2.2.

⁵³ The fuel is stored at a very low temperature at which it is liquid (thus at/below its boiling point). The onboard tanks have to be very well insulated to prevent regasification. Re-gasification can however not totally be avoided, leading to the so-called boil-off.

transported with these kinds of carriers. Ammonia and DME have a higher boiling point than propane, but all three can become liquid at relatively low pressure (Table 23) (e.g. propane is, for example, liquid for pressures above 8.4 bar at 20°C or DME at 5 bar at ambient temperatures). A tank of LPG will typically have three times larger volume than a tank with oil-based fuel, even though the lower heating values of 46.3 MJ/kg for propane and 45.4 MJ/kg for butane are slightly higher than for oil-based fuels. This is partly because of the round shape of a cylindrical tank and partly due to lower density. The densities of propane and n-butane are 0.49 kg/dm³ and 0.57 kg/dm³ respectively (DNV GL 2017b).

- Larger ships will have to use cryogenic or cryo-compressed⁵⁴ storage of liquid hydrogen and not compressed storage of gaseous hydrogen (Table 24).⁵⁵ Storage tanks would otherwise be too large or ships would have to refuel too often. According to Van Biert et al. (2016), cryo-compressed storage of hydrogen is currently the most energy dense physical storage method. Little experience has been gathered with cryogenic storage tanks for liquid hydrogen in the shipping sector to date: A first hydrogen carrier is currently being built as part of the HySTRA demonstration project. The vacuum insulated storage tank was installed in 2020 and the carrier is expected to be ready for testing in 2021 (Kawasaki 2020). Also a first car and passenger ferry equipped with fuel cells and liquid hydrogen tanks is currently under construction and a coastal cruise ferry is planned to be retrofitted with fuel cells and tanks for liquid hydrogen (Table 22). Alternative methods for storing hydrogen such as the storage of hydrogen in metal hydrides and chemical compounds are still under investigation (Van Biert et al. 2016; Knight 2018). Hydrogen can, for example, be bound with toluene, converting it to methyl cyclohexane (MCH) by hydrogenation. Cryogenic storage and liquefaction can thereby be avoided, but the resulting density is lower than for liquid hydrogen (Knight 2018).

Table 23: Boiling point of post-fossil fuels and onboard storage methods of the liquid fuel

		Boiling point (rounded)	Liquid at room temperature, at pressure above ...	On board storage methods of the liquid fuel
Hydrogen	Gaseous at ambient temperature	-253°C		Cryo-compressed/cryogenic
Methane		-162°C		Cryogenic
Propane		-42°C	8.4 bar	Compressed/semi-compressed /fully refrigerated
Ammonia		-33°C	10 bar	Compressed/semi-compressed /fully refrigerated
DME		-24°C	5 bar	Compressed/semi-compressed/fully refrigerated
Methanol	Liquid at ambient temperature	65°C		
Ethanol		78°C		

⁵⁴ "It is possible to liquefy hydrogen at temperatures up to 33 Kelvin (-240°C) by increasing the pressure towards the 'critical pressure' for hydrogen, which is 13 bar." (DNV GL (2018a)).

⁵⁵ Compressed hydrogen: It is estimated that, depending on the pressure, the tank size must be 10-15 times larger than required for heavy fuel oil (JRC (2016)).

Sources: WHO 2021; Cardona et al. 2010; DNV GL 2017a; SSPA Sweden AB et al. 2014; C-Job Naval Architects 2018

Table 24: Density of compressed gaseous and liquid hydrogen compared with HFO

Type of Barrier	Fuel density (kg/m ³)	Energy density LHV (MJ/Litre)	Compared to HFO	Compared to liquid hydrogen
HFO	1 010	39		
CGH ₂ (300 bar)	20	2.6	15	3
CGH ₂ (700 bar)	40	3.9	10	2
LH ₂	71	8.5	5	

Sources: DNV GL 2018a; Makridis 2016

To obtain an idea of the storage space requirement of the different fuels, we have calculated the energy content per litre of the different fuels and compared them to HFO. As Table 23 and Figure 33 show, HFO has the highest energy content per litre and liquid hydrogen the lowest energy content per litre. In terms of energy content per litre, propane would be the most promising option.

This comparison does not reflect that the fuels require different tank types with different insulation requirements. It also does not reflect the differences in energy efficiencies of the engines and thus the differences in the amount of energy required by the different engines.

Other than hydrogen, the fuels differ less in terms of energy density per litre, if only the hydrogen energy content of the fuels is considered (Figure 33). This means that when it comes to the selection of an alternative hydrogen carrier to be used in a fuel cell which cannot use an alternative hydrogen carrier directly, the storage method (cryogenic yes/no) is the main factor to be considered. Methanol, ethanol and ammonia are then more attractive options than methane or propane.

The use of cryogenic stored fuels by larger ships has the advantage that higher capacity tanks exhibit a lower boil-off rate. Storage space requirements, however, might mean that these cannot be used on large ships at all.

MAN Diesel & Turbo explains that, due to the high storage cost and requirement of space on board, their exploratory work changed direction to examine converting hydrogen into methanol as a carbon-free ship fuel.

According to the Royal Academy of Engineering (2013), increased above water structures, which are required to accommodate the fuel storage capacity, may create difficulties in retrofitting ships to use liquid hydrogen fuel.

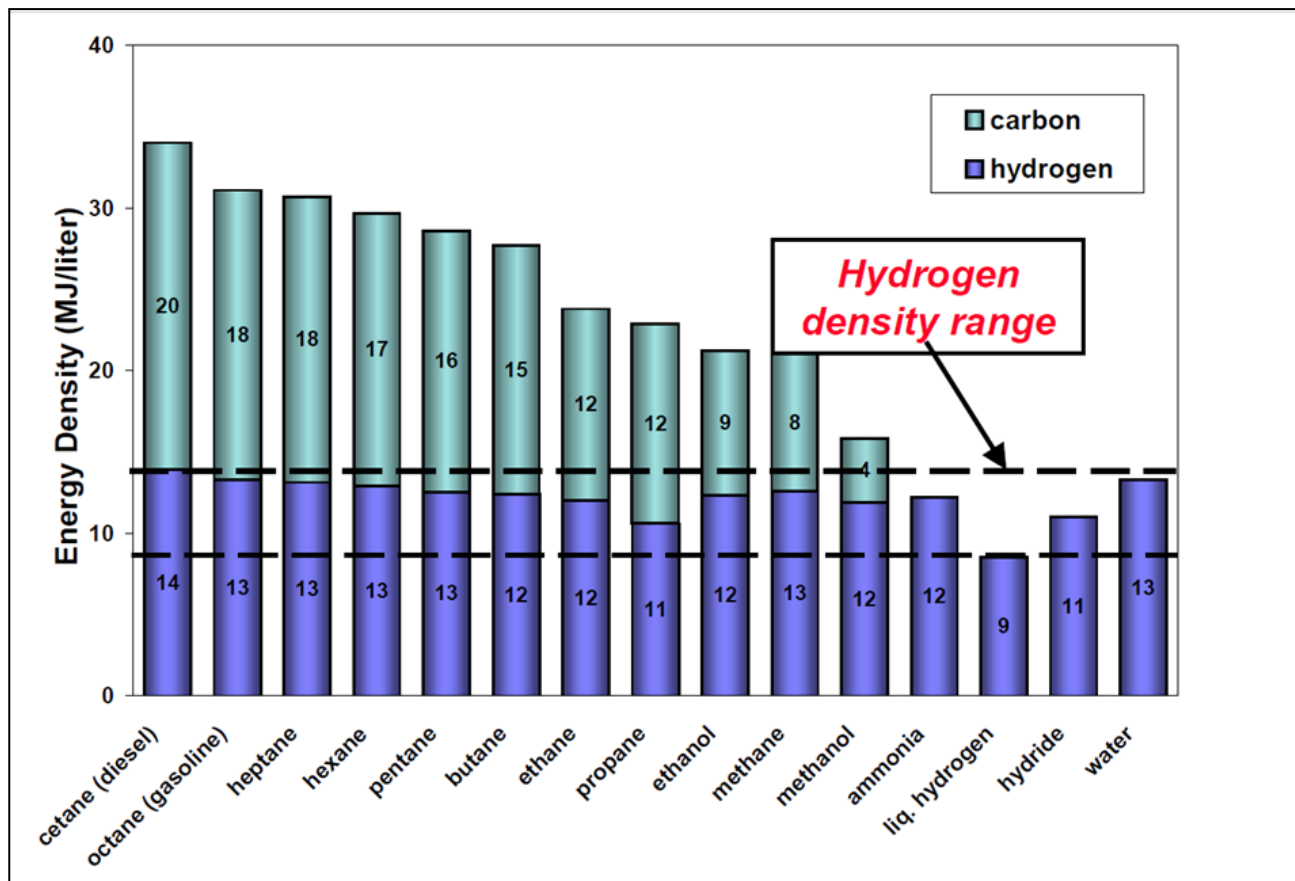
Table 25: Energy densities of liquid post-fossil fuels [MJ/litre] compared to HFO

Fuel type	Lower heating value (MJ/kg)	Liquid density [kg/m ³ ; at boiling point and 1.013 bar if not indicated otherwise]	Energy density (LHV; MJ/litre)	Compared to HFO
HFO	39	max. 920-1 010 at 15°C	36-39	
Propane	46	581	27	1.4-1.5
Ethanol	27	794 at 15°C	21	1.7-1.9
DME	29	735	21	1.7-1.9
Methane	47	423	20	1.8-1.9
Methanol	20	798	16	2.3-2.5
Ammonia	18.6	682	13	2.8-3.1

Hydrogen	120	71	8.5	4.2-4.6
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Sources: Air Liquide 2019; Cardona et al. 2010; ISO 2017 and authors' own calculation based on Boundy et al. (2011)

Figure 33: Energy densities (LHV) for fuels in liquid state



Source: SNL 2003

Frequency of refuelling and time required

Depending on the volumetric density of the fuel and the according storage space requirement, ships might have to refuel more often or might choose to refuel more often. Independently of the frequency of refuelling, the time required for the refuelling of post-fossil fuels might increase, e.g. due to safety procedures. In both cases, time losses and thus revenue losses would accrue. The possibility for loading and unloading in parallel to bunkering would, therefore, benefit the business case and risk assessment would be useful in this context.

Institutional and legal barriers

The uptake of post-fossil fuels could be hindered if international safety standards, the rules of classification societies and fuel quality standards do not cover post-fossil fuels.

The International Convention for the Safety of Life at Sea (SOLAS) requires new and converted ships of 500 GT and above⁵⁶ and which are using gases or other low-flashpoint

⁵⁶ International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

fuels, to comply with the requirements of the IGF Code – the International Code of Safety for Ships using Gases or other low-flashpoint fuels (MSC.391(95)).

Low-flashpoint fuel means gaseous or liquid fuel which has a flashpoint lower than otherwise permitted under paragraph 2.1.1 of SOLAS Regulation II-2/4, i.e. all fuels with a flashpoint below 60°C.

The code provides mandatory criteria for the arrangement and installation of machinery, equipment and systems to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved.

The code focused initially on LNG only, but meanwhile the Maritime Safety Committee (MSC) approved in its 102nd session interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel (MSC.1/Circ.1621) and the Sub-Committee on Carriage of Cargoes and Containers (CCC) is developing draft interim guidelines for the safety of ships using fuel cell power installations (IMO 2020c).

Low-flashpoint diesel (like automotive diesel), LPG, DME, hydrogen and ammonia are, however, not yet covered by the IGF code. A ship that wants to sail on these fuels would have to get approval by using an alternative design (section 2.3 of the IGF code) and having to prove that an equivalent level of safety can be met. The use of these fuels is thus not prohibited, but the approval procedure requires greater effort and is associated with more uncertainties.

However, the CCC Sub-Committee is currently developing draft amendments to the IGF Code to include safety provisions for ships which use low-flashpoint oil fuels like low-flashpoint diesel (IMO 2020c).

The revised IMO IGC (International Gas Carrier) code allows LNG carriers to use the vapour/boil-off gas of their cargo (LNG) as fuel under the requirements as specified in the Code (Resolution MSC.370(93)). If acceptable to a ship's administration, other cargo gases may be used as fuel too, providing that the same level of safety as for natural gas is ensured. However, the use of cargoes identified as toxic products is not permitted. It is currently not allowed to use ammonia cargo boil-off as fuel.

When ship owners consider operating a ship on a post-fossil fuel, they will need/seek approval of its flag state and its classification society for the engine, the fuel supply system and the fuel tank. This will not only be associated with costs but could prove to be a time-consuming task, especially if a fuel was used for which no class rules are in place and tests would be required before an approval can be granted.⁵⁷

Classification societies are gradually developing class rules for alternative fuel types (e.g. DNV GL 2019), but not all potential fuel/propulsion combinations are covered yet (this applies, for example, the use of ammonia in internal combustion engines and the use of fuels other than hydrogen and methanol in fuel cells).

International bunker fuel standards that specify requirements for bunker fuels provide safety for ship operators in the sense that a standard allows them to assess whether a fuel is not only compatible with certain regulations (e.g. sulphur requirements), but also whether it is compatible with their engines. For the same reason, the warranties of engine manufacturers will not cover engine damages in most cases if a bunker fuel is used that is not in line with an international fuel standard. In addition, engine manufacturers may specify additional fuel quality requirements.

The quality of conventional marine fuels is covered under ISO 8216 and 8217. The scope of ISO 8217 was expanded in 2017 to allow for the inclusion of fuels containing not only hydrocarbons from petroleum crude oil but also from oil sands and shale, and hydrocarbons from synthetic or renewable sources.

⁵⁷ The IGF code allows the use of alternate fuel. A risk assessment will, however, have to be completed which demonstrate the same level of safety as using LNG.

The IMO has invited ISO to develop a standard for methyl/ethyl alcohol as a marine fuel and a standard for methyl/ethyl alcohol fuel couplings (IBIA 2018), which will probably also cover DME. The specifications of LNG as a fuel for marine applications (ISO 23306:2020) has recently (October 2020) been published. A fuel quality standard for LPG, ammonia and hydrogen as a marine fuel would still need to be developed to stimulate the uptake of these post-fossil fuels. This is especially important given that some fuel cells are very sensitive to fuel impurities.

MARPOL Annex VI, Regulation 18 requires that fuel oil for combustion purposes derived by methods other than petroleum refining shall not cause an engine to exceed the applicable NO_x emission limit set forth in paragraphs 3, 4, 5.1.1 and 7.4 of Regulation 13. This means that, if an e-fuel or biofuel is used, compliance with the NO_x requirements as laid down in MARPOL Annex VI, Regulation 13 has to be proven. This can be time-consuming and complex.⁵⁸ In contrast, for hydrocarbons derived from petroleum refining, engine certification according to the NO_x technical code is an established procedure.

3.1.2.4 Barriers to the transportation of the post-fossil fuels to ports

Post-fossil fuels might either be transported to the ports by chemical tankers (methanol, ethanol) or by refrigerated/semi-pressurized/fully-pressurized gas tankers (hydrogen, methane, propane, DME, ammonia).

Technological barriers

There are chemical tankers in place that transport methanol and ethanol. There are also LNG carriers in place that can transport liquid methane and LPG and ethylene carriers that can transport propane, DME and ammonia. However, the very first tanker being able to transport liquefied hydrogen is only just being built as part of a demonstration project.

Institutional and legal barriers

An extension of the IMO IGC Code is also required to cover hydrogen as cargo. Currently, interim guidelines for the carriage of liquid hydrogen in bulk have been attached to the IGC Code, being formally adopted by IMO on 25/11/2016 (LR 2020b).

3.1.2.5 Barriers at port level

Ships can only bunker post-fossil fuels if the corresponding port infrastructure is in place and if crew and bunker fuel supplier know how to handle the fuel safely.

The required port infrastructure, like storage tanks, pipelines or bunker vessel, depends on the fuel characteristics type and the bunkering method which can either be truck-to-ship, shore-to-ship or ship-to-ship.

Technological barriers

LPG, methanol, ethanol, and ammonia are globally traded goods which are transported by ships on a large scale. For ammonia for example, there are, according to Alfa Laval et al. (2020), special ammonia terminals in 38 ports which export ammonia, and in 88 ports which import ammonia, including 6 ports which export and import ammonia. Many of these terminals are, however, part of ammonia/fertilizer plants. According to the Methanol Institute (2020b), fossil methanol is available in over a 100 ports today. Port loading and

⁵⁸ DNV, 14/10/2020, Using biodiesel in marine diesel engines: new fuels, new challenges, <https://www.dnv.com/news/using-biodiesel-in-marine-diesel-engines-new-fuels-new-challenges-186705>.

storage facilities are being established for these fuels, which is why we do not expect technological barriers to hinder the development of bunkering infrastructure for these fuel types.

DME production facilities are currently concentrated in China, with smaller capacity in Japan, Korea and Germany (AZoCleantech 2018) and DME is not shipped on a large scale. However, DME is largely used for blending with LPG (IEA 2018b) and physical properties of DME resemble those of LPG. Therefore, fuelling and storage requirements of these fuels closely resemble each other. The same infrastructure could be used with some modifications to the pumps, seals and gaskets (IEA-AMF 2009).

Hydrogen is currently transported either by trucks or by pipelines (Hydrogen Europe 2018), with a limited pipeline network. So far, hydrogen is not transported by ships, which is why no hydrogen port infrastructure is being established. Since there is also currently no demand for H₂ bunker fuel, there is no distribution or bunkering infrastructure for ships in place. However, the very first tanker able to transport liquefied hydrogen is currently being built as part of a demonstration project. This will deliver insights for the design of bunker vessels for liquefied hydrogen, too. According to SWZ (2020), ship-to-truck bunkering could – as with LNG – also be an option for liquid hydrogen, at least from a technological standpoint.

Bunkering vessels for LPG/DME/ammonia have not yet been built. However, existing LPG carriers could be turned into LPG/ammonia bunker vessels and new build LPG/ammonia bunkering vessels could be built in line with LPG carriers. No major technological barriers do thus exist in this regard.

Economic barriers

Ship owners will only decide to invest into a post-fossil-fuelled ship if there is sufficient post-fossil fuel available in the ports relevant for them.

Currently, only for conventional bunker fuel a widespread and large-scale infrastructure is available.

The dedicated LNG bunkering infrastructure for ships is still limited and a large share of LNG bunkering as well as LNG distribution to bunkering locations still takes place by road (DNV GL 2018a). However, the number of LNG bunkering vessels is increasing with the increasing uptake of LNG fuelled vessels.

The Swedish methanol-fuelled ferry bunkers by means of trucks. The renewable methanol bunkered by the German inland ferry is partially produced on the spot, but is mainly imported from Iceland (WAZ 2017). Either shore-to-ship or truck-to-ship bunkering thus possibly applies.

Bunker suppliers might be hesitant to invest into the port infrastructure for post-fossil fuels for two reasons. Firstly, the absence of demand for post-fossil fuels (chicken and egg problem) and, secondly, the investment uncertainty regarding the kind of post-fossil fuel(s) that eventually will be used by the sector.

Institutional and legal barriers

To ensure safe handling of the post-fossil fuels, standards/guidelines for the bunkering process and the design of the infrastructure need to be in place.

For LNG, several standards/guidelines have been developed, e.g. ISO 20519 (Ships and marine technology – Specification for bunkering of liquefied natural gas-fuelled vessels). For methanol, LR (2020a) has recently developed several guidance documents outlining the procedures required for the safe bunkering of methanol including checklists to assist shipowners/operators, ports, bunker suppliers and other stakeholders with safe storage and handling. These guidance documents are also relevant for ships operated on DME with methanol converted onboard the ship.

For ethanol, LPG, DME, ammonia, and hydrogen international standards/guidelines would still have to be developed, at least when it comes to port infrastructure other than storage. Standards/guidelines for

handling of ethanol, LPG and ammonia as cargo will be useful in this context and the methanol guidance documents will probably allow a rather quick development of ethanol guidelines.

Independently of the fuel type, the use of post-fossil fuel could be impeded and discouraged if regulations were not standardized and differed between ports and countries.

3.1.2.6 Conclusions

For maritime shipping, different post-fossil fuel options are conceivable: Due to air quality regulation and the heterogeneity of the sector, different fossil bunker fuel types are currently being used (HFO, MGO, LNG, methanol) and further fossil bunker fuel types (DME, LPG) are being tested/considered. This has led to a variety of internal combustion engines (ICE) which are being used and are under development as well as to the development of ICE which allow for fuel flexibility. In principle, all these bunker fuel types could thus be used as e-fuels in order to decarbonize the maritime shipping sector. Since these fuel types are hydrogen carriers, they could also be used in fuel cells, too. In addition, the use of hydrogen and ammonia are considered to be options for decarbonizing the sector, both for use in fuel cells and for use in ICE.

Therefore, the post-fossil fuel options for maritime shipping can in principle be used in either ICE or in fuel cells.

Regarding the use of post-fossil fuel in ICE, there are alternative fuel types which, next to e-diesel, are promising since the technology readiness level of the corresponding ICE engine is relatively high (Table 26).

Currently, for each type of ICE engine there is, in principle, an e-fuel alternative that could be applied if available, but not all of these fuel options can be used in all engine types⁵⁹ and system costs differ highly between fuel types (see Table 26 for relative assessment).

Table 26: Comparison of technology readiness and system costs if fuels are used in ICE

Post-fossil fuel type	Technology readiness* ICE	System costs ICE
Diesel	++	++
Methane	++	--
Methanol	+	+
DME	0	+
Propane	0	-
Hydrogen	-	--
Ammonia	--	-

Notes: A plus indicates that an option is assessed as relatively better compared to the other options, whereas a minus indicates that an option is assessed less positively.

*The technological readiness has been assessed based on the analysis presented in this report. No specific, standardized guideline to determine quantitative technological readiness levels has been applied to this end.

Source: Author's own compilation

Technology readiness and system costs are obviously the best for diesel.

Methane is already used in maritime shipping, but system costs for cryogenic fuel supply and tank systems are rather high and if used in Otto cycle engines, methane slip can occur.

⁵⁹ Especially for four-stroke engines, there seem to be less options.

With a relatively high technology readiness and relatively low system costs, methanol seems to be a promising option for the use in ICE engines, but depending on the relative e-fuel prices, DME and propane might become relevant options too.

Given the technology readiness level of the corresponding engine, ammonia is an option for the medium term. The development of a marine hydrogen ICE is more advanced at this stage, but the engines under development are suitable for relatively small ships only. System costs for hydrogen can be expected to be higher than for methane and for ammonia we expect them to be comparable with propane/LPG. However, depending on the ship's year of build, aftertreatment systems to reduce the NO_x emissions might have to be applied to an ammonia-fuelled ship and aftertreatment systems to reduce N₂O might also be required, both increasing the system costs associated with ammonia.

Due to the tank storage space requirement, hydrogen might not be an option for very small ships and due to its low energy density also not for very large ships, at least if a higher frequency of bunkering is not an option. A higher frequency of bunkering is more likely an option for smaller vessels, which in general sail shorter distances between port calls.

A potential large-scale application of the different fuel types depends on whether ships can/will be retrofitted to use the fuels.

Depending on the fuel price, e-diesel and e-methane could be an attractive e-fuel option for ships that are currently HFO/MGO-fuelled and LNG-fuelled respectively since no retrofit costs would accrue.

For ships that are already equipped with a gas engine or a dual-fuel engine, the affordable range of post-fossil fuels other than e-diesel can in general be expected to be higher in terms of retrofit costs.

For ships that are not equipped with a gas or dual fuel engine, methanol seems again to be a promising option since it is liquid at ambient temperature like diesel and system costs seem to be relatively low.

In general, ship conversions are rather expensive, which is why only relative expensive ships have been converted on a commercial basis in the past. Greenhouse gas reduction measures for ships might thus also induce earlier scrapping of ships.

The use of post-fossil fuels in fuel cells is, due to the high system costs, not an option in the short and probably also not in the medium term. If system costs drop and the technological readiness improves, they could become a viable option, also considering that e-fuels will be relatively expensive⁶⁰ and given the relatively high energy efficiency of fuel cells.

For maritime shipping, it holds that mainly hydrogen- and methanol-fuelled FCs have been tested, which is why the technology readiness level is expected to be higher for these two fuel types. Due to the high efficiency of the fuel cells, tank storage space required for hydrogen might be less than for comparable ships equipped with an ICE and thus might allow hydrogen to be applied to more ships. However, the size of the fuel cells might prevent fuel cells to be used on large ships. Regarding existing ships, the application of fuel cells only makes sense for ships that are already equipped with an electric engine, which greatly reduces the scale for retrofitting.

Table 27: Comparison of technology readiness and system costs if fuels are used in fuel cells

Post-fossil fuel types	Technology readiness fuel cell	System cost fuel cell
Methane	--	--
Methanol	-	--

⁶⁰ For production cost estimates of post-fossil fuels, see e.g. AVW; AEW; FE (2018); Cerulogy (2018). Brynolf et al. (2017).

DME	--	--
Propane	--	--
Ammonia	--	--
Hydrogen	-	--

Notes: A plus indicates that an option is assessed as relatively better compared to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Author's own compilation

DNV GL (2017d) considers the following three fuel cell types as most promising for marine applications: PEMFC, HT-PEMFC, SOFC.

Comparing the different post-fossil fuel options, hydrogen is the most efficient option in the sense that if applied to fuel cells it requires the least pre-processing before it can be used in a fuel cell. It makes sense to use hydrogen in a PEMFC, which is relatively sensitive to fuel impurities but cheaper than HT-PEMFC as well as SOFC and which has an electrical efficiency comparable with HT-PEMFC. This is also the case given the fact that a PEMFC is operated at a relatively low temperature, making it safer in combination with the extremely flammable hydrogen on board.

If another H₂-carrier is used as fuel, more pre-processing is required, depending on the sensitivity of the FC to fuel impurities. HT-PEMFC and SOFC are more expensive than a PEMFC but require less pre-processing. SOFC is more expensive than HT-PEMFC, but is also more efficient, especially if waste heat recovery is applied. Both HT-PEMFC and SOFC have been tested with methanol. Should liquid hydrogen turn out to be significantly more expensive than other e-fuels, the costs for pre-processing other hydrogen carriers to be used in a fuel cell might make sense too.

Independently of the propulsion system, the fuels differ in the tank storage space requirement, which can have an impact on the revenue of the ships if cargo or passenger space is lost. Also independently of the propulsion system, there are safety aspects to be considered for the different fuels, which not only have an impact of the ship's system and operational costs, but which should also be considered if fuel-specific policies are developed, depending on whether these are options to be incentivized.

Table 28: Comparison of relative storage space requirements, toxicity and flammability of the different fuel types

Post-fossil fuel types	Relative storage space requirement	Toxicity	Flammability
Diesel	++	-	+
Methane	-	0	-
Methanol	+	-	0
DME	0	0	-
Propane	0	0	-
Ammonia	-	--	+
Hydrogen	--	0	--

Notes: A plus indicates that an option is assessed as relatively better compared to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Author's own compilation

Hydrogen has relatively low energy content per litre and has to be stored in insulated tanks, thus requiring a relatively large amount of tank space. Methane has relatively high energy content per litre, but has also to be stored in insulated tanks, though less insulated than hydrogen tanks. Propane, DME, and ammonia

can be stored in less insulated tanks compared to methane; of the three fuels, propane has the highest and ammonia the lowest energy content per litre. Methanol is liquid at ambient temperature and has an energy content per litre which lies between methane and ammonia.

Both methanol and ammonia are toxic to humans, with ammonia also being very toxic to aquatic life.⁶¹ Regarding flammability, however, ammonia is a less dangerous substance than the other fuel options considered, because it is classified as flammable only, whereas methanol as highly flammable and the other fuel options as extremely flammable. In addition, for the ignition of hydrogen, very little energy is required and it escapes relatively easily, increasing the likelihood for an explosion.

Institutional and legal barriers (in terms of voids that need to be filled) are the highest for those fuel types, for which the ICE engines have a relatively low technology readiness level (ammonia, hydrogen) and for which no/relatively little experience is readily available from the transport of the fuels as cargo (hydrogen). The latter is also relevant for the technology readiness of the corresponding port infrastructure.

Table 29: Comparison of fuel types in terms of institutional and legal barriers and the technology readiness of port infrastructure and of marine transport

Post-fossil fuel types	Institutional and legal barriers	Technology readiness port infrastructure	Technology readiness of ships that can transport the fuels to the ports
Methane	+	++	+
Methanol	0	+	+
DME	-	0	0
Propane	-	0	+
Ammonia	--	0	+
Hydrogen	---	-	-

Notes: A plus indicates that an option is assessed as relatively better compared to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Author's own compilation

The following table provides an overview of the advantages and disadvantages of the different fuels if applied in shipping, along with the major barriers to use of the fuels in shipping.

Table 30: Overview of main advantages, disadvantages and major barriers to the use of the fuel types that could be addressed

	Advantages	Disadvantages (second column: potential non-CO ₂ greenhouse gases)	Major barriers to the use of the e-fuel that could be addressed
Diesel	<ul style="list-style-type: none"> - Can be used by majority of ships (with compression ignition engines) without substantial additional capital costs - supply infrastructure readily available 	<ul style="list-style-type: none"> - Probably not a good option for fuel cells - Toxic to aquatic life 	Regulations not fully developed for e-diesel and low-flashpoint diesel

⁶¹ Note: residual bunker fuel is also classified as very toxic to aquatic life.

	Advantages	Disadvantages (second column: potential non-CO₂ greenhouse gases)		Major barriers to the use of the e-fuel that could be addressed
Methane	ICE available and LNG-fuelled ships (500 expected in 2020) can substitute LNG by e-methane	<ul style="list-style-type: none"> - Space requirement of tanks might not allow application to very small ships - Space requirement of tanks can lead to a loss of cargo/passenger space - High system costs due to cryogenic storage and very high safety requirements - Formaldehyde emissions if Otto cycle engines is used 	<ul style="list-style-type: none"> - Methane slip and according global warming effect 	<ul style="list-style-type: none"> - Availability of supply infrastructure - Aftertreatment systems with catalysts to oxidize the residuals of unburned methane not yet available
Methanol	<ul style="list-style-type: none"> - ICE available and there is already a small number of methanol-fuelled ships - No cryogenic storage required since liquid at ambient temperature. - Relatively low system costs - There is some experience with the use of methanol in marine fuel cells. - Rules and regulations already under development 	<ul style="list-style-type: none"> - Toxicity to humans - Formaldehyde emissions if Otto cycle engines is used - Certain materials have to be avoided due to corrosiveness 		<ul style="list-style-type: none"> - Availability of supply infrastructure - Rules and regulations currently only partially developed
DME	<ul style="list-style-type: none"> - ICE available - Does not require dual fuel system 	<ul style="list-style-type: none"> - High safety requirements due to extreme flammability - Certain materials have to be avoided due to corrosiveness 		<ul style="list-style-type: none"> - Availability of supply infrastructure - DME not included in current rules and regulations

	Advantages	Disadvantages (second column: potential non-CO₂ greenhouse gases)	Major barriers to the use of the e-fuel that could be addressed
Propane	<ul style="list-style-type: none"> - ICE available - Several projects with Approval in Principle from major classification societies are ongoing - LPG is shipped as cargo by liquefied gas carriers and LPG is used as automotive fuel which means that there is experience to build on - Space requirement of tanks is lower than for methane and hydrogen 	<ul style="list-style-type: none"> - High safety requirements due to extreme flammability 	<ul style="list-style-type: none"> - Availability of supply infrastructure - LPG not included in current rules and regulations
Ammonia	<ul style="list-style-type: none"> - Carbon-free fuel - Low flammability makes it relatively safe in terms of explosiveness - Space requirement of tanks is lower than for methane and hydrogen - Ammonia is being shipped as cargo by liquefied gas carriers which means that there is experience to build on 	<ul style="list-style-type: none"> - ICE still under development - Certain materials have to be avoided due to corrosiveness - Toxicity to humans and aquatic life - Medium system costs due to storage and high safety requirements (due to toxicity) - Relatively high NO_x emissions if used in internal combustion engine may require aftertreatment (EGR or an SCR requiring ammonia could be used here) - For ICE under development N₂O emissions is a challenge and technology to clean exhaust gas not proven yet 	<ul style="list-style-type: none"> - Technology readiness of ICE - Availability of supply infrastructure - Ammonia not included in current rules and regulations

	Advantages	Disadvantages (second column: potential non-CO ₂ greenhouse gases)		Major barriers to the use of the e-fuel that could be addressed
Hydrogen	<ul style="list-style-type: none"> - Carbon-free fuel - Can be used in fuel cells with least pre-processing effort 	<ul style="list-style-type: none"> - ICE not yet available - Space requirement of tanks might not allow application to very small ships - Space requirement of tanks can lead to a loss of cargo/passenger space - Low energy density of LH₂ might require large ships to refuel more often; if ships operated on relatively short distances (e.g. ferries) this might however not be an issue - High system costs due to cryogenic storage and very high safety requirements - Relatively high NO_x emissions if used in ICE may require aftertreatment 	<ul style="list-style-type: none"> - If hydrogen slips, it is very likely to have a small, indirect warming effect, but exact GWP is still uncertain 	<ul style="list-style-type: none"> - Technology readiness of ICE - Space requirement of tanks - Technology readiness of supply infrastructure - Hydrogen not included in current rules and regulations

Source: Author's own compilation

3.2 Potential instruments to facilitate the use of e-fuels

After the in-depth description of barriers to the use of e-fuels, the following chapter provides an overview over the potential instruments to facilitate the use of e-fuels. The potential instruments discussed are differentiated by three different levels in the value chain that can be addressed:

- ▶ research and development,
- ▶ production and
- ▶ use.

Each step has particular challenges; the political instruments are linked and should be used in a stepwise approach. For instance, it could be relatively inefficient to address incentives for the use of e-fuels in an early stage, when challenges concerning processes and facilities for large-scale production are still unresolved. However, considering the limited time-frame to decarbonize aviation, some level of inefficiency might need to be tolerated to ensure an appropriate contribution of aviation to global GHG mitigation efforts. Furthermore, this chapter aims to at least briefly outline advantages and disadvantages for each political instrument aiming at incentivizing e-fuels.

3.2.1 Research and development of e-fuels

A review of the existing literature reveals that the basic processes for the production of e-fuels are well understood. However, further significant efforts are needed to achieve a large-scale application and commercialisation at acceptable production cost levels. Even under favourable parameters, it is likely that PtL production will be costlier in the long term than today's jet fuels based on mineral oil.

Key research and development efforts and large-scale demonstrators are required, for instance, in the sector of water electrolysis with renewable electricity, CO₂ extraction from industrial process or CO₂ capture from the atmosphere as well as the development of processes and catalysts for both the Fischer-Tropsch

and the methanol route for PtL production. All these elements are ultimately cost inputs for PtL production. Some examples illustrate the long way that is still to go to realize large-scale PtL production. For instance, the world's largest water electrolyser to be built at the refinery in Wesseling in Germany with a 10 MW peak capacity will require an investment of € 20 million with an estimated output of 1 300 tonnes of hydrogen per year, while the overall refinery requires 180 000 tonnes of hydrogen for its processes (ITM Power 2019), which continue to be produced with high greenhouse gas emissions originating from steam reforming.

Hence, it can be considered that a key element for a progress in PtL production/use is the increase in efforts for research and development of processes and their large-scale commercialization. It seems to be realistic that private investment alone will be insufficient to achieve an accelerated progress with PtL production/use. State support seems to be important, as research and development with regard to e-fuels is subject to market failure. Investments in R&D by private stakeholders are considered to be too risky; therefore, not enough funds are invested in the R&D efforts.

Besides subsidies for the R&D of processes, the state could intervene by funding pilot e-fuels refineries. This could be a valuable proof of concept in case no private investment is offered. Efforts in this direction are, for instance, being made by the Joint Technology Initiative Fuel Cells and Hydrogen, which contributes € 10 million to the above-mentioned water electrolyser at the refinery in Wesseling.

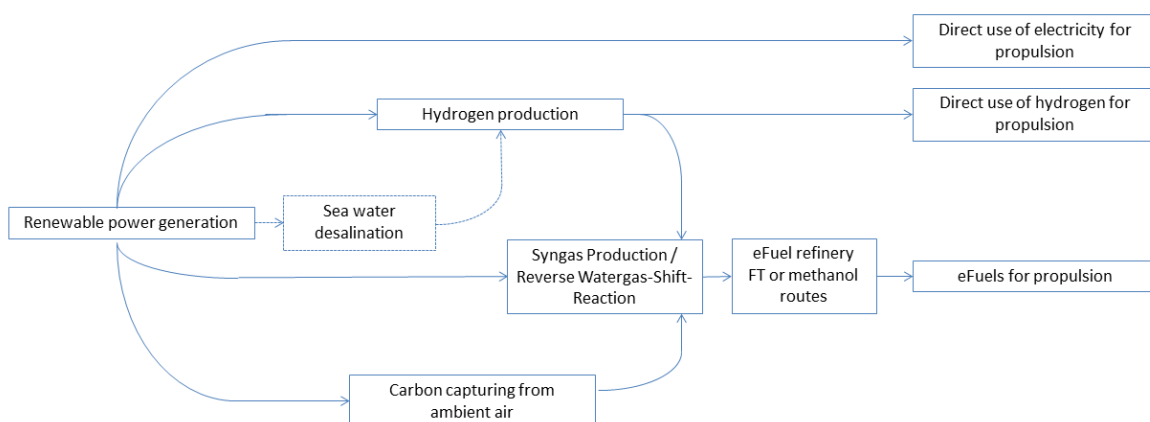
Incentives for the development of e-fuels can play an important role to convince investors to invest money into risky projects, which could yield substantial returns in the long term.

3.2.2 Production of e-fuels

Once the key challenges in the area of physical/chemical processes are solved and the most promising technological routes are identified, the large-scale production of e-fuels could start. Various further challenges emerge here.

The following figure shows a schematic overview of potential PtL production routes with the Fischer-Tropsch or methanol routes, illustrating two key drivers of e-fuels production costs: energy input costs and capital costs for energy generation and refinery facilities.

Figure 34: Flow chart of PtL production with Fischer-Tropsch or Methanol routes



Source: Author's own compilation

In the centre of the PtL production process is electrical energy from renewable sources, which is required for hydrogen production, carbon capture, running the PtL refinery and potentially run desalination plants for sea water. Hence, we can conclude that e-fuels production costs will ultimately be driven by energy

costs and capital costs to build hydrogen production and carbon capture facilities, desalination plants, e-fuels refineries and initially also renewable power generation plants.

At this point, we can already conclude that focusing only on the aviation sector when trying to develop a successful e-fuels roadmap is an insufficient strategy. Aviation fuel demand alone is not likely to achieve sufficient scale economies in the components required for e-fuel production. Components that are part of the Sustainable Alternative Fuels (SAF) production process such as green hydrogen generation and direct air capture of CO₂ are also required for other applications, not only in the transport sector. Hence, the view must be widened as many elements of energy, industry and transport policy interact and need to be adjusted to fit well together. For example, there might be other sectors in which electrical energy from renewable sources could replace energy from fossil fuels more efficiently (e.g. an earlier cut-off of coal-based power plants which generate electric power for general use in households).

More research on hydrogen production and carbon capturing is research (e.g. conducting pilot projects for direct air capture). Key research challenges in this area are the increase in efficiency for electrolysis and an increase in the efficiency of carbon capturing. System aspects may also play a large role here, e.g. in relation to whether hydrogen production should be centralized or de-centralized (e.g. at individual wind turbines at times when no electricity is demanded by the network). Concerning carbon capture, solutions for efficiency challenges have to be found when it is applied to non-concentrated CO₂ flows, i.e. capturing carbon from the ambient air, which currently is highly inefficient. To date, direct air capture (DAC) of CO₂ has been realized only on relatively small scales, with costs well above 200 €/tCO₂ captured. This is expected to decrease to 38-54 €/tCO₂ in 2050 (Fasihi et al. 2019). In the study conducted by FE (2018), these elements of an e-fuels introduction strategy are called 'pillar technologies,' for which tailored roadmaps need to be developed.

From the physical facilities required for the e-fuels production chain, we can further conclude that a substantial amount of capital will be required to set up all elements of the production chain. With a reduction of capital costs, the production costs of key input factors for the e-fuels production chain (electricity, hydrogen, carbon) can also be reduced.

The **capital cost problem** could be addressed directly by the state, e.g. in the form of loan guarantees for private investors. Subsidies for the construction cost of elements of the e-fuels production chain could also be applied, as was the case with the Rhineland refinery 10 MW electrolyser, for which the Fuel Cells and Hydrogen Joint Undertaking of the EU supplied half of the € 20 million investment costs (FCH 2019).

To date, considerable uncertainties exist concerning the amortization of investments in e-fuels production infrastructure (e.g. technological progress, carbon prices, public subsidy policy to name). They impede a quick introduction of e-fuels into the market. The effective and efficient policies to overcome these uncertainties are discussed. However, advocates of a market-based approach argue that a market failure exists, which should be corrected by political intervention. Others argue that markets are not the right tool for ensuring a system transition in a short period of time. The appropriate approach is probably an effective regulation, which establishes incentives for private investors, which currently are hesitant to become first movers. Changes in framework conditions over the economic lifespan of the projects may render any investments obsolete before they have amortized. Hence, it is logical and economically prudent for the state to act. However, in all cases, it would have to be assessed to what extent other use of public money could generate higher benefits.

In order to avoid the market failure emanating from the first mover disadvantage, the state could offer **guaranteed prices for e-fuels**. This would create legal certainty for investors and incentives for PtL production. The economic rationale of this instrument was applied when setting up the German Renewable Energy Sources Act (EEG), which provided investors incentives to invest into renewable power generation. This was particularly important when wind and photovoltaic energy generation emerged, but still had a relatively

high cost disadvantage compared to conventional electricity generation. A key challenge associated with this instrument is the generation of funds that can be re-distributed to the e-fuels production. In the EEG system, surcharges are levied on the consumers of electricity and paid to the operators of renewable power generation facilities which feed electricity into the network.

With regards to the incentives to invest into renewable power generation, the EEG system can be considered to be successful, as more than 40% of electricity consumed in Germany was from renewable sources in 2018. However, it is often criticized that the EEG system has led to a redistribution of more than € 30 billion (BMW 2018) from consumers to the renewable energy industry.

A similar approach could be developed for the e-fuels system, which requires users to pay a surcharge to subsidize the production of e-fuels. While an EEG-like system for e-fuels in aviation is theoretically conceivable, its compatibility with European and international law should be addressed. In aviation, bilateral air service agreements govern the legal aspects of commercial air transport between two states. Typically, fuel taken on board for international flights is exempted from taxes and other charges (UBA 2005). It should be analyzed whether an EEG-like surcharge would constitute a form of 'charges', which would then be excluded in the majority of bilateral air service agreements.

Alternatively, any surcharge for the production of e-fuels could also be levied upstream at the level of fuel producers or distributors. This could potentially avoid any conflicts with aviation law.

Theoretically, it is conceivable that an EEG-like surcharge could be applied on domestic flights only (based on an amendment of national law⁶²) or on intra-European flights only (based on an amendment of EU law). This, however, would substantially reduce the environmental effectiveness, as according to DLR estimations, of the 8.7 million metric tonnes of jet fuel used on flights departing Germany in 2016, only 0.57 million tonnes were used on domestic flights and 2.8 million tonnes on flights to geographical Europe. However, it may also take some time until production capacities are built up in order to produce enough synthetic fuels required to be used on all types of flights.

A key benefit of the surcharge policy instrument is the separation of financial flows for the support of e-fuels production and the physical use of e-fuels. If the physical distribution to all users is too costly or complicated, users not using e-fuels physically would still contribute to the PtL production. This resembles the network characteristics of the electricity market: not all users receive the same amount of renewable energy, but all users contribute to the production of electricity from renewable sources with the same surcharge per kWh of electricity consumption.

Finally, the **international dimension** of e-fuels production should also be considered. As energy costs will be a major driver of e-fuel costs, the location of the e-fuels production chain or parts of it should be considered with respect to economic efficiency. This could result in production locations, for instance, around the 'sunbelt' of the equator where photovoltaic electricity generation is favourable or in places with a particular efficiency for wind power or geothermal energy. Hence, e-fuels production may also have a favourable impact on economic development for countries that have a potential to participate in international energy projects. Any development aid in this direction could have positive impacts not only on the receiving countries, but also for the consumers of energy in the developed countries.

⁶² Directive 2003/96/EC Art. 14 (2) allows Member States to introduce a tax on fuels used for commercial aviation for domestic services. It is beyond the scope of this study to assess whether a surcharge for the promotion of e-fuels production would violate the tax exemption of Directive 2003/96/EC on intra-community or international flights.

3.2.3 Use of e-fuels

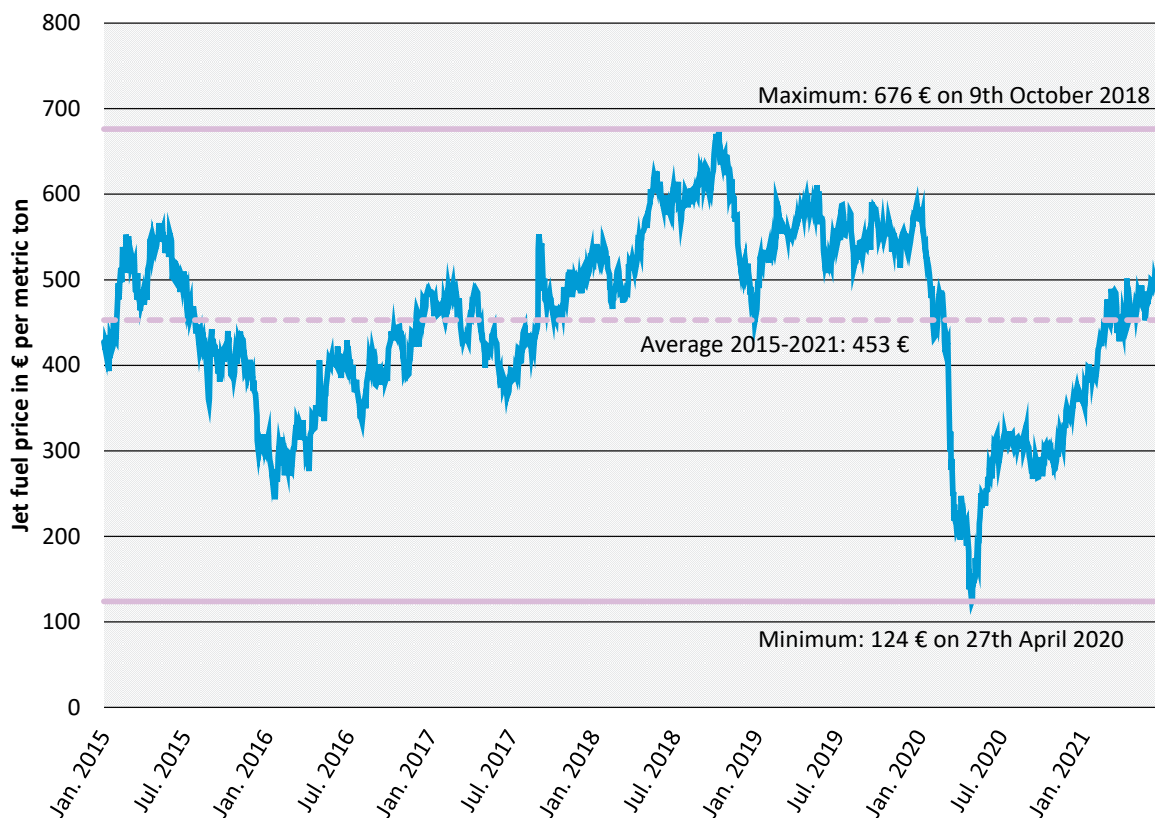
3.2.3.1 Aviation

Besides research, development and deployment, policies which incentivize the use of e-fuels are the third pillar in the introduction roadmap.

One major leverage point is **reducing the price differential** of conventional fuels and e-fuels for the users. Even under favourable conditions, future production costs of e-fuels are expected to be higher than the costs of conventional fuels by the majority of literature sources. Although it is highly uncertain in which direction future fuel prices will develop, as increasingly exhausted oil fields resulting in higher production costs on average will coincide with a potentially declining demand, when other sectors will have shifted to regenerative energy sources. In any case, developing and introducing policies which address a potential longer lasting competitive disadvantage of e-fuels compared to petroleum-based fuels is a prudent strategy. Several policies could be applied in order to reduce the price differential:

A potential policy could be to increase the costs of emitting carbon dioxide from the use of conventional fuels, while exempting users from any taxes, charges or emissions allowances from the portion of fuel consumption that comes from e-fuels. In aviation, carbon dioxide emissions are currently priced via the EU ETS aviation within the European Economic Area, where the allowances for emitting one tonne of carbon dioxide are currently (as of March 2021) priced at approx. 40 €/t, although a substantial number of allowances is distributed free of charge to the aircraft operators. Generally, at a price level of 40 €/t of CO₂, incentives to reduce carbon dioxide emissions are relatively low, as one tonne of fuel was in a price range of 124 € to 676 € in the timeframe 2015 to 2021 (Figure 35).

Figure 35: Jet fuel price development 2015-2019



Source: Based on data of the US Energy Information Administration and European Central Bank

Based on prices at the European Energy Exchange, the costs of emissions allowances required for using one ton of fuel are currently approx. € 120. The actual 'surcharge level' is far lower as allowances are distributed free of charge in the EU ETS; and under Carbon Offset and Reduction Scheme for International Aviation (CORSIA), the baseline of 2019 emissions applies without any offset obligation. From 2021 onwards, CORSIA will require aircraft operators to surrender offsets for emissions exceeding the 2019 baseline of emissions for all flights between countries participating in the CORSIA scheme (the previously agreed baseline of average 2019/2020 emissions is no longer valid for the Pilot Phase of CORSIA up to 2023 to account for the COVID-19 induced decline in 2020). It is likely that the cost of allowances to be accepted in CORSIA will be substantially lower than within the EU ETS, as e.g. Certified Emissions Reductions (CER) from the Clean Development Mechanism (CDM) are likely to be accepted, which had a price of just € 0.21-0.22 per ton CO₂ in December 2019 (Refinitiv 2020). Hence, it is less likely that CORSIA will reduce the price difference between conventional fuels and e-fuels significantly.

As fuel used in commercial aviation is not subject to a fuel or carbon tax (with the exception of a small number of domestic markets), it is likely that a change in the taxation regime for petroleum-based fuels would be required in order to achieve an effective incentive scheme for the use of e-fuels. At least for domestic flights, EU Member States could introduce a tax for fuels used by commercial aviation (cf. Directive 2003/96/EC Art. 14 (2)). Generally, it is perceived that this instrument is not widely accepted by industry and policy stakeholders, as it will result in a direct cost increase for operators. Typical arguments presented in this context are job losses due to reduced travel activity and fewer revenues from income taxes, revenues and profits. However, a fuel or carbon tax can be a very effective instrument, as the funds generated could be re-distributed to promote projects which foster the transport and energy system transition. However, with the general characteristics of a tax, this appropriation is not guaranteed.

With or without an increase of taxes on petroleum-based fuels, an accompanying policy that could further reduce the differential of end-user fuel prices could be a reduction of or exemption from taxes for e-fuels. Although fuels used for commercial aviation are widely exempted from taxes and hence a tax exemption of e-fuels would not constitute a difference to the use of petroleum-based jet fuel, the spill-over effects of such a policy for the aviation sector should not be underestimated.

In the production chain for synthetic fuels to be used for aviation, there are multiple systemic connections and synergies with supply and demand. This concerns first and foremost the use of electricity from regenerative sources, which has the highest sensitivity for e-fuel production cost. It also concerns various chemical products that are either required as inputs for e-fuel production (e.g. hydrogen, methane or ethanol) or will be produced as side-products which can subsequently be used for other purposes (e.g. oxygen).

With its high dependency on hydrocarbons, the aviation industry can be a pioneer in the set-up of e-fuel production chains, but in the medium to long term, it can be also a beneficiary of economies of scale coming from other sectors. Aviation consumes a relatively small fraction of all liquid hydrocarbons sold in Germany (e.g. 8.7 million tons of jet fuel, compared to 18.3 million tons of gasoline and more than 30 million tons of Diesel in 2016). Due to the systemic interdependencies, policies in other areas of the energy and transport system will also have indirect repercussions on the aviation sector if fuel production infrastructures are built up for other sectors.

One of the key challenges in this regard will be that e-fuels are not necessarily the most favourable strategy for defossilization of ground transport when it comes to efficiency and costs. Even if different strategies are applied for ground transport and other technologies break through (e.g. either direct use of regenerative electricity with battery-power or hydrogen fuel cells for cars), at least part of the technologies used will have a positive impact on e-fuels for aviation, such as affordable power generation from renewable sources or hydrogen production.

If the use of e-fuels for road transport were subject to reduced or exempted energy taxation, it could trigger a considerable incentive for investments in e-fuels production capacities. The positive spill-over effects are based on the assumption that future e-fuels refineries can switch production between road transport and aviation uses.

Another effective policy instrument would be to introduce a **compulsory blending quota** for aviation fuels. This instrument would work analogously to the blending quota applied in Germany for road transport fuels based on the EU Directive 2009/28/EC and German Federal Emissions Law (BImSchG) §37a. Up to now, the blending quota is only applicable to fuels covered by the Energy Taxation Law, where fuels used in commercial aviation are exempted. Currently (as of March 2021), several national blending quotas have either been introduced or are in the legislative process. For instance, Norway has introduced a mandatory blending quota (drop-in) for advanced biofuels in 2020, starting at a low level of 0.5% (Karagiannopoulos und Solsvik 2018). In the Netherlands, discussions are being held on fulfilling a quota of 14% sustainable aviation fuel by 2030.⁶³ In Germany, an e-fuel quota has been proposed by the Federal Cabinet in February 2021 with a revised law transposing the EU Directive for renewable energies in transport (RED II). The e-fuel quota for aviation will start at 0.5% in 2026, increasing over time to 1% by 2028 and 2% by 2030.⁶⁴ Based on the aviation fuel consumption in 2019, this translates into a need for e-fuels of 50,000 t in 2026, 100 000 t in 2028 and 200 000 t in 2030.

For air transport, the blending quota will probably cause fewer challenges than those experienced for road transport. In road transport, a small percentage of vehicles has not been certified for operation with fuels with a higher content of ethanol (E10), hence it was prescribed that gas stations have to offer two different qualities of gasoline (E5 and E10). In aviation, e-fuels blends of up to 50% PtL content are fully compliant with the jet fuel specifications published by ASTM. Hence, it is understood that all commercial aircraft are certified to use of these e-fuels blends. Any duplication of infrastructures in fuel distribution could therefore be avoided as blending will take place directly at the refinery or distribution points outside the airport.

A compulsory blending quota could be considered an effective policy to promote the use of e-fuels. Also with regards to dynamic efficiency, a blending quota could be regarded as preferential: through a compulsory quota to be set in advance, a signal will be given to any potential investors in the e-fuels market that it is efficient to develop cost-efficient production processes and mass-production facilities. Moreover, a competition for the most cost-efficient production process could be triggered if the blending quota is tailored to CO₂ emission reduction and leaves it to the market to develop the best route and production process to achieve this goal.

The costs for users could remain at acceptable levels as the following exemplary calculation shows: a 5% compulsory blending quota at an assumed price of initially 3 000 €/t for e-fuel would increase the jet fuel price from today's level of 500 €/t to 625 €/t. If this blending quota were applied to all flights departing Germany, a demand for more than 430 000 t of e-fuels would arise. Under these assumptions, user costs would increase by approx. € 1.1 billion (cost difference of 2 500 €/t of fuel multiplied by the consumption of 430 000 t). This cost level approximately equals the revenue of the German Air Passenger Duty, with the result that if the political objective eliminates any potential competitive distortions, this revenue could be

⁶³ Government of the Netherlands, 04/03/2020, Minister Van Nieuwenhuizen imposes use of cleaner fuel in aviation sector, <https://www.government.nl/latest/news/2020/03/04/minister-van-nieuwenhuizen-imposes-use-of-cleaner-fuel-in-aviation-sector>.

⁶⁴ BMU, 03/02/2021, Federal Cabinet adopts new provisions for renewable energy in transport, <https://www.bmu.de/en/pressrelease/9429/>.

re-allocated to the aviation system dedicated to the introduction of sustainable aviation fuels. The aviation industry would support this use of the air passenger duty (BDL 2019).

A key advantage of the blending quota is that it could be introduced with a clear signal to investors with regard to the required size of mass production levels and could be increased gradually as technological progress leads to falling production costs in order to gain acceptance from stakeholders and to avoid cost increases detrimental to overall economic development. It will nevertheless be challenging to set the schedule and quota correctly in order to achieve effective incentives, to consider technological progress appropriately and to avoid a watering down by lobbyism.

First indications of atmospheric researchers show that the use of e-fuels would optimally be prioritized for long-haul flights. These flights fly at high altitudes over long distances through areas with atmospheric conditions promoting relatively large non-CO₂ effects. Research suggests that e-fuels show reduced non-CO₂ effects as the emissions of particles and NO_x is reduced (Braun-Unkhoff et al. 2017). This, however, would induce logistical challenges of distributing e-fuels separately for particular flights. From a transaction cost perspective, it is more likely that e-fuels would be blended directly at a refinery or a fuel distribution centre.

Generally, the transaction costs for a blending quota applied directly at the level of mineral oil producers or distributors would be relatively low. However, the distribution of e-fuels might be challenging: for efficiency reasons not the total jet fuel at each of the German airports may have the same e-fuel content. For instance, it could be the case that an e-fuels refinery exclusively delivers its fuels to a given airport, where an overall blending level of 30% is achieved. At other airports, however, the blending level would be much less or even zero. If the e-fuels quota of, for example, 5% is achieved based on total jet fuel distributed at German airports, this would be acceptable as far as the environmental effectiveness is concerned. However, the distribution of costs for e-fuels among users has to be organized in a fair and equal way in order to avoid the competitive disadvantage for airlines operating at an airport with a higher e-fuels share than others. Hence, the policy might need to have elements of compensation payments, which would then resemble more an EEG-style surcharge model.

The main challenge of a model with surcharges for conventional fuels to support the production and use of e-fuels is the organization of financial flows. As aviation is an international market, a scheme with surcharges would also preferentially cover as many international participants as possible. The negotiations for CORSIA have shown that reaching a global solution can be extremely difficult. Even within Europe, positions on aviation are diverging and would not necessarily result in an efficient European regulation.

The compulsory blending quota which leads to a cost increase in retail fuel costs would have some competitive effects as aircraft operators with a higher share of fuel costs in total operational costs will be affected more intensely by this instrument. This likely applies to long-haul operations, which are generally relatively fuel-intensive. Moreover, with an 'artificial' cost increase for jet fuel, airlines may have a higher incentive than today to operate with a practice called 'tankering'. This means that airlines voluntarily take more fuel aboard at airports with relatively low fuel costs than actually required to operate the next flight segment. This practice is economically reasonable for the operator, when the savings resulting from the price difference for fuel are higher than the costs caused by additional fuel consumption due to the higher total aircraft mass on departure. From the environmental perspective, tankering is considered unfavourable, as emissions increase due to higher fuel consumption.

German aviation industry group BDL, which represents among others key German airlines, most airports with regular passenger or cargo traffic, the air navigation services provider, is concerned about the potential competitive distortions, even at a very small blending quota, as airlines react with a high sensitivity to fuel price differentials, as dedicated tools used in flight planning optimize fuel uptake based on current prices in real-time. BDL suggests a subsidization of e-fuels by revenues generated from the Air Passenger Duty in order to minimize competitive distortions. This suggestion should be investigated further as the

imposition of the duty is independent from the nationality of an airline, the destination of a flight or the fuel taken on board. Hence, all passengers departing from a German airport would contribute and airlines do not have an incentive to reduce fuel uptake at German airports. This step could also have positive impacts on acceptance and visibility as passengers could be made aware that the Air Passenger Duty has a direct connection to emissions reduction. Still, issues have to be resolved under such a proposal as for instance the air passenger duty is not applied for air cargo currently.

A further disadvantage of the blending quota is that it is difficult to achieve any voluntary commitment surpassing the compulsory blending quota. As only one type of jet fuel is delivered, it would be logistically complicated to use fuels with higher e-fuels content.

Besides the economic effects derived from a blending quota, legal aspects also have to be considered. The question is if such a blending quota can be introduced on a compulsory basis for the aviation sector and – if this can be affirmed – on which level of legislation such a step can be initiated. More precisely, the question is whether a technical specification of jet fuel as e-fuel blend could be made mandatory on the level of mineral oil producers or distributors, in order to avoid any legal problems in case this would be done at the level of airlines. At least the introduction of a blending quota in Norway and first steps in the direction of a European blending quota show that the legal obstacles can be surpassed.

Before a blending quota is introduced, exact definitions of sustainability criteria should be provided as it is of utmost importance to avoid any detrimental effects of sustainable aviation fuel production. This could also concern social standards for production, especially when fuels are produced abroad and imported. When the particular emphasis is on a promotion of the introduction of e-fuels, a relatively exact definition of a sustainable aviation fuel quota will be necessary. Since there are very different production processes for sustainable aviation fuels, production costs are also likely to differ. With only one sustainable aviation fuel quota, producers and users might focus on minimizing short-run costs for production and usage. Production technologies at early stages of the learning curve might be disadvantaged under such a regime. This could particularly concern e-fuels, hence the blending quota may need to have sub-quotas for individual production processes (e.g. sustainable biofuels vs. e-fuels).

A further policy instrument that could be used to incentivize the use of e-fuels is the introduction of **green certificates**. Green certificates could prove that a certain level of e-fuels is used somewhere in the aviation system, but do not necessarily require that holder of the certificates uses the e-fuels directly for the own operations. Hence, the main advantage of the use of green certificates is that physical use of e-fuels and monetary support for the production/use of e-fuels are split. Hence, any logistical issues with providing the right quantity of e-fuels at all airports at all times can be overcome. Fuel can be blended according to the level of certificates purchased in the overall system (e.g. Germany or Europe). A green certificate system could be made compulsory with a pre-defined level of green certificates to be held (as a 'virtual blending quota') or used voluntarily with an individually preferred level of contribution. Then, certificates are the means to prove that e-fuels have been used somewhere in the aviation system. The green certificate system could be regarded as a hybrid between blending quota and surcharge. As an element of the blending quota, the overall quantity of certificates determines the average share of e-fuel in the system (e.g. Germany or Europe). As an element of the surcharge, the funding raised by green certificates is re-distributed to the producers or users of e-fuels. Hence, these stakeholders are compensated by the users of green certificates for the higher costs associated with e-fuels. The voluntary use of green certificates can be found in the retail electricity market as suppliers want to offer electricity from renewable sources, for which consumers may have an additional willingness to pay. Due to the network nature of the power grid, however, it is not physically possible to deliver electricity from renewable sources to every individual household that has purchased only 'green' energy. In the aviation market, a voluntary solution might not work, however, as the additional costs for e-fuels are far higher than in the electricity sector, where production from some renewable sources is almost on the same level as from conventional power generation. Moreover, owning

green certificates might not give the same marketing advantage for airlines as in the retail electricity market; in the latter, customers have developed a relatively high awareness for 'green' energy and passengers have a much smaller choice of airlines on many routes than they have in the electricity market.

As with the other policies, the introduction of green certificates should also be checked with regard to the compatibility with the existing legal framework. Again, it would be preferential if such a policy could be applied on the level of mineral oil producers or distributors in order to avoid the constraints of bilateral air service agreements concerning levies, taxes and charges on fuel. Moreover, on the airline level, there might be only limited acceptance as airlines are currently obliged to comply with the EU ETS and CORSIA which is currently limited to 2035. A system of green certificates would be a third system in parallel, which might be problematic with regard to transaction costs and the interaction between the different policies. Also, with regards to the number of regulated entities, an upstream approach would be preferential as there are only very few fuel suppliers, but many more airplane operators. This could ultimately lead to a reduction in transaction costs. Potentially, a trial of the instrument could be launched for domestic flights, which are by definition excluded from ICAO's CORSIA; hence no overlap between the two policies would occur. However, a number of challenges (among them tankering, documentation of fuel used, low environmental effectiveness compared to all flights) would still need to be overcome. An interesting approach could also be the interaction with ICAO's CORSIA for which 'eligible fuels' are foreseen, which reduce the offsetting requirements.

Generally, a green certificate system seems to be preferential for a number of issues (re-distribution of financial budgets to users/producers of e-fuels, overcoming of logistical issues of a uniform blending quota, possibility for a gradual implementation, etc.).

Any policy supporting the introduction of e-fuels to the market should be designed in order to overcome the initial barriers to market entry. Perverse incentives which will result in a perpetuation of the need for subsidies for users or producers should be avoided. Hence, any instrument should be reviewed in line with technological progress and the price differential between conventional fuels and e-fuels.

3.2.3.2 Shipping

Different actions on different levels can be taken to stimulate the uptake of post-fossil fuels by the maritime shipping sector.

On the international IMO level, the existing energy efficiency policies in principle already incentivize the use of post-fossil fuels: The Energy Efficiency Design Index (EEDI) sets minimum requirements for the technical carbon efficiency of newbuild ships. A ship's attained EEDI is thereby calculated by applying a fuel carbon factor. In principle, this carbon factor would be reduced below the value of fossil fuels if post-fossil fuel was used, improving the ship's attained EEDI. However, it is not clear that this would be an effective policy, because verification of the EEDI value is only done once in the lifetime of a ship, namely at the delivery of the ship to the ship owner. For this mechanism to be effective, ships should thus become obliged to prove that they are actually operated on a low/zero carbon fuel on a structural basis and not revert from post-fossil fuels to fossil fuels after delivery of the ship. The CII regulation, currently under development on the IMO level,⁶⁵ could be useful in this context. For ships already subject to the IMO Data Collection System requirements, a mandatory Carbon Intensity Indicator (CII) and a rating scheme based on the CII has been agreed upon. Each year, the actual achieved CII and the corresponding ranking of the ships (A to E) will be determined, with the rating thresholds becoming increasingly stringent up to 2030. For ships that achieve a D

⁶⁵ If the according amendments to MARPOL Annex VI are adopted by MEPC 76 and not objected by a certain number of member states during the subsequent six months, ships would have to calculate the CII from 2022 on and would have to report the CII from 2023 onwards.

rating for three consecutive years or an E rating, a corrective action plan needs to be developed and approved as part of the Ship Energy Efficiency Management Plan. By means of post-fossil fuels, ships could thus improve their CII and CII ranking, with fuel types used being documented by means of the Data Collection System.

Another possible group of policies that could be taken at the IMO level are policies that aim to reduce the costs associated with the use of post-fossil fuels by reducing the relative price of the fuels, like a fossil-CO₂ levy. The design of the policy instrument should thereby ensure that post-fossil hydrocarbons are treated differently than fossil hydrocarbons. Such market-based policies have been discussed previously, but at that time the IMO could not reach an agreement to implement them.

On the international IMO level, it would also be possible to adopt a fuel carbon mandate that obliges ships to (gradually) reduce the fossil carbon content of the fuel used. Such a policy has not yet been proposed or discussed.

At a regional level, e.g. EU-level, similar policies can be contemplated. These would be subject to avoidance which could limit their effectiveness, but they could still have an impact on GHG emissions (CE Delft et al. 2009; Ricardo-AEA et al. 2013). Such instruments include:

- ▶ inclusion of shipping emissions in the EU ETS;
- ▶ a levy on emissions of voyages to EU ports;
- ▶ an obligation to use low- or zero-carbon fuels in specific ship segments (e.g. ferries or short-sea shipping) or in certain regions.

On the national level, fiscal policies could be amended to ensure equal fiscal treatment of post-fossil fuels: Electricity used to produce e-fuels is taxed whereas conventional fossil fuels used by the maritime shipping sector are exempted from energy taxes.

National fiscal policies could also be differentiated by treating investment in ships that can be operated on post-fossil fuels favourably.

Building on the analysis of the barriers that prevent the use of post-fossil fuels in shipping, actions that contribute to overcoming these barriers could be taken on the IMO, EU and/or national level.

In order to reduce the costs associated with the use of post-fossil fuels, R&D projects could be supported that aim to reduce the costs of using post-fossil fuels, e.g. to develop more efficient storage methods for hydrogen or at reducing the costs and life time of fuel cells.

Uncertainties could be reduced by taking the following actions:

- ▶ The development of IMO codes (e.g. IGF code), guidelines (e.g. bunkering guidelines), and ISO standards (e.g. for fuel specifications) could be facilitated by engaging in the according international bodies and committees. LNG can serve as a blueprint for the according processes here.
- ▶ The generation of information could be facilitated by supporting projects that generate relevant input for the development of the guidelines, class rules, IMO codes, ISO standards etc.
- ▶ The exchange of information between stakeholders could be facilitated, e.g. between parties that have tested certain fuels and the potential user of the fuels. On EU level, for example, a European Sustainable Shipping Forum (ESSF) sub-group focusing on 'Sustainable Alternative Power for Shipping' has been established to this end.

- ▶ Investment uncertainty could be reduced by deciding at an early stage whether certain fuel types will be discarded, for example, from a safety point of view. Projects that explore, for example, the requirements and costs to ensure safe handling of ammonia as a bunker fuel (which is very toxic to aquatic life) could be facilitated here.
- ▶ Investment uncertainty could be reduced by stimulating the development of flexible options, both for ships and for fuel suppliers.
- ▶ On the EU level, the Directive on the deployment of alternative fuels infrastructure (2014/94/EU) could be amended to stimulate the provision of post-fossil fuels supply infrastructure too.

3.3 Stakeholder analysis

3.3.1 Aviation

At first sight, the main stakeholders for identifying and implementing paths towards the use of e-fuels in aviation seem to be obvious: fuel suppliers, airframe and engine manufacturers, airlines (e.g. represented by IATA), the legislation and competent authorities (be it at the EU or national levels) and ICAO.

However, a focus at the air transport level and a development of potential measures in cooperation or consultation with airline industry stakeholders might be critical for three reasons:

Firstly, as discussed above, a successful introduction of large quantities of e-fuels might require a system-wide approach for the entire transport sector and not just for air transport, which only represents a rather small share of transport energy consumption and CO₂ emissions. Especially the high levels of energy taxation in the road transport sector might be a good starting point and more efficient leverage for the introduction of e-fuels as the latter's higher costs would have less net impact there.

Secondly, CORSIA can be regarded as a current example for the slow genesis (>10 years) and environmentally ineffectiveness (only post-2019 growth, no consideration of annual emissions levels generated before 2019) of environmental policies at the worldwide (airline) level. Also, it is unlikely that any voluntary commitments by airlines would have a visible effect. On the one hand, a commitment to use e-fuels would be virtually useless as long as synthetic fuels are not supplied ubiquitously. On the other hand, heavy levels of price competition between airlines are likely to bring down any ambitions to voluntarily pay more for more expensive (blended) fuel. However, the situation and willingness of the airlines to use blended fuel is highly dependent on fuel price developments. In order to reduce the exposure to fluctuating oil prices, United Airlines has, for instance, invested in Fulcrum BioEnergy, a company which develops technologies to produce fuels from waste (WT 2015). This could be considered as an example of how airlines could get a direct influence on the development and production of fuels from renewable sources and might also be a role model for e-fuels.

Finally, for any policy, the larger number of airlines worldwide (compared to much smaller numbers of fuel providers) would increase the risk of high(er) monitoring, reporting and verification (i.e. transaction) costs.

Against this background and based on the experiences made with the implementation of CORSIA, leaving the airlines out of the process as much as possible and dealing with the fuel sector only when it comes to compulsory regulatory instruments (like e.g. blending quotas, green certificates or EEG-like apportionments) designed to speed up a potential introduction of e-fuels could therefore be considered. This way, no active involvement of the end-users (=airlines) would be necessary, and more efforts could be put into setting up a regulatory policy at the national or EU level to increase the use of e-fuels in the transport sector (e.g. a rising blending quota for jet fuel provided at EU airports).

Another advantage of implementing any policy, e.g. a blending quota, at the fuel supply/refinery level only is the smaller number of stakeholders to deal with. Any policy to be implemented at the airline (aircraft

operator) level, in contrast, would require the authorities to interact with some 750 European airlines⁶⁶ alone, plus – if applicable – any non-EU carriers operating into Europe.

If a blending quota or different policy, however, was introduced at the refinery level, the number of administratively affected stakeholders would decline hugely. Table 49 in the Annex (p. 236), which is based on extensive desk research using different databases and websites, provides an overview of all refineries which currently produce jet fuel and/or kerosene.⁶⁷ Of the 92 refineries operating in the EU and in the EFTA countries Norway and Switzerland,⁶⁸ only 67 could be identified as producers of jet fuel (Table 49, Annex, p. 236) – a number much more manageable to deal with than the European or even global airline landscape.

Finally, another important player not yet discussed here are the oil-producing and refining countries. They will have to get on board in a system-wide approach to boost the use of e-fuels, e.g. by providing them firm perspectives for a participation in the e-fuels process. Otherwise, there is a high risk that they respond to (and suppress) any serious e-fuel approach with cheap oil.

3.3.2 Shipping

As discussed in section 3.2.3.2, different actions on different levels can be taken to stimulate the uptake of post-fossil fuels by the maritime shipping sector.

From the European perspective, there are three main levels with regards to policy decision-making: the IMO, the EU, and the national, i.e. the EU Member State level. Most relevant bodies in this context are:

- ▶ At the IMO level: The Marine Environment Protection Committee (MEPC) and some of its sub-committees, such as the Sub-Committee on Carriage of Cargoes and Containers;
- ▶ At the EU level: The EU Commission (especially DG CLIMA, DG MOVE, DG ENER, DG RTD), the European Parliament together with the associated ENVI and TRAN Committees as well as the Council of the European Union;
- ▶ At the national level: governments and according ministries.

For the development of a global policy to reduce the GHG emissions of maritime shipping and stimulate the use of post-fossil fuels on a global level, MEPC is the relevant committee to engage in as a national state. In order to reduce legal barriers to the use of post-fossil fuels, the relevant committee would be the Sub-Committee on Carriage of Cargoes and Containers. EU and/or national projects can inform these processes.

Should the European Commission propose a regional policy to reduce GHG emissions from maritime shipping, the European Parliament and the Council of the European Union would have to agree with/agree upon amendments to the proposal. In this process, the Council of the European Union would be the major platform for an EU national state to engage in. In addition, the relevant authorities of Member States can engage in the ESSF, a platform for structural dialogue, exchange of technical knowledge, cooperation, and coordination between the Commission, Member States and the relevant maritime transport stakeholders, with a view to assisting the Commission in relation to the implementation of the Union's activities and

⁶⁶ An analysis of the aircraft operator database provided by ch-aviation.com on 30/01/2019 revealed 742 different airlines and aircraft operators being presently active and registered in the EU or the EFTA countries.

⁶⁷ Jet Fuel, e.g. Jet A-1, is a kerosene-type fuel subject to very comprehensive, internationally standardized quality specifications. In the databases we used, some refineries report simply 'kerosene' as product, while others differ between 'kerosene' and 'jet fuel,' or between 'kerosene' and 'aviation fuel'. In the following, we assume that jet fuel is produced in all refineries which report either 'kerosene' or 'jet fuel'/'aviation fuel' as output product.

⁶⁸ There are no refineries in Liechtenstein or Iceland.

programmes aimed at fostering sustainable maritime transport and promoting the competitiveness of maritime transport in Europe.⁶⁹

There are many other stakeholders on the international and national level that are relevant in this context:

- ▶ ship owner and operators and the according national and international associations like International Chamber of Shipping (ICS), World Shipping Council (WSC), European Community Shipowner's Association (ECSA), Bimco, Intertanko, Verband Deutscher Reeder (VDR) etc.;
- ▶ shipyards and maritime equipment manufacturers and the corresponding associations such as Sea Europe, International Council on Combustion Engines (CIMAC), European Association of Internal Combustion Engine Manufacturers (EUROMOT), Verband für Schiffbau und Meerestechnik (VSM), der Deutsche Boots- und Schiffbauerverband (DBSV) etc.;
- ▶ bunker fuel suppliers and according national and international associations such as IBIA (International Bunker Industry Association);
- ▶ classification societies such as DNV GL, Lloyd's Register, Bureau Veritas, Rina, ABS, ClassNK etc.;
- ▶ Individual ports and according international and national associations such as European Seaport Organisation (ESPO), World Port Climate Initiative (WPCI) and/or the International Association of Ports and Harbors (IAPH), Zentralverband der deutschen Seehafenbetriebe etc.;
- ▶ Bodies and agencies that may be involved in the enforcement of specific policies such as Flag States, European Maritime Safety Agency (EMSA), etc.;
- ▶ International Organization for Standardization (ISO).

3.4 Conclusion

Research has revealed that limited availability and high costs compared to conventional fuels are the main barriers to the use of synthetic fuels in the air transport sector, while technical and certification issues seem to be of lower relevance at least for blending quotas below 50%.

We have shown that, in principle, different types of policies could be applied to support the use of e-fuels in air transport. These include mandatory blending quotas (which could probably increase over time), green certificates, or EEG-like levy. All these policies would avoid a costly duplication of infrastructures in fuel distribution.

It seems more practical and efficient to apply any policy at the fuel provision level and not at the airline level, e.g. to reduce the risk of a delay of the implementation of e-fuels-related policies caused by lobbying and to reduce transaction costs.

In the maritime shipping sector, as in the aviation sector (except for few pilot projects and niches), no e-fuels are currently used. The environmental policy incentives are not sufficient to stimulate the use and the supply of these fuels.

⁶⁹ European Commission, 27/07/2018, Commission decision setting up the group of experts on maritime transport sustainability - The European Sustainable Shipping Forum (ESSF), <https://ec.europa.eu/transport/sites/transport/files/c20184908.pdf>.

However, for the maritime shipping sector there is, in contrast to the aviation sector, a whole range of potential e-fuel options under discussion.

E-diesel could be the obvious choice, being fully compatible with the current system. This option is, however, barely discussed in the literature. This might be the case since e-diesel would not be the obvious choice when it comes to fuel cell application or because it is an option discarded beforehand due to an expected high fuel price.

Various non-diesel fuel options are being discussed for maritime shipping, as the sector is looking for alternative fuels due to stricter air pollution regulations and because fuel cells are looked into as a future alternative for the internal combustion engine. These fuel options are, as fossil variants, developed to very different degrees for the use in maritime shipping.

In addition to environmental policies, targeted policies and actions for eliminating specific barriers to the supply and use of these fuels could be implemented at various policy levels to advance the supply and use of these fuels. The development of LNG supply could serve as a blueprint in this context.

The problem is, however, that it is currently not clear which of the fuel options will prevail. This will highly depend on the price of these fuels and whether options will prove technically superior to others. The optimal solution might also vary between ship types and their activities.

Policies and actions to eliminate specific barriers to the supply and use of post-fossil fuels could therefore be of more generic nature. Or, since the uncertainty itself can be a major barrier to the uptake and supply of post-fossil fuels in maritime shipping, they could be aimed at reducing the uncertainty by either quickly identifying comparatively bad options and/or by stimulating the development of flexible options, both for ships as well as for fuel suppliers.

4 Post-fossil energy supply options

We expand the analyses from technical options for using post-fossil fuels in aircrafts and ships in the previous chapter to include challenges and options of the production of these fuels. Both will be used to weigh the strengths and weaknesses of the various options against each other and to assess the options. The focus in this chapter is on various electricity-based fuels (e.g. green hydrogen and synthetic e-fuels), which we compare these fuels in detail. To this end, we first evaluate the status of green hydrogen and synthetic e-fuels in a comprehensive way according to the following five criteria:

- ▶ technical and market status quo;
- ▶ production cost;
- ▶ specific GHG mitigation potential;
- ▶ water demand and land use;
- ▶ potential to meet long-term fuel demand.

In a second step, we take up the various technologies for production and examine the individual process steps, the integration of the various processes and the resulting impact of the fuel production on other categories.

4.1 General evaluation of green hydrogen and synthetic e-fuels

4.1.1 Technical and market status quo

Hydrogen production by electrolysis is a central (sub)process of all e-fuel production processes. In this process, water is electrochemically split into hydrogen and oxygen by adding electrical energy. In water electrolysis, a basic distinction can be made between low-temperature electrolysis (LTEL) and high-temperature electrolysis (HTEL).

Two major low-temperature electrolysis technologies are currently commercially available: alkaline electrolysis (AEL) is well-established in the market: however, polymer electrolyte membrane electrolysis (PEM⁷⁰ electrolysis or PEMEL) has recently gained attention and increased its market share (Schmidt 2019). Overall, however, electrolysis currently accounts for a very small share (4%) of global hydrogen use⁷¹ and, due to its production costs, is only used when external framework conditions do not permit the use of fossil production options (International Renewable Energy Agency 2018). The current global market for electrolyzers is correspondingly small: IEA (2021b) estimates the global market for new electrolyzers at less than 500 MW per year. Today, electrolyzers in the MW range are produced in semi-manual production; firstly, automated production for electrolyzers would need to be established to scale the technology and develop the market for the technology. In contrast, the HTEL, which permits higher efficiencies, but also requires a constant high-temperature supply and is significantly less dynamic in operation, is less developed. However, a larger scale HTEL unit is planned as part of a first e-crude⁷² production plan in Norway (Holen und Bruknapp 2019).

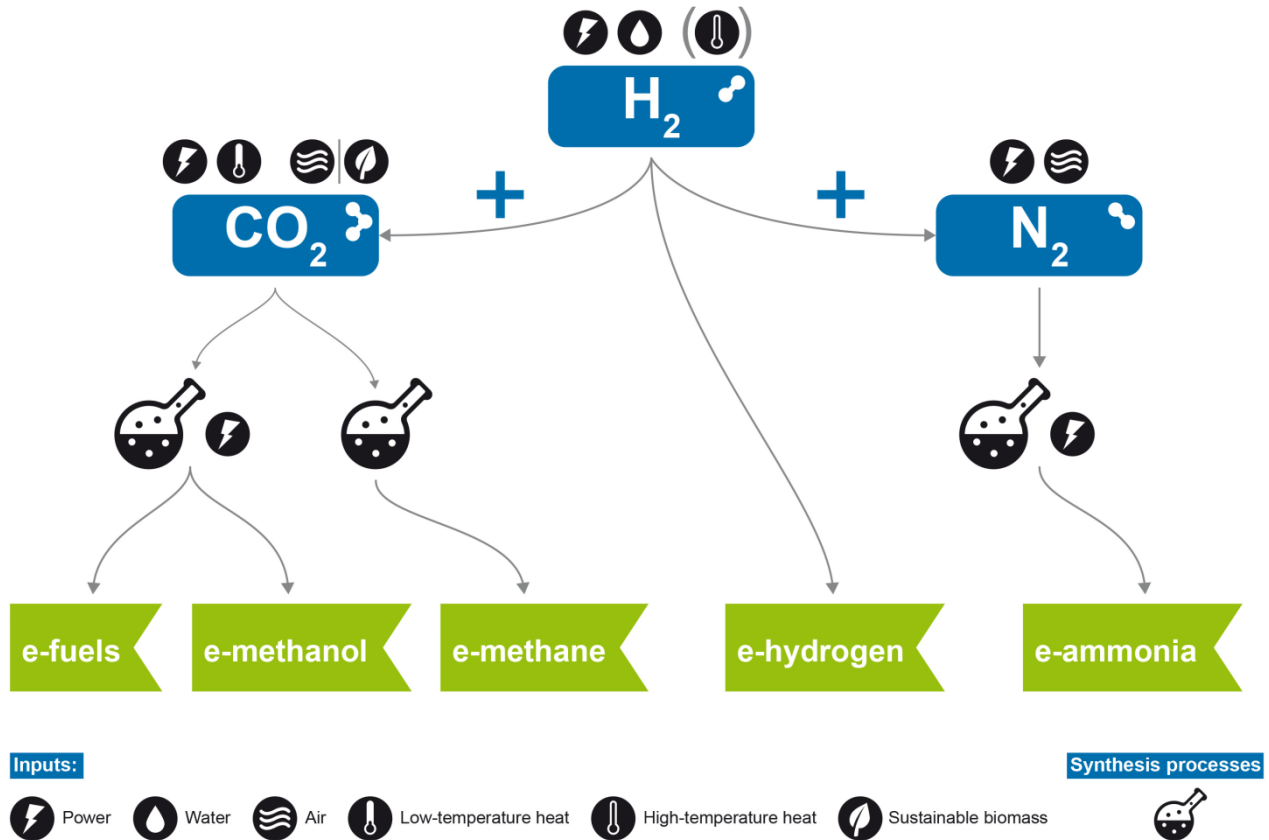
⁷⁰ PEM is also referred to as 'proton exchange membrane'.

⁷¹ Most of today's hydrogen from electrolysis is a by-product of chlor-alkali electrolysis, which is used to produce the basic chemicals chlorine and sodium hydroxide solution.

⁷² E-crude is a mix of hydrocarbons which could be used as a substitute of crude oil as the basis for post-processing into defined marketable products.

The hydrogen produced by electrolysis can be liquefied for transport, if necessary. For use in shipping liquefaction this is a necessary process step (chapter 3). Technically, liquefaction is an established process (section 4.2.1). However, the infrastructure for distribution and the propulsion/storage technology on ships for the use of hydrogen does not yet exist (chapter 3). The substitution of fossil hydrogen in the refining of fossil crude oil products seems to be a plausible application as well, especially for the first market ramp-up phase.

Figure 36: Schematic representation of the production steps of various e-fuels



Notes: The term e-fuels in this figure stands for all liquid hydrocarbon liquid e-fuels.

Source: Authors' own compilation

Another possibility for using hydrogen in air and maritime transport is the synthesis of hydrogen and carbon dioxide or nitrogen into hydrocarbon end products and ammonia (Figure 36). The separation of nitrogen from the ambient air is the standard process for ammonia production, as is the Haber-Bosch process (ammonia synthesis). For e-ammonia production, 'only' fossil hydrogen would have to be replaced by hydrogen from electricity to produce this kind of e-fuel.

The state-of-the-art in the production of post-fossil e-hydrocarbons is at a different level. For GHG-neutral production of the hydrocarbon products, most of the carbon dioxide used in the fuel synthesis processes will come from the ambient air⁷³ (sections 4.1.3 and 4.1.5). Accordingly, only carbon dioxide from processes with sustainable biomass use (indirect carbon cycle) or directly from the ambient air will be available in relevant quantities for post-fossil hydrocarbon production if global demand for e-fuels increases. The separation of

⁷³ Carbon dioxide may also come from other natural sources to be considered climate-neutral. This option is explained in more detail in section 4.1.3, as is the much-discussed use of fossil CO₂ emissions.

carbon dioxide from exhaust gas streams from biogenic industrial processes is an available standard technology which requires rather small energy input (ifeu 2019), but the local concentration and its total volume will be limited. Despite considerable technological progress, carbon dioxide separation from air continues to exist only in the demonstration stage and at rather high cost.

There are basically two process routes available for the synthesis of hydrocarbons: The Fischer-Tropsch synthesis (FT synthesis) and the methanol synthesis (Figure 41). Both, the FT process and today's standard process of methanol synthesis are standard processes on an industrial scale and require pre-treatment of carbon dioxide and hydrogen to produce a syngas via the reverse water gas shift reaction (RWGS reaction). Unlike the synthesis processes, the syngas production has so far only been demonstrated in small-scale plants. In a different production path, methanol is produced by a direct synthesis process of carbon dioxide and hydrogen. This process exists only in the demonstration and small-scale industrial stage,⁷⁴ but might allow faster upscaling than the two-step route via syngas.

Methanol can either be used directly as a fuel after a standard post-processing step of the raw methanol (e.g. in shipping) or can be processed into a wide variety of other fuels (e.g. DME⁷⁵, kerosene⁷⁶) using other raw methanol treatment processes. The methanol path allows for high selectivity of specific end products, but specific fuels are not expected to be the only end-product. Post-processing for certain end products such as kerosene is feasible with existing technology and, however, has not yet been demonstrated. The resulting mixture of hydrocarbons from FT synthesis (e-crude) has to be post-processed and can substitute crude oil in refineries which currently produce various end products for all types of transport and other sectors (e.g. heating, industry sector). Specific process steps, such as the production of long-chain hydrocarbons in the FT process and a very selective refining process can also achieve kerosene shares of 70% and more via this process route.

The synthesis to methane via the Sabatier process is a rather far developed established single-stage reaction that can directly utilize carbon dioxide and hydrogen. There are demonstration plants (e.g. in Werlte, Germany) and they still have to be scaled for industrial use. Liquefaction is additionally required for methane use in shipping.

The analysis clearly shows that e-fuels do not yet have a relevant market share and production still needs to be scaled-up to the industrial scale. This is mainly due to the high costs (section 0) and, for some energy sources, ships, airplanes and infrastructure are not equipped for usage of these fuels. The prerequisite for the large-scale production of e-fuels is the establishment of new and large-scale production capacities for electrolyzers. However, e-hydrogen and e-ammonia appear to be the most technically-advanced production routes of the possible e-fuel options in aviation and shipping. The production of these two energy supply options do not require any new technologies other than fossil hydrogen substitution.

All end-products that require carbon face the challenge of having access to a climate-friendly carbon source in the relevant scale. Since carbon dioxide separation from the ambient air only exists on a small-scale and processes based on biogenic feedstock only provide comparatively small amounts of CO₂, the speed of expansion and the scaling of plant sizes are limited (section 4.1.5). While direct methanol and methane synthesis are well understood on a demonstration and a small industrial scale, it lacks production at large industrial

⁷⁴ The methanol production process from CRI in Grindavik (<https://www.carbonrecycling.is/>) is a direct methanol synthesis process. Recently, the construction of another methanol production facility at small industrial scale via this process route was announced (<https://press.siemens-energy.com/global/de/pressemitteilung/siemens-energy-und-porsche-treiben-mit-partnern-die-entwicklung-klimaneutraler>).

⁷⁵ Dimethyl ether.

⁷⁶ Kerosene from the methanol pathway has not yet been approved for aviation purposes (section 3.1.1.2).

stage. Additionally, there is still a need for research and development of the FT path (e.g. syngas production) and some processing pathways of raw methanol (i.e. methanol-to-kerosene).

For reasons of cost degression, all processes other than ammonia production must still be extended over several development stages to large industrial plants. Time constants for the scaling of the technology, but also for the planning and approval of new plants limit the short- and medium-term availability of fuels for most fuel options. The expectation is that the first large-scale plants can start operating in the period 2028-2030 (NPM, AG 1 2020).

Table 31: Comparison of the technical state of the art and short-term potential of e-fuels

	Technical short-term potential	Comments
Ammonia	+	Production of green hydrogen required
DME	o	Production of green hydrogen required; large-scale sustainable carbon dioxide source missing; upscaling of either direct methanol synthesis or reverse water gas shift reaction required
Hydrogen	+	Production of green hydrogen
Methane	o	Production of green hydrogen; large-scale sustainable carbon dioxide source missing; upscaling of Sabatier process required
Methanol	o	Production of green hydrogen; large-scale sustainable carbon dioxide source missing; upscaling of direct methanol synthesis or reverse water gas shift reaction required
Liquid e-fuels	-	Production of green hydrogen; large-scale sustainable carbon dioxide source missing; upscaling of direct methanol synthesis or reverse water gas shift reaction required; methanol to kerosene processing required

Notes: ++ very positive, + positive, o medium, - negative, -- very negative

Source: Authors' own assessment

4.1.2 Production cost and prices

Decisive factors for the costs of e-fuel generation are the level of the capital costs as well as the costs for the electricity used and the utilization rate of the fuel production plant. Lower costs for renewable electricity generation and a potentially higher utilization rate of the fuel plant speak for the production of e-fuels at favourable locations for renewable electricity generation. For the production of hydrocarbons, the supply of carbon dioxide can also be a relevant cost component (Brynnolf et al. 2017).

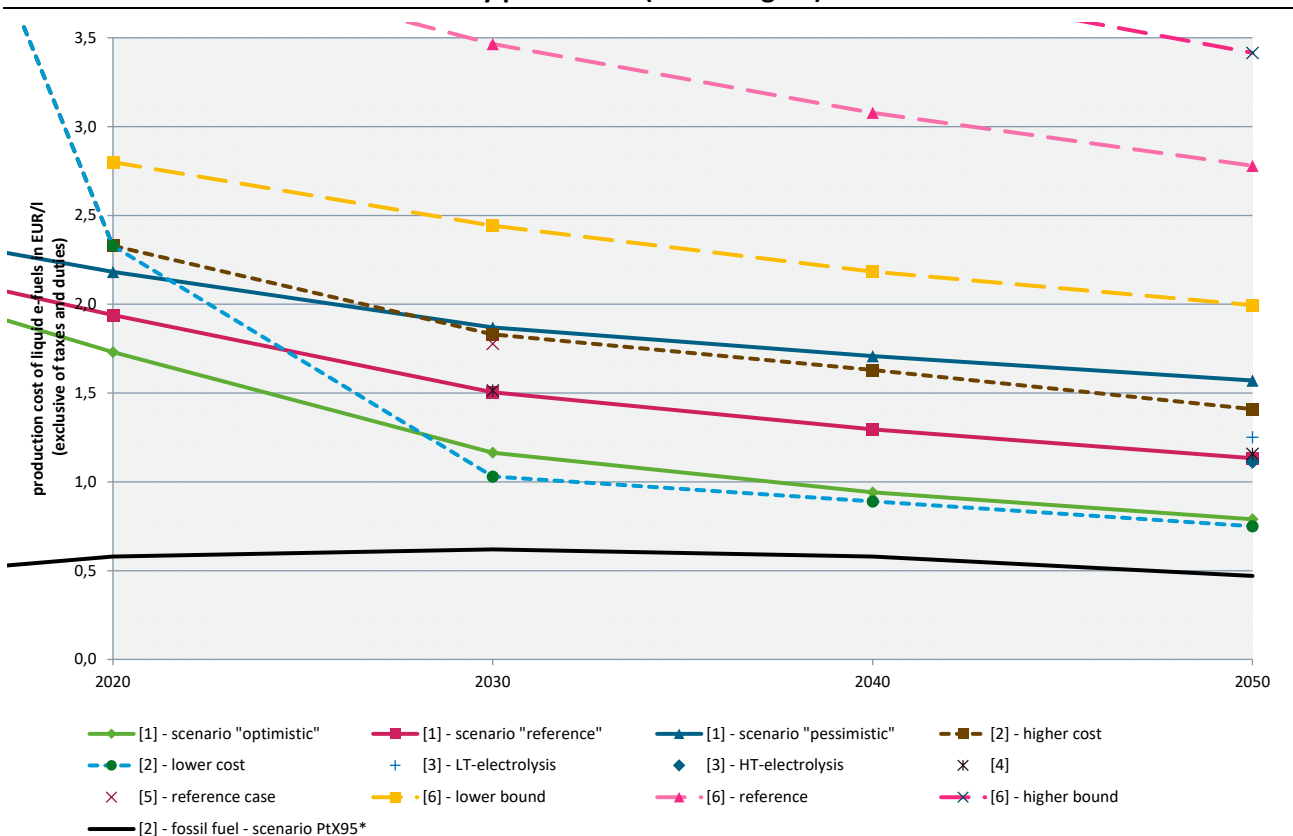
However, there is a trade-off between cost-efficient and GHG-friendly fuel production, especially in the short to medium term during which, in many parts of the world, electricity is still predominantly generated from fossil sources (section 4.1.3). High full load hours and the use of fossil carbon dioxide for the production of hydrocarbons are, for example, modes of operation that bring economic advantages but are problematic for GHG emission reduction in economies with fossil electricity production.

Currently, the production costs of e-fuels are many times higher than the costs of their respective fossil alternatives. As an example, Figure 37 provides an overview of different cost scenarios for the production of liquid e-fuels at favourable sites for renewable electricity production in the Middle East & North African (MENA) region. The estimated production costs for 2020 are no less than three to four times higher than those for fossil fuels. In the scenarios with positive cost developments, i.e. with low costs for renewable

electricity generation and low investment costs for electrolysers and the synthesis plants of fuel production, the costs for the production of liquid e-fuels are higher than those of fossil fuels in the long term. Figure 37 also shows the high uncertainty of potential future e-fuel costs as the high cost scenarios at least more or less double the cost scenarios with the most advantageous cost development in most cost calculations.

The cost scenarios of Prognos (2020) differ from most cost studies with much higher costs. In these cost calculations, it is assumed that fuel production does not take place at optimal but at good locations in the MENA region and that electrolysers are subject to performance degradation and a lifetime limitation. They also assume higher financing costs in the reference and high cost cases than those in other scenarios (Figure 38).

Figure 37: Different production cost scenarios for liquid e-fuel production at a favourable location for renewable electricity production (MENA region)



Notes: The production cost of fossil fuel refers to fossil diesel in the cited study.

Sources: Own collection of different sources: [1]: AVW; AEW; FE (2018); [2]: MWV; IWO; MEW; UNITI (2018); [3]: dena; LBST (2017); [4]: IWES (2017); [5]: CTH; IVL (2017); [6]: Prognos (2020)

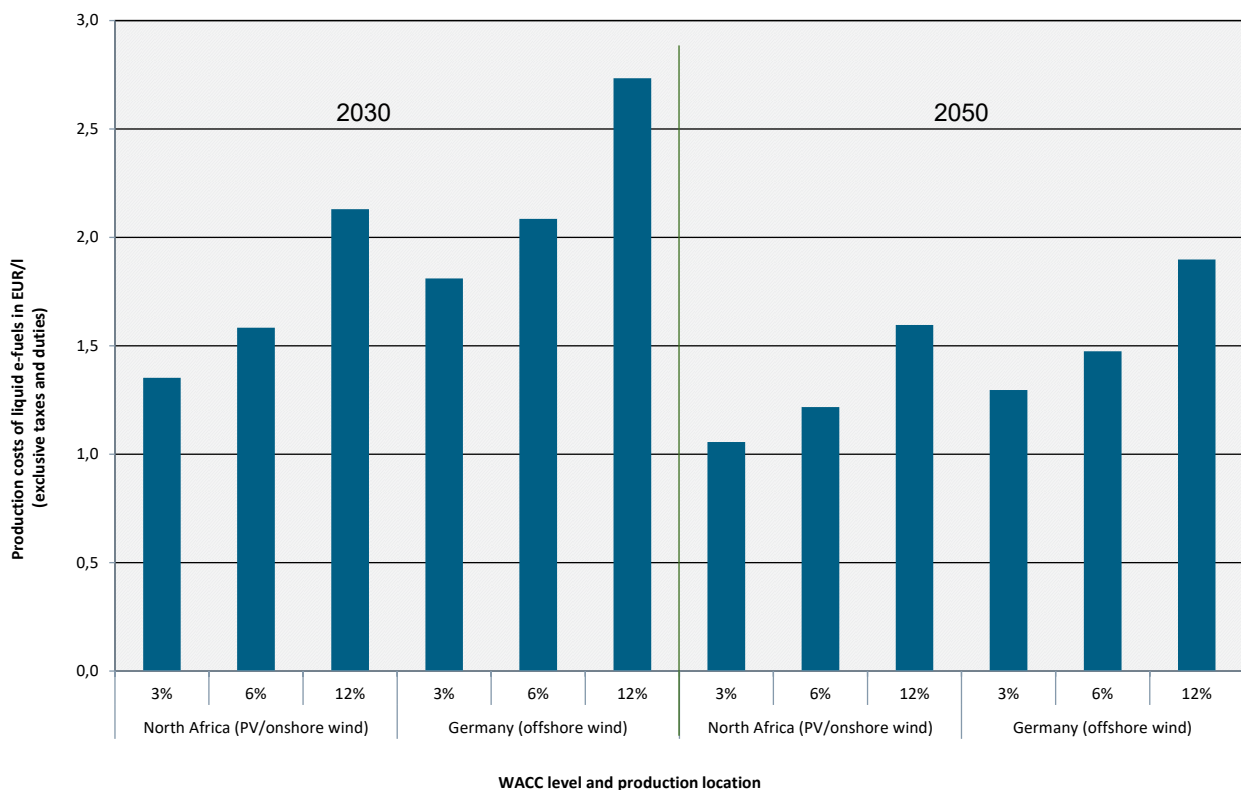
The gap between the production costs of e-fuels and those of fossil fuels also depends on the evolution of fossil fuel costs. The low costs of fossil liquefied natural gas (LNG), however, complicates market access for e-methane compared to the other energy supply options (see cost calculations in AVW; AEW; FE 2018).

A frequently neglected factor in the discussion of future costs of e-fuel production is the weighted average cost of capital (Weighted Average Capital Cost, WACC), which reflects the expected return on equity and the interest on leveraged capital. It has a significant impact on the cost of e-fuel production (Figure 38). Most cost studies expect a WACC of 5-7% regardless of the production location. For countries with good governance structures, such financing conditions may be possible. Studies on renewable energy deployment in the electricity sector show that in the EU there can already be high differences for the WACC (Ecofys; eclareon; ISI; NTUA; LEI; TU Wien 2016). In countries outside the EU/OECD with less advantageous governance

structures, interest rates and WACCs above 10% are therefore very likely for the high investment volumes of fuel production capacities.

The cost calculations with different WACC levels (Figure 38) show that the WACC level strongly influences the production costs for e-fuels. Cost advantages for potentially preferential e-fuel production locations resulting from low electricity generation costs and high utilization rates of production facilities can be completely lost due to higher interest rates for financing e-fuel facility capital costs. A plausible assumption is, therefore, that production sites for e-fuels will initially be in regions with high political stability and favourable investment conditions (FE 2018). The extent to which production will take place in less stable world regions is uncertain, partly due to the WACC.

Figure 38: Production costs of liquid e-fuels at different locations and varying WACC levels



Source: Authors' own calculations based on data from FE; AEW; AVW (2017)

As with other fuels, the price of e-fuels will ultimately evolve from the supply of and demand for the fuels and not just from the cost of production. It can happen, especially in an initial market phase, that a few production sites and regions dominate production. The potential consequence could be a high market power of these stakeholders, which would have to be taken into account in possible roll-out strategies for e-fuel production.

Table 32: Overall evaluation of e-fuel cost potential

	Short-term cost potential	Long-term/bulk fuel cost potential
e-fuels	--	-

Notes: A plus indicates that an option is assessed relatively better in comparison to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Authors' own assessment

4.1.3 GHG mitigation potential

E-fuels have the potential to be produced in a very climate-friendly way and thus to tremendously improve the GHG balance of aviation and shipping. Decisive for the GHG assessment is the source of electricity and – if necessary – of carbon dioxide.

Similar to production costs, electricity consumption is the most decisive factor for the climate impact of e-fuel production. They have a considerable GHG savings potential, but this depends on the GHG intensity of the electricity used (Figure 39). The high conversion losses and the energy requirement for carbon dioxide supply make it necessary for the electricity used to have a GHG intensity of approx. 120 to 250 g CO₂e per kWh of electricity (including upstream emissions) and less, depending on the amount of conversion losses, in order to have a positive climate effect compared to fossil fuels. The embedded GHG emissions from renewable electricity generation capacities and other potential environmental impacts, which gain in importance in the GHG assessment of e-fuels as the GHG intensity of electricity generation decreases, must also be included in the assessment (DECHEMA 2019).

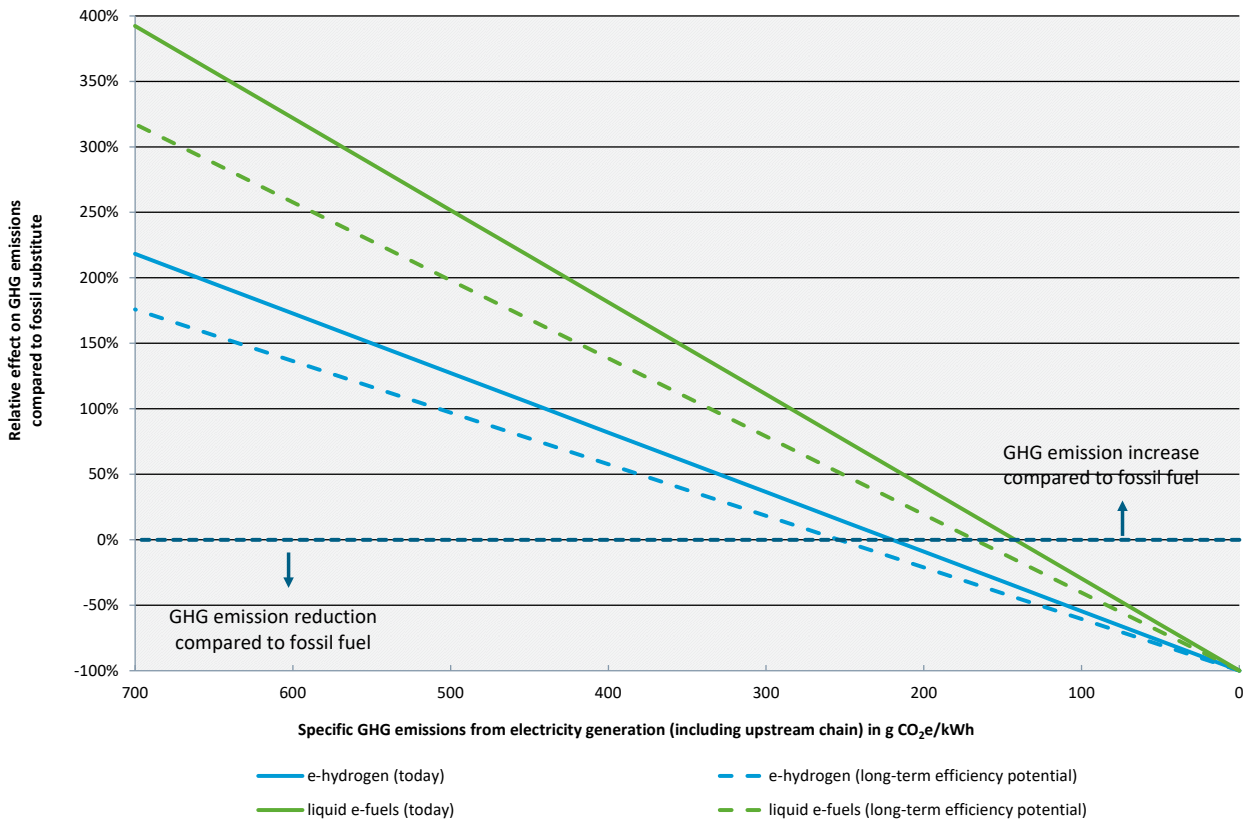
Most studies on the costs of e-fuel production are based on the assumption that electricity will be obtained from PV and wind power plants in the long term. The potential GHG emissions of these technologies are, therefore, decisive for the assessment of GHG emissions, when high shares of renewable energy input are used for e-fuel production.

Currently, photovoltaic modules have higher upstream emissions than wind turbines. UBA (2019b) and Ecoinvent Centre (2018) estimate that 67⁷⁷-89 g CO₂e/kWh_{el} respectively will be generated from photovoltaic (PV) systems in Germany. The wind turbines used in Germany (onshore and offshore) show clearly lower upstream GHG emissions (6-18 g CO₂e/kWh_{el}). The origin of the emissions is also different. While GHG emissions mainly originate from the electricity requirements of PV plant production,⁷⁸ the material requirements (e.g. steel, iron and plastics) are relevant causes of GHG emissions in the upstream chain of wind power plants. With a higher utilization of the power plants at favourable locations for renewable power generation outside of Germany, the specific GHG emissions of renewable power generation are already well below the above-mentioned values. This is particularly true for power generation with PV systems, which can achieve significantly higher yields of electricity in preferred regions for power generation from solar power. Additionally, the embedded GHG emissions of renewable power generation decrease over time with the expected transformation of the energy sector and the industrial production into low-carbon sectors. However, a fully GHG neutral PV and wind power plant stock for electricity input into e-fuel production cannot be expected until 2050 (UBA 2020); a completely climate-neutral fuel production would only be possible once the renewable electricity production is also completely climate-neutral including its embedded emissions.

⁷⁷ This value does not include the power inverter and the wiring of the PV plants.

⁷⁸ Global PV plant production is dominated by production in China, which causes rather high upfront GHG emissions.

Figure 39: GHG emissions of liquid e-fuels and e-hydrogen production depending on the GHG intensity of electricity input



Notes: Applied data for fossil energy carriers: 338 g CO₂e/kWh (fossil hydrogen); 317 g CO₂e/kWh (fossil liquid).

Sources: Author's own illustration; data for fossil energy carriers from Ecoinvent Centre (2018) and thinkstep AG (2018)

It is clear that during the transition to an emission-free energy system, existing fossil power generation capacities cannot be used more if e-fuels should be associated with GHG reduction. The production of e-fuels as climate-friendly as possible requires certain production conditions when integrated into existing energy systems. For the GHG accounting, it is necessary to assess the effects of the additional electricity demand at system level. A balance purely around a fuel production plant is not sufficient to assess GHG emissions (Oeko-Institut 2019a). Particularly in energy systems that still have a high proportion of fossil electricity generation in their electricity mix during the transformation period to GHG-neutral energy supply, special prerequisites must therefore apply in order to produce climate-friendly e-fuels.⁷⁹

To be able to count the electricity used as zero-emission electricity, this electricity must come from renewable energy plants that are commissioned in addition to the planned expansion path. These renewable energy plants must not, therefore, be counted towards the existing renewable energy expansion targets in the producing countries, or the expansion targets must be raised accordingly. In addition, attention must be paid to climate-friendly and system-oriented integration of the production facilities: the operation of the electrolyzers and other processes requiring electricity must, therefore, be orientated at times when the share of

⁷⁹ The average GHG emissions of electricity in Germany in 2018 are estimated to have produced as much as 641 g CO₂e/kWh UBA (2019b). Current e-hydrogen and e-liquids production would lead to 2.1 (e-hydrogen) to 3.7 times (e-liquids) as high GHG emissions as with its fossil counterparts by applying this value for electricity input into e-fuel production.

renewable energy production is high. Moreover, current or imminent grid bottlenecks – such as those that exist in Germany due to the strong concentration of renewable electricity potential in northern Germany – should not be exacerbated by the new, additional demand for electricity. This can be ensured by a suitable localization of the fuel systems and by the suitable operation of the systems.

Table 33: Overview of relevant criteria (electricity input) for low GHG emission e-fuel production

Criterion	Comment
GHG emissions of electricity input (including upstream emissions)	GHG emission reduction compared to fossil substitutes requires electricity carbon intensity below 120 to 250 g CO _{2e} /kWh _{el} (depending on conversion losses)
Additionality of renewable electricity production	Low GHG emission- e-fuel production requires additional renewable capacities compared to expected RE expansion pathway (e.g. by not counting additional RE production against RE targets)
Flexible operation of e-fuel production	System-oriented load management demands operation orientated at times of high renewables shares in the electricity production (e.g. by regulation of required RE shares in operation hours)
Electricity grid orientated e-fuel production	Localization in front of grid bottlenecks and grid-orientated flexible operation of e-fuel production (e.g. by curtailing operation in case of grid congestion if needed)
Energy transition compliant integration of e-fuel production	Additional renewable electricity demand must now slow down and/or increase cost of transition to low GHG emission electricity sector (especially relevant for potential e-fuel exporting regions)

Source: Authors' own assessment

The cost considerations indicate very strongly that e-fuels will be located in favourable locations for renewable energies with good governance environment (section 0). Like crude oil production, it can be assumed that regional hotspots for e-fuel production will emerge in the global context, from which considerable quantities of e-fuels will be exported. However, the above criteria must also apply to these potential exporting countries and regions to contribute to GHG reduction. From a sustainability and GHG reduction perspective, it is important that exports of e-fuels do not make the GHG reduction of the domestic energy system more expensive or slower.

For the production of e-fuels with carbon demand, the carbon dioxide supply is a second relevant parameter that has an impact on the GHG assessment of e-fuels. The carbon dioxide supply is GHG-neutral if the carbon dioxide used enables a cycle with the ambient air or if the carbon dioxide is released naturally to the environment. Accordingly, carbon dioxide from ambient air, from processes using sustainable biomass and, to a very limited extent, from geological processes is to be assessed as sustainable and potentially GHG-neutral. The energy required to capture the carbon dioxide (electricity and heat) must meet the above criteria for the use of electricity in the production facilities in order to make the production of hydrocarbon e-fuels as climate-friendly as possible and potentially climate-neutral.

However, there are very different characteristics for the use of the two central, potentially climate-neutral sources of carbon dioxide supply. In today's standard biogenic processes such as bioethanol and biogas production, the carbon dioxide content in the flue gas is very high (up to 100% for bioethanol and around 40% for biogas plants) and there are simple and established carbon dioxide separation processes that work with low energy consumption (ifeu 2019). Accordingly, the additional costs and energy required for CO₂ supply are low (Reiter und Lindorfer 2015). However, this can lead to a continued use of non-sustainable biomass sources such as maize and corn, with the result that only CO₂ from genuinely sustainable biomass processes can be considered sustainable. The use of these carbon dioxide sources is therefore severely restricted with regard to available quantities. For industrial production of hydrocarbon e-fuels, large quantities of carbon

dioxide are needed that are concentrated in one place. Bioethanol plants generally have a larger fuel output than biogas plants. However, the amount of carbon dioxide even from larger bioethanol plants only allows plant concepts for first small scale industrial e-fuel production plants in single digit PJ scale.⁸⁰ The very decentralized and rather small biogas plants are only suitable for very small production plants of 0.1 PJ and less.⁸¹ Thus, only a very fragmented and widely ramified carbon dioxide transport system which would require cost and time to be installed would facilitate the use of biogenic carbon dioxide in relevant quantities for e-fuel production. Both would also add to the energy demand and cost for e-fuel production.

Carbon capture from the ambient air, however, is the least developed process for providing carbon dioxide. This is due to the high cost and the amount of energy required to capture carbon dioxide from the air, which results directly from the low carbon dioxide content in the atmosphere (Reiter und Lindorfer 2015). However, in contrast to biomass processes, the provision of carbon dioxide can be scaled very well if there is sufficient available land area for the carbon dioxide capturing plants as well as for the required renewable electricity capacities. For this reason, most studies identify carbon dioxide from the ambient air as the major source of carbon dioxide for carbon-based e-fuels in the long-term perspective (AVW; AEW; FE 2018; MWV; IWO; MEW; UNITI 2018; IWES 2017) and this technology will be pivotal for a climate-neutral carbon dioxide supply for e-fuel production.

The use of carbon dioxide from fossil point sources such as industrial and power plant processes is controversial. From a cost and energy demand perspective and due to the local concentration of large quantities of carbon dioxide, the use of these carbon dioxide sources is associated with operational advantages. However, GHG emissions from energy production and industry processes have to decrease to as minimal GHG emissions as possible. Also the capture rate of CO₂ is only approx. 90% (Reiter und Lindorfer 2015). The use of CO₂ from fossil sources for e-fuel production must, therefore, not lead to a delayed reduction of the targeted GHG emissions from the respective plants and to a postponed transformation of the electricity and industry sector. Renewable electricity supply facilitates emission-free energy use in the electricity sector. In the industrial sector, GHG emissions from energy supply can also be reduced completely (e.g. by using e-fuels), but not all process emissions can be avoided (e.g. from glass, cement and lime production) despite potentially improved processes (Figure 40). Depending on the climate protection strategy – whether CCS is considered as a potential climate protection solution (BCG; Prognos 2018; EC 2018) – these process emissions may or may not be available as a possible source of carbon dioxide in the long term. If no CCS is used as a climate change strategy, these process emissions are suitable carbon dioxide sources for the production of e-fuels, which require low energy consumption compared to CO₂ capture from the air.

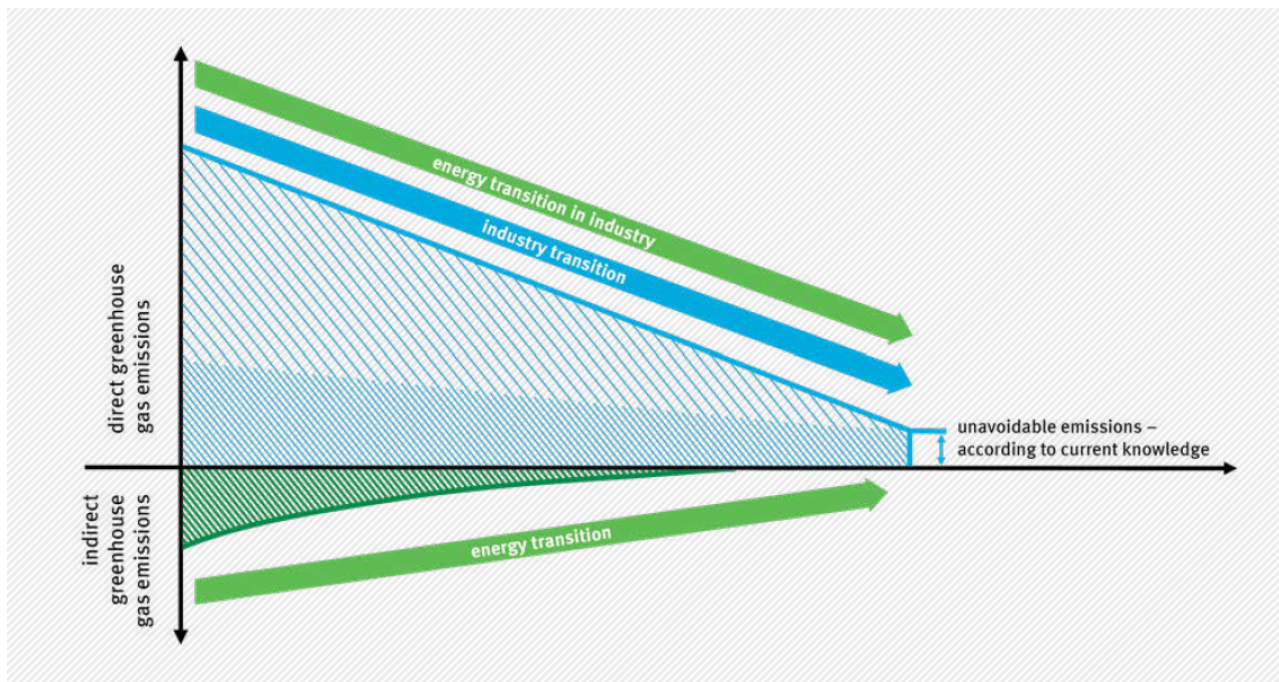
As with the requirements for electricity consumption, there is a risk of adverse effects when carbon dioxide is provided for e-fuel production in the transition phase to a climate-neutral system. For such concentrated point sources which provide carbon dioxide for e-fuel production, the incentive to reduce GHG emissions to the extent necessary for climate protection is lost. From a systemic point of view, the reference for GHG emission assessment must be the necessary reduction pathway for these processes (Oeko-Institut 2019a). Policy instruments and the necessary technical and societal transformation processes for GHG reduction in the energy production and industry sector must not be affected and the GHG reduction in these sectors must

⁸⁰ Bioethanol plants have carbon dioxide emissions of 50 000 to 100 000 t CO₂ per year (Crop Energies GmbH (2019); Clariant (2019)). From one million t of carbon dioxide, approx. 13.5 PJ of liquid e-fuels can be produced. Thus, carbon dioxide-emissions from one bioethanol plant would allow liquid e-fuels production of around 0.65 – 1.3 PJ (16 000 – 32 000 t).

⁸¹ In Germany, carbon dioxide capture is installed in around 225 biogas plants for upgrading to biomethane (DBFZ; dena; IWES (2017)). ifeu ((2019)) estimates the amount of carbon dioxide available from these plants at 0.8 million t. CO₂. The average amount of carbon dioxide available per biomethane plant is therefore around 3 500 t from which approx. 0.05 PJ liquid e-fuels per biomethane plant can be produced.

not be slowed down by the potential use of carbon dioxide emissions from large point sources. Without strict compliance rules, the use of fossil carbon dioxide sources is thus associated with a risk of creating a long-term lock-in in fossil processes and GHG emissions in these sectors.

Figure 40: Qualitative illustration of GHG emission development of the industry sector in climate-neutral long-term scenarios



Source: UBA (2019c)

In general, the amount of carbon dioxide emissions at which the emissions from fossil point sources exceed the reference development necessary for climate protection must be assessed as additional GHG emissions and allocated to e-fuel production. For the GHG assessment, the worst outcome of carbon dioxide supply from fossil sources could be that the whole carbon content of the produced e-fuel has to be accounted as fossil carbon.⁸² This is the case if the total amount of carbon used in e-fuel production has to be considered additional to the emission reduction pathway of the energy and industry sector. No direct GHG emission reduction impact would be associated with e-fuel production in this case.

Table 34: Overview of main potential carbon dioxide sources for e-fuel production

Criterion	Comment
Carbon dioxide from ambient air	Rather high energy requirements for carbon dioxide capturing; technology only available in demonstration scale; facilitates large-scale e-fuel production capacities; expected to be main carbon dioxide source in the long term;
Carbon dioxide from biogenic waste streams	Very low energy requirements for carbon dioxide capturing; established and available technologies; limitation of carbon dioxide supply to small-scale e-fuel production plants without very fragmented and widely ramified carbon dioxide transport system

⁸² If the energy required for carbon dioxide capture from the process waste streams is not fully renewable, the GHG emissions impact could be even higher since the carbon dioxide process would also add to the GHG emission accounting.

Criterion	Comment
Carbon dioxide from fossil point sources	Medium energy requirements for carbon dioxide capturing; available technologies; potential long-term lock-in in avoidable GHG emissions from fossil sources

Source: Authors' own assessment

From the discussion about possible positive and negative climate impacts of e-fuels it becomes clear that, like the use of biogenic feedstocks, criteria have to be developed, monitored and probably repeatedly adapted to ensure the positive climate impact of e-fuels. To date, such criteria and verification procedures for ensuring positive climate impact do not exist. In 2021, the European Commission will for the first time define criteria for the GHG calculation of e-fuels in a delegated act within the framework of the Renewable Energies Directive.⁸³ The extent to which these criteria will meet the criteria mentioned above is still open from today's perspective. With regard to the criteria, a short introduction phase with slightly reduced requirements for fuel production could be a reasonable option in order to facilitate a market entry of e-fuels in terms of costs. However, it would have to be guaranteed that the full requirements apply after an initial market introduction phase and that this phase of reduced requirements for fuel production does not prevent the development of technologies, operating concepts and business models with a long-term sustainability perspective.

However, e-fuels can be produced in a climate-friendly way if the production of the e-fuels complies with certain production criteria. These production criteria are even more important in the transition phase to a completely climate-neutral system. A completely GHG-neutral production by 2050, however, does not seem plausible. To this end, the upstream emissions of renewable electricity generation must also be completely reduced to zero. In the transition phase from a fossil-based energy system to a fully renewable electricity system, the production criteria must prevent fossil electricity generation from being stimulated to a considerable extent and from generating more GHG emissions than with fossil fuel use.

If carbon dioxide is required for the production of e-fuels, carbon dioxide capture from ambient air and waste gas flows from processes with sustainable biomass use are the main climate-neutral options. Unavoidable CO₂ emissions from industrial processes can also be a sustainable usable source of CO₂ if long-term storage of CO₂ is not assessed as a climate protection option worth aiming for. Due to the limited availability of sustainable biomass and the rather small biomass processes, carbon dioxide use from biogenic sources seems to be limited and would be economically penalized in the case of CO₂ transportation system for locally concentrating available CO₂ from biomass for industrial-scale production facilities. Thus, carbon capture from the ambient air is a key technology that needs to be further developed from small-scale plants to a large-scale industrial application. GHG emissions from fossil energy and industrial processes must decrease to as minimal GHG emissions as possible up to 2050 and beyond for effective climate protection. The economically preferred use of waste gas streams from fossil point sources implies a risk of fossil carbon lock-in and cannot, therefore, be treated as a climate-friendly carbon source for e-fuels in the short, medium, and long term.

For these reasons, the definition of the production criteria is of outstanding importance for the climate protection effect of e-fuels. This applies even more in the transformation phase from today's fossil energy supply to future renewable and climate-friendly energy systems. Otherwise, there is a risk of producing e-fuels with higher GHG emissions than fossil fuels during this transitional period. In principle, however, the production of largely climate-neutral e-fuels is possible in the long term.

⁸³ Article 27(3) and Article 28(5) ask the EU Commission to provide criteria for the electricity input into the e-fuel production to be accounted as fully renewable and for a methodology of GHG emission accounting of e-fuel production.

Table 35: Overall evaluation of GHG mitigation potential

	Short-term GHG mitigation potential	Long-term GHG mitigation potential
e-fuels	0 (fully depending on production criteria)	++

Notes: A plus indicates that an option is assessed relatively better in comparison to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Authors' own assessment

4.1.4 Water demand and land use

The production of e-fuels requires water and the use of considerable land if the electricity used comes from renewable sources. Effects of possible e-fuel production usually occur locally for both dimensions (water and land use) and in addition to ecological effects, social impacts can occur. For this reason, aspects relating to water and land use are also particularly important for the acceptance of possible e-fuel production, especially among the local population in the vicinity of the production facilities.

The water demand for the e-fuel production results from the material conversion of water into hydrogen (and oxygen) and from possible water requirements for the operation of the chemical processes (e.g. cooling and heat transfer purposes) and the renewable power generation plants (e.g. wet-cooling of concentrated solar power plant). The amount of required water for the conversion from water into hydrogen (approx. 1.4 l_{H₂O} per l of liquid e-fuels) is considerably lower than the water demand for other purposes (approx. 70 l_{H₂O} per l of e-liquids in the case of wet-cooling of concentrated solar power plants), however. Additionally, technologies which require smaller amounts of water such as dry-cooling of concentrated solar power plants might reduce the potential water demand of e-fuel production. All in all, Cerology (2018) estimates the water demand of large-scale e-fuel production to be comparable with other industrial plants and very low compared to the water demand of biomass growth.

At the national level, even in very arid areas with water scarcity, the impact of e-fuel production on water availability thus appears to be rather limited; at the local level, however, the impact on water availability and also on water prices can be significant. Sustainability management and impact evaluation at local level should, therefore, be the minimum standard for the commissioning and operation of e-fuel facilities. A detailed water impact assessment and incentives for using technologies of low water demand (e.g. dry-cooling of concentrated solar power plants) are sustainability requirements for e-fuel production in very arid areas and local water availability must remain the priority in potential fuel production locations. In some regions, seawater desalination is a possible option for the water supply of e-fuel production. The brine mixed with chemicals of the desalination process can have negative environmental effects on benthic organisms and the fish population in the vicinity of the backflow. Suitable sites for discharging the brine into the sea and suitable measures for diluting the brine are prerequisites for the water treatment of seawater for sustainable e-fuel production (Oeko-Institut 2019a).

The land use required for the e-fuel production facilities is similarly small as for other industrial facilities. Not to be neglected, however, are the land use requirements for renewable power generation plants and, to a lesser extent, for possible plants for carbon dioxide separation from the air. Here, however, land use is comparatively low in contrast to biomass growth, too. UBA (2016) estimates the land use requirements for liquid e-fuel production to be approx. 5 to 20 times smaller than for the biomass growth for sustainable biofuel production.

The requirements for the quality of the land which is potentially used for e-fuel production is also different to the production of sustainable biofuels. In the case of e-fuel production, there is no competition to land use for food and crop production on nutrient-rich soils. In some cases, the previously existing use can be

continued in large parts if the renewable electricity comes from wind power plants, since the wind power plants are installed on only a rather small part of the total area used (approx. 3% according to UBA 2016). Land used for electricity generation from PV and concentrated solar power plants should also be areas that have been little used to date in order not to create competition for use.

However, a different competition to land use is emerging for e-fuel production. In the future, the electricity production for traditional electricity applications will have to be switched from fossil to renewable and climate-friendly sources to meet the global goals on climate protection. Therefore, potential e-fuel production, like the traditional electricity applications, requires using land that allows PV and wind power plants to generate electricity at the lowest possible cost. Due to the higher efficiency of use and the higher GHG intensity of the substitute (e.g. electricity generation from coal), the direct use of renewable electricity is usually associated with a higher GHG mitigation than the production and use of e-fuels in the transport sector.

In some countries with a high population density and comparatively high renewable shares in electricity generation (e.g. Germany), a societal discourse is already taking place on which land should be used for renewable electricity generation and which should not. The limit of usable land for renewable power generation, therefore, does not result from a techno-economic analysis, but from societal negotiation processes.

Many potential regions for e-fuel production have great potentials with regard to preferential areas for renewable electricity generation (section 4.1.5). Nevertheless, even in these regions there are prime locations for renewable power generation and use, which are characterized, for example, by their proximity to traditional power applications, an existing infrastructure and the potential to rapidly install new renewable capacities. If these locations are used for e-fuel production, there is a risk of slowing down and increasing the cost of transforming the electricity supply for traditional and upcoming electricity applications by forcing them to obtain electricity from less suitable locations for electricity generation. Some potential production regions also face the challenge of providing access to electricity for the entire population in the first place.

Therefore, some form of regulation will be needed to prevent adverse GHG mitigation and negative social impacts by hampering the transformation of the traditional electricity sector. This is particularly important in regions that produce e-fuels mainly for export, still have a high share of fossil electricity generation in the energy system and where supplying the entire population with electricity is a challenge. A mapping of best sites for renewable electricity generation and its use as well as restrictions on the use of these areas in e-fuel production could be an approach for the necessary land regulation (Oeko-Institut 2019a).

In addition to the possible impact on the energy system, land use for e-fuel production will imply local effects on how land is available for other purposes and the land use of e-fuel production is perceived by the public. The local impact analysis and local sustainability management are therefore prerequisites for a positive sustainability impact and local acceptance for e-fuel production facilities. The close and early participation of local residents in the planning and the local involvement in the operation of potential e-fuel plants is therefore necessary to take into account the needs and concerns of local civil society in building capacity for e-fuel production. Both the lack of sustainability governance and the lack of acceptance can limit the volume potential of e-fuel production.

The water and land requirements are the main categories of environmental impacts resulting from a strong increase in e-fuel production. However, UBA (2020) also shows that in almost all impact categories of typical life cycle assessments, with the exception of GHG emissions, additional impacts occur compared to today's fossil fuels. A general environmental and sustainability assessment is therefore a central element in ensuring the sustainability of e-fuels.

Compared to biomass production, the production of e-fuels requires considerably less land and less water. Nevertheless, e-fuel production facilities will have a strong impact on land use and water availability in the

local context. Local sustainability management, which includes both ecological (e.g. impact of seawater desalination plants), social (e.g. access and costs for water and electricity) and economic (e.g. local value added), and the involvement of the local population in decisions on e-fuel production are key elements for the acceptance of an industrial e-fuel production process. In relation to land use, e-fuel production creates new competition with renewable electricity generation for the direct use of electricity. It is necessary, therefore, to develop a regulatory framework that is applied globally in order to prevent possible adverse effects on the transformation of the energy system in the producing countries towards a climate-friendly electricity supply and to impede negative social impact as much as possible.

Table 36: Overall evaluation of impact on water and land use

	Water demand	Land use
e-fuels	o	o

Notes: A plus indicates that an option is assessed relatively better in comparison to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Authors' own assessment

4.1.5 Potential to meet long-term fuel demand

It can be assumed that technical development will be possible for all the production paths described (sections 4.1.1 and 4.2.1) and that all the production paths mentioned will be technically usable latest in the medium and long term. For a simple technical-economic analysis of long-term production potentials the renewable electricity potentials which are directly related to the access to areas of high wind and solar potentials and are associated to certain costs are a relevant parameter. In a number of studies the research group around Fasihi show that there is sufficient technical land use potential available worldwide for the production of e-fuels on a large scale (LUT 2017a; Fasihi et al. 2016; Horvath et al. 2018). Despite a limitation to 10% of the land area, according to LUT (2017a) there is a technical-economic potential for the production of e-methane and liquid e-fuels in the order of 790 EJ in the North African Maghreb region alone in 2040. In Fasihi et al. (2016), they identify Africa, South America and Asia as the continents with largest potential of very low cost e-fuel production. The only limitation in these potential analyses is the available area for renewable electricity production. From this point of view, the future energy requirements of aviation and maritime transport (39 to 68 EJ, Table 15) could therefore be achieved without any doubts.

Simple technical-economic studies, however, which only examine partial aspects of e-fuel production potential limits, have limited validity for the actual quantity potentials of e-fuel production and neglect relevant challenges to the development of e-fuel production capacities. Ultimately, this only shows that there are theoretically enough land areas and energy available to meet global energy demand. Decisive factors for realistic quantity potential assessment of future e-fuel production are among others the following aspects:⁸⁴

- From a technical point of view, there are time constraints that limit the speed of construction and thus the capacity of e-fuel production facilities. DECHEMA (2019) points out that there are no e-fuel production plants on an industrial scale yet (section 4.1.1). Like Timmerberg und Kaltschmitt (2019), DECHEMA (2019) also sees at least two development stages towards large-scale industrial production plants in order to build and operate a 'first-of-its-kind' plant on an industrial scale. In the ideal case, both analyses indicate approx. 10 years as the possible time period for scaling to a 'first-of-its-kind' system. NPM, AG 1 (2020) expects first large-scale production of liquid e-fuels in the period of 2028 – 2030. The

⁸⁴ This list is not to be understood as a complete list. There may be other factors that limit the volume potential of e-fuels that are not listed here.

construction of other plants on an industrial scale requires less time following such a first plant at large industrial scale. Relevant production quantities of e-fuels can, therefore, only be expected in the period after 2030. Timmerberg und Kaltschmitt (2019) estimate – from a German perspective – the production potential of e-liquids at approx. 30 PJ in 2030 under ideal framework conditions and smooth technical progress. The global potential for the production of liquid e-fuels may well be greater than the value mentioned above. It can be assumed, however, that the step towards large production plants can take place around the year 2030.

- ▶ Hydrogen and ammonia production are an exception in terms of time constraints from technical development requirements. In both cases ‘only’ the fossil hydrogen production has to be replaced by renewable hydrogen. Scaling of electrolyzers without a connected synthesis process is easier due to the modular design of electrolysis. Since electrolyser production in the MW range is today carried out in non-automated manufacturing operations due to the low demand (ISE; E4tech; IPA 2018), the main technical limitation for fast installation of large-scale electrolyzers is from producing electrolyzers.
- ▶ Limitations on the speed of deployment and the absolute amount of e-fuel production capacity are also set by the potential lack of availability of means of production and infrastructure. For the climate-friendly production of e-fuels, additional renewable power generation capacities need to be built, the planning, approval and construction of which takes time. With a production of 30 PJ of e-fuels (see previous indent), for example, approx. 600 offshore wind power plants or approx. 2 750 onshore wind power plants would have to be built⁸⁵ in addition to the existing renewable expansion targets if climatic conditions in Germany are applied. At locations with a higher utilization potential for wind turbines, the number of turbines required would be reduced. However, this calculation shows the challenge of providing enough additional renewable electricity for e-fuel production. Prerequisites for the development of these power generation capacities include the public acceptance of land use, availability of technical equipment for construction (e.g. special cranes for the construction of wind turbines, suitable roads for transporting the individual components) and skilled workers for the construction as well as established legal procedures for approval processes. Depending on the production location, the challenges for the availability of renewable power generation will differ.
- ▶ Similar conditions also apply to the other means of production, water and carbon dioxide. These facilities must also be planned, approved and built. While the main challenge for water use in arid regions lies in the acceptance by the local population, the lack of suitable sustainable carbon dioxide sources can severely limit the quantity of hydrocarbon e-fuel production. Biogenic process emissions permit only small production plants and carbon dioxide capture from the ambient air is only available in very small capacity ranges today (sections 4.1.1 and 4.1.3). The use of fossil carbon dioxide emissions in e-fuel production only leads to climate-friendly fuels if a regulation is in place which impedes the GHG emission reduction path of fossil processes to be slowed down.

⁸⁵ For the rough calculation, we assume an efficiency of 45% for the production of e-liquids. Offshore wind turbines have a rated output of 7MW at 4 300 full load hours (615 turbines); onshore wind turbines produce electricity in 2100 full load hours at a rated output of 3.2MW (2 756 turbines). The assumptions for the wind turbines are taken from 50 Hertz; Amprion; TenneT; TransnetBW (2019).

- ▶ Another prerequisite for e-fuel production and use are distribution infrastructures which are required to transport the means of production to the fuel production facilities and the e-fuels from production facilities to the users (DECHEMA 2019). Depending on the location of production, new transport infrastructures might be required which could add to the costs and time until e-fuels can be used in aviation and shipping.
- ▶ In addition, other raw material requirements for fast deployment and large quantities of e-fuel production capacity have not been analysed in detail. DECHEMA (2019), for example, points to the high demand for iridium from PEM electrolyzers, which today is only degraded in small quantities as a by-product of platinum mining. The reduction of the iridium content in PEM electrolyzers is therefore the prerequisite for using this technology on a relevant scale for the production of hydrogen and synthetic e-fuels.
- ▶ The construction and operation of e-fuel and the renewable electricity production facilities require high investments which are currently associated with financial and technical risks. Industry stakeholders, therefore, ask for a high level of security of investment and a policy framework, which supports the e-fuel production to overcome the high level of cost disadvantage compared to fossil fuels (Oeko-Institut 2019b). Stable production criteria with regard to sustainability and GHG emission reductions and a stable long-term policy framework for market support therefore facilitate investment in e-fuel production. Both requirements to reduce the risk of investors and to create a potential market for e-fuels are currently not existing. The EU Commission will set a first regulation on how to assess GHG emissions of e-fuels and on which requirements to apply for the electricity input for e-fuel production in the end of 2021 (section 4.1.3). Experience gathered with the biofuel framework, however, implies that changes in the sustainability and GHG emission framework are probable over time and the production criteria might change. Implementing a rather strict sustainability framework from 2021 on could reduce the need of adjustments of the GHG accounting framework. The national implementation of the Renewable Energy Directive (RED) update for the timeframe up to 2030 is currently the most important support initiative for e-fuels at EU level. By developing international partnerships and joint e-fuel strategies, policymakers can also promote e-fuel production at preferred locations in an international context (DECHEMA 2019; FE 2018).

Very first initial approaches for a more realistic assessment of quantity potentials do exist, but comprehensive studies have not yet been carried out. LUT (2017a) shows so-called cost potential curves. In these, it becomes clear that the production costs increase if the production facilities do not have access to the very best locations for renewable energy generation. However, these very best locations are also relevant for the GHG reduction of domestic and local energy systems (see also sections 4.1.3 and 0 on competition for preferential areas for renewable electricity generation). Best sites for e-fuel production will therefore be limited from a purely technical but also sustainability perspective. FE (2018) provides indications of other criteria that can be used to assess potentially suitable production sites. In addition to the criteria mentioned in the previous section, criteria such as governance level, existing trade relations, etc. are also mentioned. A detailed analysis of realistic, global volume potentials which consider potential technical, economic and societal limitations is, however, also not carried out in FE (2018).

Even if no comprehensive analyses of realistic global, sustainable potentials for e-fuels exist to date, it can be assumed that the sustainable volume potential is higher than for biogenic fuels and it can meet the demands from aviation and shipping. However, there are relevant technical, regulatory and societal challenges that need to be overcome in the medium and long term and make a very short-term deployment of large e-

fuel production capacities unlikely. Additionally, the quantity of e-fuels is likely to be limited by economic limits since e-fuels represent an expensive climate protection measure even when produced at best locations for renewable energy generation. Moreover, involvement of the local population in the decision-making process and relevant benefits for the local population are key features for acceptance of the technology and the deployment of the technology at preferential production locations.

Table 37: Overall evaluation of long-term production potential of e-fuels

	Long-term production potential
e-fuels	+

Notes: A plus indicates that an option is assessed relatively better in comparison to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Authors' own assessment

4.1.6 Limited availability of sustainable biofuels for aviation and maritime transport

Biofuels are another climate protection option under discussion for the energy supply of aviation and maritime transport. However, biofuels are not considered in detail in this study as the usable sustainable quantities and the significance for climate protection of these fuels for aviation and maritime transport is estimated to be lower.

Conventional biofuels, which are produced from food and feed, have in the past been considered an important climate protection solution for applications where other climate protection options such as electrification are difficult to achieve. However, these biofuels cannot realize the objective of making a significant contribution to climate protection. The additional land use created by fuel production, together with changing dietary habits and the rising global population, means that the amount of agricultural land used worldwide is increasing at the expense of carbon sinks such as forests and green land. For many of the conventional biofuels, the resulting land use changes mean that the potential GHG emission benefits of conventional biofuels through the sequestration of CO₂ in biomass do not occur and no or only a small climate protection effect is achieved (e.g. IFPRI 2011).

In addition, biofuels from food and feed are often associated with further negative ecological effects in many impact categories of life cycle assessments. Land cultivation today is also associated with negative impacts on biodiversity and is the main user of freshwater globally (IPBES 2019). A comparison with e-fuels shows that conventional biofuels require orders of magnitude more land and water than is needed to produce e-fuels (LBST; BL 2016).

For these reasons, it can be assumed that conventional biofuels from feed and food will not be available for climate protection in aviation and maritime transport. From a regulatory point of view, RED II specifies that the shares of conventional biofuels in transport should not increase in the future and that such fuels, which have a high risk of land use change, should no longer be used by 2030 at the latest.

Biofuels from waste and residual biomass are more advantageous and have climate protection benefits. Specific types of these biofuels are those made from used cooking oils and animal fats, which are defined via the feedstocks listed in Annex IX Part B of RED II. By using waste and residual materials that have not yet been used as material or energetic feedstock in other uses, these biofuels can have a high climate protection effect. However, the potential quantities of feedstocks from Annex IX Part B of RED II are very small. Therefore, the crediting of these biofuels towards the shares of renewable energy in transport required in

RED II is also limited to 1.7%⁸⁶ in order to avoid possible negative ecological impacts of a strong demand from the transport sector for these feedstocks. The negative impact of these fuels can result primarily from the feedstocks being removed from other uses and these consequently have to access other sources of supply such as conventional biofuels (NNFCC 2019). Also, monitoring that used cooking oils and not virgin vegetable oils involves considerable effort and fraud cannot be ruled out in the certification of the fuels. Relevant quantities of biofuels according to Annex IX Part B of RED II for climate protection in maritime and shipping transport are not to be expected.

Other possible feedstocks from residual and waste biomass materials are listed in Annex IX Part A of RED II. In part, these feedstocks are already used for materials or energy and – as with all biomass use – further sustainability requirements for use in biofuels for transport must be considered in order not to incite negative ecological impacts through over-exploitation of the biomass. When using residues and waste from forest wood, for example, it must be considered that dead wood in forests is an essential habitat for animals and thus contributes to the preservation of biodiversity; biomass residues in agriculture are an essential source for fertility of soils and thus cannot be extracted from agricultural land in any quantity.

Studies indicate in part very widely diverging potential quantities for the available amounts of feedstocks. This is due, among other things, to the fact that – like e-fuels – theoretical, technical, economic, exploitable and sustainable potentials differ and the assumptions for defining these potentials also vary. Another difficulty is to determine the quantities of biomass feedstocks already used today and thus to reflect the existing use of biomass. In a meta-analysis, IRENA (2016) evaluates various studies on the availability of residual and waste biomass feedstock according to Annex IX Part A of RED II and determines a long-term energetic feedstock potential of 25-1 180 EJ.

The upper limit can be understood as the theoretical maximum potential. In the case of ambitious sustainability requirements, it can be assumed that the lower limit must be understood as the maximum usable quantity potential of feedstocks. The extent to which this potential can be utilized is open. However, if one takes into account that considerable losses occur during conversion into biofuels and that there is also a demand for sustainable biomass in other sectors, it becomes clear that in all likelihood significantly less than 10 EJ of sustainable biofuels will be available to the transport sector. Compared to the 16-63 EJ of energy required for maritime and air transport, this clearly shows that sustainable biofuels play a rather small role for the energy supply of these transport modes and that e-fuels are needed for the transport modes.

4.2 Detailed evaluation of different e-fuel options

The individual processes and process chains are presented in more detail in this section to allow identification of strengths, weaknesses and challenges for the different e-fuel options. The focus is on the energy requirements of the individual process steps and significant technical challenges. The reason for this is that the differences in terms of costs, land use requirements, etc. can be derived more or less directly from this. The less electricity (and heat) the process chain demands, the lower the production costs, e-fuel GHG emissions and land use if the other relevant parameters are kept constant.

4.2.1 Single processes and their energy efficiency

4.2.1.1 Hydrogen production

Electrolysis processes produce hydrogen (and oxygen) from fresh water. LT electrolysis processes are carried out at 50-80 °C and the standard technologies AEL and PEMEL are used today in the single-digit MW range.

⁸⁶ In justified cases, this quantity limit can be raised in the national support systems resulting from the RED after approval by the EU commissions.

The efficiency of both LT electrolysis processes is currently approx. 65% (Brynolf et al. 2017; AVW; AEW; FE 2018) and is reported in many studies to be just over 70% in 2030 (UBA 2019d; AVW; AEW; FE 2018; UO 2015; LUT 2017b). In the long term, efficiency may increase further: AVW; AEW; FE (2018) indicates an efficiency rate of 80%; most studies see an increase potential of up to approx. 75% as realistic (UBA 2019d; E4tech; Element Energy 2014).

LT electrolyzers are relatively insensitive to load changes and can therefore adapt their operation mode well to a fluctuating energy supply from renewable sources. The most flexible is the PEMEL, which can be operated temporarily in the power range below 10% of the nominal load if required (Brynolf et al. 2017). At the same time, there is a temporary overload capacity of up to 200-300% of the nominal load (TU Berlin 2018). Steep load gradients and the short cold start time of the PEMEL systems enable flexible operation.

HT electrolysis, also known as Solid Oxide Electrolysis, is carried out at a process temperature of 700-1 000 °C. In contrast to LT electrolysis, superheated steam is fed into the process. Since less energy is required for the decomposition of water vapor, HT electrolysis can achieve higher efficiencies. In AVW; AEW (2018) the efficiency related to electricity input is stated as 81% for 2020 and 90% for 2050. In return, HT electrolysis must be supplied with high-temperature process heat for the generation of steam, for example waste heat from coupled synthesis processes. Overheating the water vapor to 700-1 000 °C requires additional electrical energy, which reduces the efficiency rates stated above if there is no other external heat source.

HT electrolysis is less suitable for flexible plant operation as it reacts sensitively to load changes and the high temperature level makes it difficult to start up and shut down the plant quickly (Pfennig et al. 2017). Long periods of small or no load require external heating which reduces the efficiency of the technology. The HT electrolysis process is still in the demonstration stage, but first industrial-scale plants are planned in combination with the production of liquid e-fuels (Holen und Bruknapp 2019). Due to the lower technical readiness level of the technology, we neglect the technology for the following analyses.

The liquefaction of hydrogen is necessary for the use of hydrogen in ships; it might also be necessary to liquify hydrogen for transport purposes. However, such a transport infrastructure for hydrogen does not yet exist and only initial pilot projects for the transport of liquid hydrogen are being carried out. According to the current state of the art, 0.3-0.4 kWh_{el}/kWh_{H₂} (23-29% of the energy content of hydrogen) must be used for this purpose. For the future, a target value of 0.22 kWh_{el}/kWh_{H₂} is given, which corresponds to an energy loss of 18% (WI; ISI; IZES 2018; EC 2018). Further losses are caused by the continuous evaporation of the liquefied hydrogen (boil-off), which cannot be prevented technically: The literature gives an evaporation rate of 0.3-0.5% per day (DNV GL 2018). As long as the evaporated hydrogen cannot be collected and used, further losses will occur.

All technologies necessary for the production of liquefied hydrogen have a high level of technical development. In the case of LT electrolyzers, however, a scaling of the plant size and automated production processes are required in order to be able to operate e-fuel plants on an industrial scale in the future and to enable large-scale deployment of electrolyzers. However, a transport infrastructure for hydrogen, without which the use of hydrogen in shipping will not be possible, must first be established.

4.2.1.2 Carbon dioxide capturing

There are two possible sustainable carbon dioxide sources that allow an emission-free CO₂ cycle with the air: capturing it from air or from biogenic waste streams. Waste streams from fossil point sources are economically favourable, but do not comply with necessary GHG emission long-term development of the energy and industry sector (section 4.1.3). Unavoidable carbon dioxide emissions from certain industry processes (e.g. cement production) will also occur in future low-carbon energy systems; if these emissions formed as part of the chemical process are assessed as a sustainable carbon dioxide source depends on whether CCS is

considered to be a possible climate protection measure or not. However, captured carbon dioxide from air will be the main future carbon source for e-hydrocarbon production.

The extraction of carbon dioxide from the atmosphere is known as Direct Air Capture (DAC). The most mature DAC process is the Temperature Swing Adsorption (TSA) process which is used today in several demonstration projects. Furthermore, there are already first approaches to scale the technology (Müller 2018). The TSA technology uses a two-step process: in the first step, carbon dioxide is extracted from the ambient air and chemically bound to a filter material and, secondly, the carbon dioxide is separated from the filter and captured. The second step is carried out at a temperature of approx. 100 °C and regenerates the filter material. According to several sources (dena; LBST 2017; WI; ISI; IZES 2018; ifeu 2019), 1.5-2.5 kWh of low temperature thermal energy and 0.2-0.5 kWh of electricity are required to provide 1 kg of carbon dioxide. The purity of the carbon dioxide is specified in literature as >99.5%. dena; LBST (2017) therefore adds a carbon dioxide purification step which requires about 0.2 kWh_{el}/kg_{CO2} for compression and liquefaction of the carbon dioxide. The land requirements for this DAC technology is estimated to be 0.1 km² per Mt of CO₂ captured per year (WI; ISI; IZES 2018).

The second option for a sustainable carbon supply is carbon from processes on the basis of sustainable biomass feedstock. Currently, this includes carbon dioxide, for instance, from biogas or fermentation processes such as bioethanol production. Biogenic processes are also the typical carbon dioxide source for most of the existing e-fuel demonstration projects. The required energy for carbon dioxide extraction from biogenic processes is far smaller compared to the DAC technology. The electricity demand is approx. 0,1 kWh_{el} per kg carbon dioxide; the demand of low temperature heat is even smaller (ifeu 2019). However, the usability of carbon dioxide from biogenic waste streams is limited by the small local concentration and the total amount of carbon dioxide (section 4.1.3).

The carbon content of waste stream from cement production and other point sources is considerably smaller than in biogas or bioethanol processes. Therefore, more energy is needed for carbon dioxide capturing in cement production waste streams. Currently, chemical absorption is the standard process for carbon dioxide extraction from cement production waste streams. A carbon dioxide capture efficiency of 85% (Reiter und Lindorfer 2015) and the energy demand of 0,14 kWh_{el} and 1 kWh of thermal energy (ifeu 2019) are typical parameters for carbon dioxide capturing from cement processes.

However, carbon dioxide from ambient air will be the main source of carbon dioxide in the long-term perspective. Thus, all calculations in section 4.2.2 assume air as the carbon dioxide source. Other process chains with other carbon dioxide sources would require less energy, however.

4.2.1.3 Methane synthesis

The Sabatier process for methane production (chemical-catalytic methanation) is carried out at temperatures above 200 °C. Since this is an exothermic reaction, only hydrogen and carbon dioxide have to be added to the process, but not energy. Instead, waste heat is released which could, for example, be used to extract carbon dioxide from the air. The energetic efficiency of the conversion of hydrogen into methane today is just under 78% (TU Berlin 2018; AVW; AEW; FE 2018; Brynolf et al. 2017); thus, approx. 1.29 kWh_{H2} is needed to produce 1 kWh of methane. UBA (2019d) indicate a potential to improve the process to an efficiency of 90%; however, this assumption is not found in other current studies.

Methanation plants can be operated dynamically in the load range between 25% and 100% of nominal load and a load change is possible within a few seconds. A cold start, however, takes a few minutes to a few hours (TU Berlin 2018). In order to avoid cold starts, the systems can also be put into standby mode when operation is interrupted, although the temperature must be maintained at 200 °C which decreases the efficiency level of the synthesis process (WI; ISI; IZES 2018; AVW; AEW; FE 2018). Grünewald (2018) and TU Berlin (2018)

point out that current technology show a methane yield of approx. 95% in case of continuous operation which could require additional methane purification steps.

Ships require liquefied methane if used as a fuel in maritime transport. According to dena; LBST (2017), $0.06 \text{ kWh}_{\text{el}}/\text{kWh}_{\text{CH}_4}$ is required for liquefaction, which corresponds to an energy loss of approx. 5.7%. LUT (2017a) assumes that the required electricity is produced from methane and indicates an energy loss of 8% of the energy content of methane. Evaporation of liquid methane in storage tanks (boil-off) occurs and the loss rate is 0.05%-0.15% per day (Sönmez et al. 2013). The evaporated methane has to be captured to avoid the strong climate impact of potential methane slip.

The technology is demonstrated and operated in the single-digit MW range and has to be scaled to large-scale industry size. However, upscaling of the Sabatier process is also provided by numbering-up medium-sized reactors which potentially reduces the technical lead time needed for producing larger quantities of methane from electricity.

4.2.1.4 Hydrocarbons (liquid e-fuels) via Fischer-Tropsch synthesis

The production of liquid e-fuels using FT synthesis takes place in two process steps. Firstly, the reverse water gas shift reaction (RWGS reaction) produces a syngas at an operating temperature of around $1\,000\text{ °C}$, which is then converted into a hydrocarbon mixture (e-crude) in the subsequent FT synthesis. As with methanation, FT synthesis is an exothermic process, meaning that only syngas and no energy has to be supplied. Waste heat is generated at a temperature level of approx. 220 °C (IWES 2017). In contrast, the production of syngas requires an external heat supply at the temperature level of around $1\,000\text{ °C}$, which usually requires additional electricity input (IWES 2017). The third and final step is the post-processing of the e-crude into specified hydrocarbon products. The existing refinery infrastructure is suitable for post-processing of the e-crude and the typical products of the existing refineries (e.g. diesel, kerosene, industrial waxes, propane) could be produced.

The RWGS reaction and FT synthesis cannot be operated very flexibly due to the high operating temperatures, the complex process dynamics and the defined product mix of the e-crude for post-processing. The energetic efficiency for the conversion of hydrogen into fuel is given in Fasihi et al. (2016) as 65% for the year 2030.⁸⁷ The production of 1 kWh e-liquid thus requires approx. $1.54\text{ kWh}_{\text{H}_2}$. Due to the high technological maturity of the FT process, only small efficiency gains can be expected in the future.

FT synthesis is an established large-scale process that has been used to date primarily for the production of liquid fuels from coal and natural gas. The technological maturity of the RWGS reactors is at a much lower level than that of the FT reactors: UBA (2016) and Timmerberg und Kaltschmitt (2019) view the technology as in the demonstration phase and refer to demonstration plants on a small scale. Technical development is needed to allow future large-scale e-liquid production via the FT path.

4.2.1.5 Methanol and other liquid e-fuels from methanol synthesis

Methanol can either be used as a fuel in shipping or as a basic chemical to be converted into other e-liquids such as kerosene, DME and others. Generally, two different synthesis processes and thus two different production pathways exist.

Today's standard industrial-scale synthesis is a two-step process: syngas which is formed in the RWGS reaction is processed into raw methanol in the exothermic synthesis process. The resulting raw methanol consists

⁸⁷ This conversion efficiency describes the ratio of the calorific values of liquid fuel and hydrogen. It covers all energy losses that occur during RWGS, FT synthesis and subsequent fuel refining.

of by-products such as ethanol, DME and water, which have to be removed for use of methanol as a fuel. According AVW; AEW; FE (2018), the energy requirements for methanol production by this production pathway are comparable to the FT path. Energy consuming post-processing to other hydrocarbons might reduce the efficiency to slightly lower values (Brynnolf et al. 2017).

Another approach is the direct production of methanol from carbon dioxide and hydrogen in a one-step process without the generation of syngas as an intermediate. The result of direct methanol synthesis is a mixture of methanol and water which afterwards needs to be separated by distillation. Generally, a higher methanol yield can be reached in the one-step synthesis process (Dieterich et al. 2020) and a methanol purity of 99.9% is possible today (LUT 2017b). Compared to the standard two-step process, the direct methanol synthesis has a higher thermodynamic efficiency due to the lower operating temperature. However, the conversion equilibrium of the one-stage process is lower and more hydrogen is needed for methanol production, which more or less corresponds to the total efficiency of both technical approaches for methanol production (Dieterich et al. 2020). According to LUT (2017b), the conversion efficiency of the one-step methanol synthesis process is approx. 70%.

In the same study, direct methanol production in a single-unit synthesis plant is classified as a mature approach which has been used at small industrial scale in Iceland for the first time (Carbon Recycling International 2013). In Brynnolf et al. (2017), direct methanol synthesis is also described as a proven process which is carried out in a fixed-bed reactor. Upscaling and more dynamic operation would be needed for large-scale use of the direct methanol synthesis under more demanding process conditions. The methanol synthesis part of the two-step process is available at large-scale, but the RWGS reaction which is required to prepare for the syngas is in the demonstration phase (section 4.2.1.4).

The resulting raw methanol can be converted into other hydrocarbons by various post-processing processes. Further processing in DME (section 4.2.1.6) and gasoline is technically proven and used commercially. Processing methanol into kerosene is not mentioned in the literature and – to our knowledge – has not been shown in pilot and demonstration plants. However, the necessary processes are used in today's refineries and should therefore be technically available in principle. The complete production path of e-liquids such as kerosene via direct methanol synthesis should show similar efficiencies to the FT path (UBA 2016).

4.2.1.6 Dimethyl ether (DME) production

Today, DME which is a potential fuel in shipping is produced from methanol in an exothermic reaction on a commercial basis. Like the methanol production, DME can also be produced in a direct process from CO₂ and H₂ with a better energy efficiency than via the two-step methanol path (LUT 2017b; Brynnolf et al. 2017). However, the single-unit DME synthesis is currently not available on an industrial scale.

According to LUT (2017b), in both DME and methanol production the energy, material and heat flows are practically identical if the respective direct synthesis is used. According to their assumptions, the conversion efficiency from hydrogen to DME is slightly higher due to the higher energy content compared to the methanol (approx. 72%). DME is a gas under standard conditions and requires liquefaction to be used as a fuel. DME has a boiling point of -25 °C and can easily be liquefied and stored under pressure in liquid state (FVV; LBST 2013). Hence, cooling or thermal insulation is not needed for DME storage tanks.

4.2.1.7 Ammonia production

Ammonia is produced on an industrial scale by the well-established Haber-Bosch process. Hydrogen – which is produced by steam reforming of fossil feedstocks today – and nitrogen are converted into ammonia at high pressure (200-400 bar) and at a temperature of 450 °C (Ricardo Energy & Environment 2019) in this exothermic process. Under these conditions, hydrogen and nitrogen are only partially converted into ammonia. Therefore, in a final step, the resulting mixture of gases is cooled to condense and separate ammonia from

unreacted hydrogen and nitrogen which are recirculated back to the Haber-Bosch reactor. The energetic efficiency of the hydrogen-to-ammonia conversion, based on LHV, is 87%.

According to Ricardo Energy & Environment (2019), the Haber-Bosch process consumes only about 6% of the overall electricity demand of a potential power-to-ammonia process whereas electrolysis accounts for 92% of the overall electricity demand. With a presumed electricity consumption of 1.54 kWh_{el}/kWh_{H₂} for today's electrolyzers (section 4.2.1.1), these figures translate into an energy demand of 0.10 kWh_{el}/kWh_{NH₃} for the Haber-Bosch process. UO (2015) reports a very similar electricity demand for the Haber-Bosch process (0.12 kWh_{el}/kWh_{NH₃}). The remaining 2% of the overall electricity consumption can be attributed to nitrogen extraction from air and other auxiliaries. As nitrogen makes up 78% of ambient air it can be harvested relatively easy using an air separation unit. Cryogenic distillation is the most mature and cost-effective air separation technology and constitutes 90% of all nitrogen production today (Ricardo Energy & Environment 2019). Ammonia can be liquefied with low electricity input as its liquefaction occurs at a moderate temperature of -33 °C or a moderate pressure of 10 bar.

Ammonia can potentially be synthesized directly from water and nitrogen in a one-step process called Solid State Ammonia Synthesis (SSAS). This technology is currently not commercially available. However, the SSAS could reduce both cost and energy consumption. Possible efficiency improvements through SSAS are not taken into account in the following calculations, since it is uncertain whether and when the technology will reach the necessary technical level for industrial application (UBA 2019d).

4.2.2 Overall conversion efficiency of e-fuel production processes

The production of the possible final energy carriers for aviation and maritime transport consists of the single processes listed in the previous section. In this section we therefore combine the assumptions of the individual processes to full process chains for e-fuel production to compare energy efficiency and the resulting electricity demand of the whole production chain. Figure 41 shows an overview of the process chains; dotted lines indicate processes that are not currently available on an industrial scale (section 4.2.1). Some of these processes are only in the early pilot and demonstration plant phase; others are better developed and must eventually be scaled to larger capacity levels to produce e-fuels on a relevant scale.

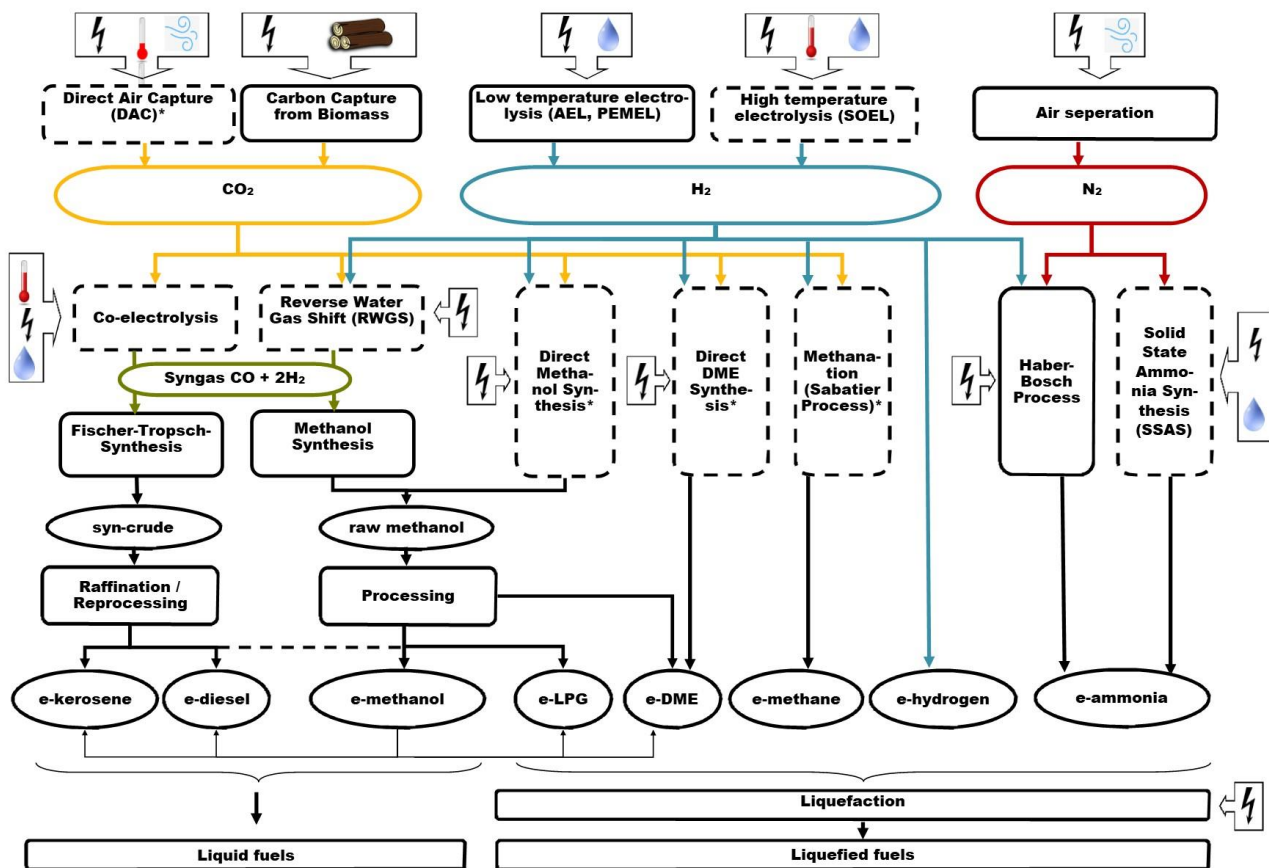
For the following calculations on the energy efficiency of the entire process chain, we also assume that hydrogen production takes place with LT-electrolyzers and carbon dioxide supply via capturing from ambient air. The limitation to these technologies is so as to be able to compare the different energy sources under the same boundary conditions and to include in the comparison those technologies which, in our view, will probably be used to a large extent for e-fuel production in the medium term. In certain contexts (e.g. additional renewable energy supply option with very high full load hours, small-scale plants using carbon dioxide from biogenic processes), e-fuel production plants can also achieve higher conversion efficiencies.

Liquefied e-hydrogen can be produced today at an overall efficiency of approx. 53%, which corresponds to an electricity demand of 1.89 kWh_{el}/kWh_{H₂}. These values are based on an electricity-to-hydrogen conversion efficiency of 65% (LT electrolysis) as described in section 4.2.1.1.⁸⁸ The underlying energy consumption for hydrogen liquefaction is 0.35 kWh_{el}/kWh_{H₂} (WI; ISI; IZES 2018). In the long term, the overall efficiency could be as high as 64% (Figure 42). This value results from an assumed improved electrolysis efficiency (up to 75%) and better hydrogen liquefaction processes (electricity demand of 0.22 kWh_{el}/kWh_{H₂}). Boil-off losses are not included in this calculation. However, they can significantly reduce the overall conversion efficiency depending on the storage time and if the evaporated hydrogen can be used for other purposes.

⁸⁸ The assumptions for electrolysis efficiencies apply to all process chains discussed.

E-ammonia could already be technically produced today on an industrial scale from renewable energy, air and water. We have determined an energy efficiency of 52% for the overall power-to-ammonia process using today's technology. This assumption includes an electricity consumption of 0.1 kWh_{el}/kWh_{H₂} for the Haber-Bosch process and a hydrogen-to-ammonia conversion efficiency of 87% (based on LHV). The assumed electricity demand for nitrogen extraction from air (0.03 kWh_{el}/kWh_{H₂}), which is derived from the assumptions for electricity required in Ricardo Energy & Environment (2019), is smaller. For the future, the overall energy efficiency of ammonia production is expected to improve according to the increase in electrolysis efficiency. Other efficiency gains are not considered due to the high maturity level of the air separation unit and the Haber-Bosch process. This results in an overall power-to-ammonia efficiency of approx. 59% for the long-term perspective. The liquefaction of ammonia is neglected in this calculation due to small electricity demand for compression. The assumption of long-term efficiency potential does not include SSAS technology, which could further reduce the need for energy.

Figure 41: Overview of different e-fuel process chains for possible e-fuel use in aviation and maritime transport (dotted lines refer to processes which are not available today at large industrial scale)

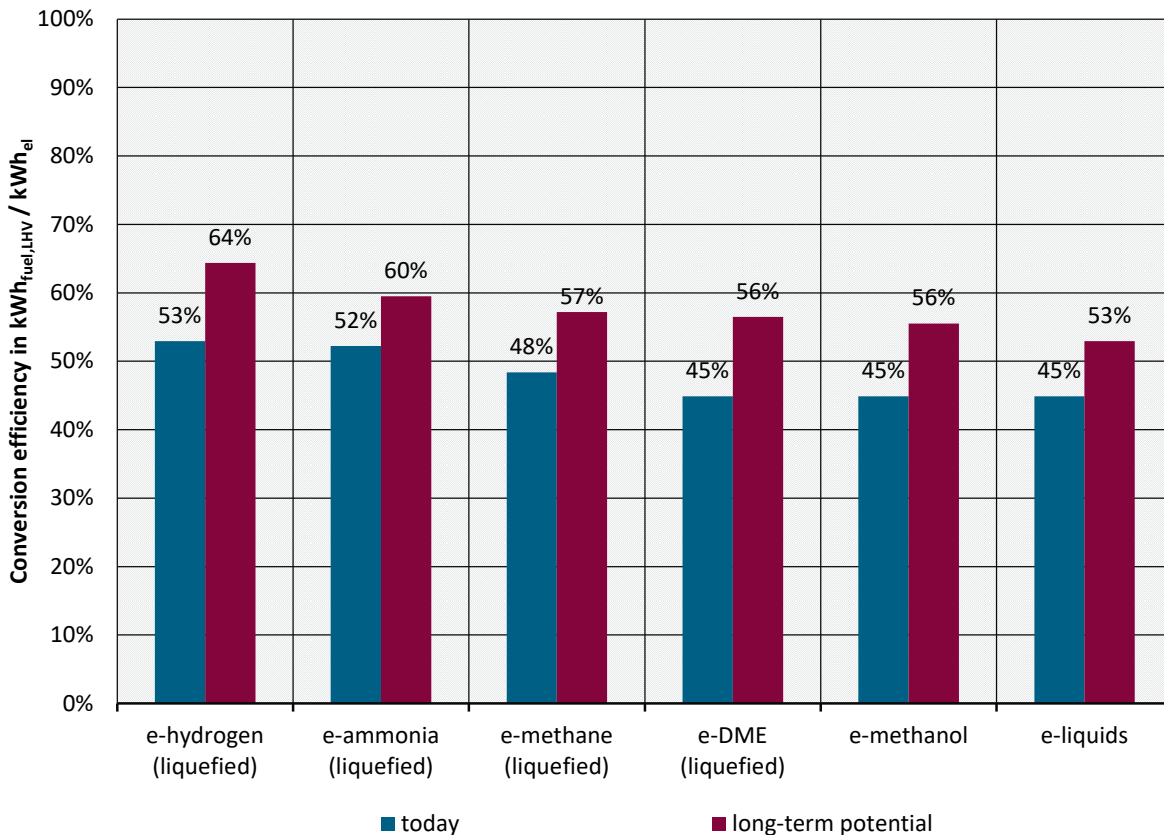


Notes: *These processes are technically available but need to be scaled up to large industrial size for industrial mass production.
 Source: Authors' own illustration

The overall power-to-gas efficiency of liquefied e-methane is assumed to be approx. 48% with today's technology under our assumptions. This calculation includes carbon dioxide extraction from the air, which is currently only demonstrated in small plants. The electricity required for carbon dioxide capturing from air is taken from LUT (2017a) and a methanation conversion efficiency of about 78% is assumed. The final step of methane liquefaction uses 8% of the produced e-methane (LUT 2017a). Technical improvements in

electrolysis and methanation (80% conversion efficiency⁸⁹) set the long-term potential at an energy efficiency of approx. 57% for the entire process chain. Similarly, to the calculation of the e-hydrogen conversion efficiency, potential additional losses due to boil-off of methane are neglected. Industrialization and scaling of the methanation technology from the single-digit MW range to the size of an industrial plant is required to produce larger quantities of e-methane. The same applies to the carbon dioxide extraction from the air.

Figure 42: Conversion efficiency from electricity input to LHV of final energy carrier



Notes: LT electrolysis and DAC assumed.

Source: Authors' own calculations

The overall production efficiency of liquid e-fuels is determined as approx. 45% for today. The underlying hydrogen-to-refined-hydrocarbons conversion efficiency is 65%. For the long-term assessment, we assume that the conversion efficiency will increase slightly to 67%.⁹⁰ Along with the efficiency gains of electrolyzers, this will result in the potential to achieve an efficiency of 53% in the long term. The assumed electricity demand for carbon dioxide extraction from the ambient air comes from Fasihi et al. (2016). The links in the FT process chain which are missing and currently technically immature are carbon dioxide extraction from the ambient air and the RWGS reaction, both of which are in the demonstration stage with small pilot plants.

⁸⁹ We assume a small efficiency gain of 3% because the Sabatier process has not been used in industrial scale and minor improvements in process and reactor design seem plausible over time.

⁹⁰ We assume again an efficiency gain of 3% because the RWGS has not been used in industrial scale and minor improvements in process and reactor design seem plausible over time.

E-methanol can be used directly in shipping or as a platform chemical for refining into other hydrocarbons. For today's methanol production, we assume a similar power-to-fuel efficiency like for e-fuel production via Fischer-Tropsch synthesis (UBA 2016)⁹¹ and today's overall energy efficiency of methanol production is thus estimated to be 45%, equalling that of hydrocarbon production by FT synthesis. According to LUT (2017b), a hydrogen-to-methanol conversion efficiency of 80% is feasible for the direct methanol synthesis. The electricity required for carbon dioxide extraction from air is taken from the same study and the efficiency for e-methanol production could, therefore, rise to above 55% in the long term. Additional energy input would be needed for refining to other hydrocarbons like kerosene and propane which would probably result in similar overall energy efficiency values as with the FT path.

As with the FT process chain, carbon dioxide from the ambient air and the syngas production are currently not available technologies. Although direct methanol synthesis avoids syngas production, it uses a synthesis process that is currently not the standard methanol production pathway. In addition, methanol processing in kerosene is still not being demonstrated to our knowledge, in contrast to refining in gasoline or DME.

At present, methanol-to-DME conversion is the standard production process for today's DME production. Additionally, DME is a by-product of the two-step methanol synthesis. As a rough estimate of the energy efficiency potentially achievable today, we use the same energy efficiency as for the FT path or methanol synthesis. LUT (2017b) estimate the energy requirements of the direct DME synthesis path to be the same as for direct methanol production. As a long-term potential, the efficiency of direct DME production is approx. 56% for the entire production path due to the higher energy content of DME compared to methanol.⁹² The energy needed for liquefaction is neglected in this calculation. The challenges for further technical development are the same as for methanol production.

Figure 42 compares the overall efficiencies of the different potential e-fuels:

- ▶ Liquefied e-hydrogen has the lowest energy requirements for production today and in the future. The reason is obvious when looking at the process chain. For the liquefaction of hydrogen, another energy-intensive process occurs after electrolysis, without eliminating its advantage as an energy carrier with a very high mass-related energy density compared to the other options. A prerequisite for this is that the energy requirement for liquefaction will – as assumed – be considerably lower in the future and that a useful application for the evaporated hydrogen from the stored liquefied hydrogen (boil-off) exists.
- ▶ For the production of ammonia, hydrogen production is followed by a single-stage ammonia synthesis from nitrogen and hydrogen (Haber-Bosch process). Compared to hydrocarbon production, this has an efficiency advantage, which is mainly due to the low energy input for separating the nitrogen from air. In contrast to methane, ammonia needs only to be compressed for liquefaction with a low energy input. Thus, e-ammonia has the second highest conversion efficiency among these options.
- ▶ For the hydrocarbons methane, methanol and DME, we anticipate single-stage synthesis processes in the medium and long term if they are produced from electricity via electrolysis. This results in very similar energy losses along the process chain. The lower carbon dioxide requirement for methane is

⁹¹ Brynolf et al. (2017) actually shows a smaller efficiency for the gasoline production through the methanol process chain than for the FT-path.

⁹² Schemme (2020). compares different pathways of e-fuel production and ranks the efficiencies of methanol, FT fuels and DME production in the same way as in Figure 42. The efficiencies calculated in Schemme (2020) differ slightly from those shown in Figure 42.

compensated for by the fact that additional energy is required for the liquefaction of methane. The post-processing requirements of the synthesis products are small compared to the production other liquid e-fuels. The appropriate use for methane boil-off is needed to prevent methane slip to the atmosphere and to reach the efficiency shown in Figure 42.

- The production of liquid e-fuels is associated with the highest energy expenditure. Compared to the other process chains, more process steps are required. Either two-stage synthesis processes with subsequent refining can be used to produce e-liquids, or more energy-intensive post-processing is necessary if the liquid e-fuels are produced via the single-stage methanol synthesis.

Table 38: Conversion efficiency from electricity to final energy carrier for different e-fuels

Conversion efficiency (kWh _{fuel,LHV} /kWh _{el})	Currently	Long-term potential	Assessment
Ammonia	52%	60%	o
DME	45%	56%	-
Hydrogen*	53%	64%	+
Methane*	48%	57%	-
Methanol	45%	56%	-
Liquid e-fuels	45%	53%	--

Notes: Data from Figure 42.

*The possible losses due to the boil-off of liquefied methane and hydrogen are neglected in the comparison of the efficiencies. It is assumed that methane and hydrogen from boil-off are captured and used and do not result in energetic losses.

Source: Authors' own compilation and assessment

4.2.3 Impact of overall energy efficiency on other evaluation criteria

The electricity consumption for e-fuel production is a very relevant factor for many of the assessment criteria discussed in section 4.1. The energy efficiency of the overall production processes is a key parameter for the evaluation criteria production costs (section 0), GHG reduction potential (section 4.1.3) and land use (section 0). The lower the energy input for the production of the e-fuel, the better the respective energy carrier performs under the same context conditions (e.g. electricity costs, GHG intensity of electricity generation, land availability) with regard to the above categories:

- Similar effects arise with regard to the GHG reduction potential for the different energy carrier options. The GHG assessment of the different energy carriers directly depends on the energy efficiency of the overall process, if the electricity input for the different process chains has the same GHG intensity. Therefore, the lower the electricity input, the better the GHG balance of the respective fuel. Hydrogen and ammonia thus also have an advantage over other fuels in this evaluation category. For hydrocarbon fuels, there is also a risk of higher GHG emissions if the use of carbon dioxide slows down GHG reduction in energy production and the industry sector. Due to the high climate impact of methane, there is also a risk of methane slip during the production, transport, storage and use of e-methane. In the long term, therefore, the use of potentially zero GHG emission e-methane cannot guarantee achievement of the necessary GHG reduction for the long-term climate protection goals (Horvath et al. 2018).
- The cost of electricity procurement and the cost of capital are decisive factors for production costs. Here, there are advantages for the processes that have better energy efficiency, too. Overall, higher energy efficiency results in a lower overall capacity of the production facilities and also requires less

electricity for the same amount of energy in the fuel produced. Another difference is the nature of the processes. Hydrogen production with electrolyzers is a rather modular process; scaling up the size of the plant tends to result in lower cost reduction potentials (DECHEMA 2019). The cost reduction potentials from various studies can be exploited with rather small electrolyser plants. In contrast, the reactor volume is a relevant factor for the costs of the synthesis processes and the cost degression is especially reached by upscaling of the reactor size. Hydrogen and ammonia (in the case of substitution of fossil hydrogen in existing ammonia production facilities) will have a cost advantage in terms of the production cost.

We are not aware of a study comparing the production costs of all the fuels examined with the same input values for cost calculations. However, various studies show a similar structure. Horvath et al. (2018) compares the costs of producing liquefied hydrogen, methanol, liquefied methane and FT diesel in Argentina. The cost potential curves provided in that study show hydrogen production to be the most favourable, followed by methanol and, after a rather small gap, methane. The highest costs arise for FT diesel in the study. A similar value at a different cost level is given by Brynolf et al. (2017), but the costs are given without liquefaction of methane and hydrogen. Methane has slightly lower production costs than methanol and DME in this study. Taking into account the energy loss during the liquefaction of methane, it can be assumed that the cost calculations show very similar costs for liquefied methane, methanol and DME. Cerulogy (2018) compares the production costs for liquid e-methane, e-ammonia and FT end products. This comparison shows the lowest production costs for e-ammonia.

Table 39: Evaluation of impact categories for different e-fuels (long-term perspective)

	Land use	Production cost	GHG mitigation potential
Ammonia	o	o	++
DME	-	-	++
Hydrogen	+	+	++
Methane	-	-	+ (risk of methane slip)
Methanol	-	-	++
Other liquids	--	--	++

Notes: A plus indicates that an option is assessed relatively better in comparison to the other options, whereas a minus indicates that an option is assessed less positively.

Source: Authors' own assessment

4.3 Summary

In aviation and maritime transport, energy sources other than liquid or liquefied fuels will only be able to be used in niches. As sustainable advanced biofuels are limited in terms of their available quantity, even in the long term, e-fuels are needed for climate protection and the goal of making these two modes of transport climate-neutral by 2050.

In principle, it is possible to produce e-fuels in such a way that they facilitate a completely post-fossil use of energy in aviation and maritime transport. The prerequisite for this is that, in addition to the use of additional renewable electricity, the carbon dioxide used – if required for the production of hydrocarbon fuels – creates a CO₂ cycle with the atmosphere. In the long term, the use of CO₂ from the ambient air will play a pivotal role in this. Moreover, for e-fuels to be completely climate-neutral, the upstream chain emissions of renewable electricity generation will need to go down to zero over time.

For the expected climate protection effect of e-fuels, the challenge is to ensure that the additional electricity demand of e-fuel production does not contribute to higher GHG emissions in the electricity system, especially

during the transformation phase of the energy systems in which fossil energy sources still contribute to electricity generation. Similarly, with an emerging demand for CO₂ as a feedstock for fuel production, the expected drop in CO₂ emissions from industrial point sources must not be slowed down. For this reason, reliable sustainability and climate protection regulations are needed to ensure the climate protection effect of the e-fuels used during the transformation phase to a fully renewable energy system.

The costs of e-fuels are higher than those of fossil fuels today and will remain higher in the long term. They thus need policy instruments to be used in aviation and maritime transport. The extent to which the costs of e-fuels drop depends above all on the investment costs in electrolyzers, the electricity costs for e-fuel production and the costs of financing the investments (WACC). Scenarios show costs for the long-term cost development that differ many times over, with the result that from today's perspective no conclusion can be drawn on the cost level which these fuels will realistically reach in the long term. For e-fuel production, locations with low generation costs of renewable electricity, available land use potential and a high governance level are advantageous. Accordingly, in the long term, imports to Germany and the EU can be expected on a considerable scale from regions with high governance level.

The production of e-fuels requires water and land, which are mainly needed for renewable electricity production. The water demand is comparable to other industrial processes. Local impacts on the availability of water and the land use will nevertheless be significant. This is especially true if fuel production takes place in regions where fresh water is a scarce resource and water availability is a challenge. For this reason, the involvement and consideration of the needs of local stakeholders in the project development of industrial e-fuel production is a prerequisite for the acceptance of the technology and the socially sustainable production of e-fuels. The use of favourable locations for renewable electricity generation must not lead to the transformation to a renewable electricity system becoming more expensive and slower at the possible production locations.

E-fuels will not be available in relevant quantities in the short term. The technical challenges are the required automation of the production of electrolyzers, the technical state of the art and the necessary scaling of single processes for e-fuel production. While hydrogen and ammonia could industrially be produced relatively soon by substituting fossil hydrogen, the commissioning of the first large-scale industrial plants for the other e-fuels is not expected until 2028-2030. In addition to the production plants, the ramp-up of production capacities also faces the challenge of being able to provide additional renewable electricity generation capacities on a sufficient scale within a short period of time. In the long term, however, it can be assumed that there is sufficient potential for the production of e-fuels to supply maritime and air transport with post-fossil fuels.

Among the different e-fuels, hydrogen and ammonia have the lowest conversion losses from electricity to the end-products. Methanol, liquefied methane and DME have higher conversion losses, but are more efficient in production than liquid e-fuels such as jet fuel. Since efficiency has a direct impact on the electricity demand for e-fuel production, a similar ranking results for the comparison of the fuel production costs and land used for e-fuel production. Purely from the perspective of fuel production, ammonia and hydrogen have, therefore, slight advantages compared to the other fuel options.

5 Roadmaps for achieving zero emissions

The focus of this chapter is to investigate how a full transition to post-fossil fuels produced from renewable energy (e-fuels) can be achieved in international aviation and maritime transport by 2050. We look at specific implementation options and practice-oriented proposals for policies and instruments at national, European and/or international level (roadmaps).

The introduction and increased uptake of post-fossil fuels must be accompanied by policies to reduce or redirect demand (avoid, shift) and to improve energy efficiency in both sectors. This is necessary because production of post-fossil fuels has an impact on the environment too and because international transport is in competition for post-fossil fuels with other sectors. Moreover, aviation induces additional climate warming beyond the direct GHG emissions due to non-CO₂ effects, which can only partly be mitigated through post-fossil fuels. However, this does not fall within the scope of this study.

The technologies for the production and use of individual e-fuels and related cost projections develop quite dynamically. Therefore, their role in the future energy supply of aviation and maritime shipping as well as the policies and instruments to promote their uptake are currently being intensively debated at several political levels and in science and industry. Against this background these roadmaps cannot reflect all nuances of these developments and discussions but should be considered as inherently consistent concepts of a potential policy design with a view to illustrating interlinkages of the activities at different policy levels. Each roadmap is thus just one concept of the potential development, which could be varied in many instances or complemented by entirely different roadmaps.

As a first step we provide relevant background for elaborating and analysing the selected roadmaps (section 5.1). This includes an estimate of the renewable electricity required to supply aviation and maritime transport with e-fuel. In addition, we look at challenges and criteria to be considered when developing the selected roadmaps and consider as a last preparatory step before elaborating the roadmaps how different policy instruments could contribute to the promotion of the accelerated uptake of post-fossil e-fuels. The aviation roadmap is described in section 5.2, followed by two roadmaps for shipping in section 5.3.

The roadmaps basically follow the same structure. We start by looking at potential activities at national level (Germany), continue with conceivable activities at European level and conclude with an analysis of possible initiatives at international level, i.e. ICAO and IMO but also initiatives and stakeholders beyond those bodies. We start the analysis with looking at operative short-term actions such as showcase or lighthouse projects to finally arrive at regulatory activities required to ensure the long-term transition towards post-fossil e-fuels. As a final step, we provide a graphical overview of each roadmap, which also indicates when the different activities have to be commenced, updated, intensified or completed to achieve defossilization of aviation and maritime transport by 2050. In the last section 5.5, we draw overarching conclusions from the analysis of the roadmaps and derive policy recommendations.

5.1 Background

5.1.1 Projected demand for renewable electricity

One key issue for the development and assessment of the roadmaps is the amount of e-fuel which needs to be supplied. In chapter 2 of this study, we compile the demand projections of various studies for global aviation and shipping. Table 15 (p. 68) provides a summary of these analyses. Aviation and maritime shipping currently consume about 27 EJ overall. Depending which of the policies projections materialize, the combined demand of both sectors could grow by 45% (low scenario) or even more than double up to 2050 (high scenario).

Based on these projections, we can roughly estimate the amount of renewable electricity required to produce the e-fuels for these demands. The well-to-tank conversion efficiency⁹³ of the considered e-fuel types ranges from 45 to 64% (Table 38). For a rough estimate, we therefore apply an average conversion efficiency of 50% up to 2050.⁹⁴ The results of these calculations are provided in Table 40.

Table 40: Potential demand for renewable electricity for producing e-fuels

	Unit	2020	2025	2030	2035	2040	2045	2050
Aviation & Shipping								
High	PWh	15.2	17.5	20.1	22.8	25.8	28.7	32.2
Low	PWh	14.9	16.1	17.3	18.4	19.6	20.5	21.7
Aviation								
High	PWh	8.8	10.3	12.2	14.3	16.8	19.8	23.3
Low	PWh	8.6	9.5	10.6	11.7	13.0	14.4	16.0
Shipping								
High	PWh	6.4	7.2	7.9	8.4	9.0	8.9	8.9
Low	PWh	6.3	6.5	6.7	6.6	6.6	6.1	5.7

Source: Authors' own calculations

To put this into context: In 2018, the total global renewable electricity generation amounted to 6.7 PWh, almost two thirds from hydropower plants (IEA 2019); currently each of the two sectors would require the total global renewable electricity generation if the current demands were to be supplied by post-fossil e-fuels. Assuming the average growth rates for wind and photovoltaics of the last 5 years (16%/y and 33%/y, respectively), all additional renewable capacity added in the next 10 years would be required to supply only the projected demand of both sectors with e-fuels in 2050. However, as some variables of three-decades-projections are inherently highly uncertain, the results differ in a wide range, giving only a glimpse of the demand in 2050.

In 2018, the EU's share in global aviation and marine fuel demand amounted to 30% and 25% respectively (IEA 2020d). Germany's share was 5.2% and 1.2% respectively (IEA 2020d). Assuming, for example, a quota of 2% e-fuel in 2030 at the EU level, 67 TWh renewable electricity would be required to generate this share of e-kerosene of the EU's total kerosene demand while 36 TWh would be needed to produce the e-fuels required to comply with that quota in the shipping sector. The equivalent figures for Germany amount to 12 TWh and 2 TWh, respectively – independently of which e-fuel(s) will finally be used in the shipping sector.

5.1.2 Challenges and criteria for developing roadmaps

The main goal of the analysis is to provide potential roadmaps which ensure that by 2050 both international aviation and maritime transport have fully switched to post-fossil fuels. Assuming these fuels were produced without fossil sources, both sectors would thus not emit GHGs. However, several challenges need to be addressed at the same time by the potential roadmaps to ensure that the overarching goal is achieved:

- incentivize the fast start of e-fuels production and continuous upscaling afterwards;

⁹³ This is the relation of the energy content in the fuel to the renewable electric energy input required to produce the e-fuel while taking into account all conversion processes required (hydrolysis, Fischer-Tropsch synthesis, etc.) and all transport losses.

⁹⁴ Improvements in conversion efficiency can be expected as probable but are not taken into account in this rough estimation.

- ▶ ensure adequate demand for the e-fuels generated;
- ▶ facilitate fuelling/bunkering infrastructure, either by adapting existing or building new infrastructure;
- ▶ promote the construction of new or adaption of existing vehicles⁹⁵, where appropriate;
- ▶ trigger cost degression through technological learning and economies of scale;
- ▶ facilitate permission for new alternative fuels (like ASTM for aviation fuels);
- ▶ where several technological options exist as for shipping, narrow down the number of options so that competition of technologies does not impede economies of scales dynamics.

Several policies and instruments can be considered to address these challenges. Depending on their specific design, some address individual challenges and others address more than one challenge at the same time. Moreover, as with most policy goals, usually more than one instrument will be required to address the challenges described above. In the next section, we discuss the suitability and effectiveness of potential policies and instruments in addressing the challenges.

⁹⁵ We use the term “vehicle” to denote both aircraft/planes and ships/vessels.

Box 1: Synergies and conflicts with e-fuel demand from other sectors

- ▶ The aviation and shipping sectors are only two of many potential users of synthetic e-fuels in a climate-neutral world. Most other industries and services will need to find alternative sources of energy and raw materials as well. Potential demand for e-fuels and green hydrogen⁹⁶ is proposed for different industry sectors such as the steel and chemical industries, the heavy-duty road transport sector and heavy off-road vehicles, e.g. for agriculture or construction. This parallel demand could interact positively or negatively with the demand from shipping and aviation. On the one hand, a larger demand – if accompanied by a larger supply – would speed up the technological learning and could make stronger use of economies of scale. On the other hand, the potential demand for e-fuels is so high that it is unlikely that all potential users can be supplied: with a conversion efficiency of roughly 50%, the current global energy demand for aviation or maritime transport is as high as the current global production of renewable electricity (section 5.1.1). In other words: if all renewable electricity globally were used only to produce e-fuels, it would be just sufficient to meet the demand from one of the two sectors, either aviation or shipping.
- ▶ It is therefore essential that e-fuels are only used in applications where no other more efficient alternatives exist. This includes green hydrogen for industrial processes but also e-methanol and e-ammonia as feedstocks for the chemical industry. In such cases the synergies of parallel demand should be used to ensure a faster and cost-efficient transition to a defossilized economy. For example, e-kerosene produced from e-methanol is one potential pathway which is still under development (section 5.2.4). While it is not yet clear whether the methanol-route for e-kerosene production is advantageous compared to the Fischer-Tropsch route, this route should be further investigated as there will be a high demand for e-methanol in the future. Moreover, e-methanol is, in addition to e-ammonia, also a potential option for defossilizing the shipping sector, with the result that both sectors might rely on the same (intermediate) e-fuel.
- ▶ In 2018, about 92 million metric tons of methanol and about 144 million metric tons of ammonia were produced worldwide from fossil sources (Kajaste et al. 2018; Methanol Institute 2020c; USGS 2020). In energy terms, the methanol production is equivalent to roughly a third of the aviation or shipping sector's energy demand in the same year while the ammonia production would cover slightly more than a fifth of maritime shipping's energy demand (IEA 2020d). E-methanol and e-ammonia production facilities will not be stranded assets, independently of the demand from aviation and maritime transport. Subsidizing such facilities can certainly be considered as a no-regret policy.
- ▶ If e-kerosene is generated from syncrude in refineries or through the Fischer-Tropsch process, a mix of outputs including e-gasoline, e-diesel, e-paraffins and liquid e-gases are produced in parallel.⁹⁷ The relationship between these outputs depend on the process parameters and can be influenced to a certain extent. These by-products could either be re-inserted into the process as feedstock or used directly: there is a high potential demand for these products, e.g. as a fuel in the shipping industry, for off-road machineries or feedstock for chemical processes.

- ▶ For road transport, the situation is more complex. The efficiency loss of battery-electric vehicles is only about 25%, i.e. for each kWh of electricity produced, 0.75 kWh are used actually to drive the car. For combustion vehicles using synthetic fuels, the efficiency loss is about 85%, i.e. only 15% of the produced electricity is actually used to move the vehicle (AVW; AEW; FE 2018). Taking into account the size of the road transport sector globally, it becomes clear that synthetic e-fuels are not a viable alternative to battery-electric vehicles.
- ▶ Yet it is conceivable that road transport could play a role in the build-up phase and could shoulder a part of the economic costs: if initial e-fuel installations also produced fuels for the road transport sector, the impact on consumer prices would be very low due to the much bigger market compared to aviation or shipping but also due to fuel prices for road transport, which are typically twice as high due to fuel taxes. While the aviation and shipping sectors might profit from the lower costs that they would need to finance, it is essential that the phase-out of synthetic fuels in road transport is already planned from the beginning to avoid a long-term supply shortage for sectors for which no alternatives exist. One option to ensure the phase-out could be to limit the use of e-fuel in road transport to currently existing cars while no new cars with a combustion engine could be registered. European countries and cities have already announced or adopted such policies (ICCT 2020e).

5.1.3 Suitability of potential policies and instruments

For the assessment, we apply the analysis roster below and distinguish between the instrument type, their policy focus, which barriers they address, and at which level they can be implemented:

- ▶ Instrument type
- ▶ Project funding: funding of research and development, investments in pilot projects for e-fuels production or for making existing or new vehicles ready for using e-fuels.
- ▶ Production subsidies: Financial support to produce e-fuels with a view to closing the gap between their production costs and the market price for fossil fuels.
- ▶ Economic incentives: Internalization of at least parts of the external climate effects of fossil fuels while narrowing the price differential between fossil and e-fuel.
- ▶ Regulatory standards: Technical standards such as minimum requirements for the composition of e-fuels or for the design of vehicles and infrastructure.
- ▶ Policy focus

⁹⁶ Green hydrogen is produced from water through electrolysis using renewable electricity only.

⁹⁷ Sunfire, power-to-liquid: "This renewable crude can be refined into different blends of e-Fuel such as jet fuel, diesel, gasoline and other hydrocarbon fuels." <https://www.sunfire.de/en/e-fuel>.

- ▶ R&D: While many technological process steps to produce e-fuels are ready for upscaling (e.g. hydrolysis), others are still under development (e.g. reverse water-gas-shift reaction, direct air capture).
- ▶ Production: Incentivizing upscaling the production of e-fuels.
- ▶ Use: Ensuring that the e-fuels produced are used.
- ▶ Vehicles: Support the adjustment of existing vehicles or adapting the design of new vehicles to make them e-fuels ready so that they use e-fuels in the future.
- ▶ Infrastructure: Facilitate that the infrastructure for fuelling/bunkering including storage capacities is developed at the same pace as the demand and supply for e-fuels increases.
- ▶ Barrier addressed (section 3.1)
- ▶ Investment risks: Under current market conditions investing in e-fuel production facilities is a high-risk venture. Some of the required technologies are not yet mature, demand for e-fuels is uncertain and the long return of investment periods require equally long-term political frameworks to ensure a return on investment.
- ▶ Capital costs: Investments of billions of Euro will be needed globally to construct sufficient production facilities and renewable electricity generation capacity to meet the continuously increasing demand if the transition towards e-fuels is underway.
- ▶ First mover disadvantage: Some of the steps of the e-fuel production process are still early in their technological development cycle. The first installations applying these processes on a large scale will be less efficient than later plants and might not be able to sell their product at cost-covering prices anymore.
- ▶ Reducing price differential: Even under optimistic assumptions, e-fuels will remain considerably more expensive than fossil fuels. To compensate for this, the cost of fossil fuels could be increased (e.g. through carbon taxes)⁹⁸ or for e-fuels be reduced (e.g. through subsidies).
- ▶ Regulatory scope
- ▶ Unilateral (Germany): For internationally operating sectors such as aviation and maritime transport, a global policy would usually be optimal and induce the least distortion. Nevertheless, some policies to increase the market penetration of new technologies can – as the promotion of wind and photovoltaics via the German Renewable Energy Sources Act (EEG) has shown – be initiated unilaterally.

⁹⁸ If the price of fuel is increased through taxes, emissions trading or mandatory requirement such as an e-fuel quota not at a global, but at regional level like the EU, operators have an incentive to evade the price difference by bunkering or fuelling (tankering) outside the regulated region. This could undermine the effectiveness of the regulation by inducing carbon leakage and result in a distortion of competition. In section 5.1.3.6, we briefly elaborate the extent to which this concern applies and what strategies can be applied to mitigate such incentives.

- ▶ EU: Some of the policies which would (indirectly) improve the competitiveness of e-fuels with fossil fuels are beyond the competence of national governments and can thus be more easily addressed through a joint effort within the EU.
- ▶ Multilateral: To ensure a global transition towards post-fossil fuels, ultimately an agreement at the international level will be required, i.e. at ICAO and IMO. However, reaching global agreements can be complex and require time; the pace of these processes can potentially be accelerated by individual countries or a group of countries which act as frontrunners. Moreover, specific initiatives under already existing multilateral structures such as G20 may also be used to coordinate the promotion for increasing the uptake of e-fuels.

Before we apply this roster on potential instruments (section 5.1.4), we briefly describe how they could be designed for promoting the transition from fossil to e-fuels and discuss how their special characteristics can be utilized towards that aim.

5.1.3.1 Subsidies for research and development (R&D)

Even though several of the processes required for producing e-fuels have been well-known for many years, there are processes for which considerable gaps in knowledge still exist (water-gas-shift reaction, DAC, etc.). Moreover, since the generation of e-fuels requires several processes, the interdependency of these processes including potential synergies and conflicts of their operation require further research. Further R&D is also required with regard to certification of the fuels both in terms of safety and life cycle sustainability.

R&D can contribute to reducing the price difference between fossil and e-fuels, e.g. if it helps to increase the efficiency of individual steps in the production and enhance synergies between the steps. In a competitive market context, companies invest in R&D to the extent that they can increase their profits through innovative technologies or processes (Baumol 2002). However, such innovation processes take time, but they could be accelerated by publicly-funded R&D.

Funding of such R&D projects can be made at national and European level. Another option would be establishing a research fund at international level, e.g. under the auspices of ICAO or IMO.⁹⁹ However, establishing international instruments for raising financial resources and criteria for allocating these resources to prospective R&D projects can be time-consuming since many of the design features will result in advantages of a group of countries and disadvantages for another group. This is not an argument to disregard this route but it can play an important role in order to not lose time for the transition towards post-fossil e-fuels domestic and/or European R&D funding.

The financial resources required for funding R&D could be drawn from the government's budget or from revenues of economic instruments such as ETS or taxes.

5.1.3.2 Subsidies for e-fuel installations

In addition to closing knowledge gaps it is important to trigger 'learning by doing' through supply of e-fuels to the market. This allows identification of where the new production technologies do not work as expected and of ideas for how such problems can be addressed. Therefore, R&D and deployment need to be conducted in close cooperation. One option to promote such deployment projects is to subsidize the investments required to establish the production installations. However, renewable electricity is a major

⁹⁹ Along with other organisations, the International Chamber of Shipping (ICS) suggests that an International Maritime Research and Development Board (IMRB) should be established to promote e-fuels in maritime transport IMO (2019).

input factor. If generation of additional renewable energy is not part of the pilot project but will be purchased from other providers, such projects face a high share in operating expenditure (OPEX) while the capital expenditure (CAPEX) is small compared to other renewable technologies (Steffen 2019). Thus, even if the CAPEX is largely subsidized, the installations may cease operation if the OPEX is too high to compete with fossil fuels. So, only funding pilot projects may not ensure that the funded installations stay in operation. They may need to be combined with incentives which ensure that the installations are operated over a longer period.

5.1.3.3 Subsidies for e-fuel production

With a view to overcoming the CAPEX/OPEX dilemma of subsidizing project investments which involve a considerable share of OPEX, subsidizing e-fuel production can be considered. Both approaches are not necessarily mutually exclusive but could be combined so that a certain share of the total subsidy for ensuring the production is paid upfront to incentivize the investment in the installations while the other share is paid on delivery of the product to incentivize that the installations are actually utilized. Like the goal of subsidizing investments in e-fuel manufacturing facilities, the goal of such production subsidy is to trigger technological learning by ensuring continuous and long-term production and subsequently to decrease production cost, which provides the opportunity to reduce the subsidy over time.

The subsidy could be designed similarly to the support established to promote the deployment of renewable electricity in Germany (EEG, i.e. the Renewable Energy Sources Act) and could look as follows:

- ▶ Fixed subsidy per unit of e-fuel for limited period, e.g. 12 years;¹⁰⁰ the subsidy will be paid on delivery of the product to incentivize utilization of the production facilities.
- ▶ The subsidy should eliminate the price difference between fossil and e-fuels, with the result that e-fuels can compete at the market with fossil fuel.

Such a design may induce free riding if the subsidy cannot be adjusted as quickly as the production costs decline due to technological learning. To avoid or at least reduce such free riding the subsidy could be auctioned: producers can offer certain amounts of e-fuels at certain subsidy. The producer who offers the production at the lowest subsidy will win the auction. The auctions will be held frequently with the view that technological learning is reflected in declining subsidies and to ensure continuous upscaling of e-fuel production capacities.

Alternatively, the subsidy can be auctioned on the basis of so-called 'contracts for difference' (CfD, for more details see: LCCC 2020; Richstein 2017). E-fuel producers would offer delivering a certain amount of e-fuel over a predetermined period at a price per unit of e-fuel (strike price), which would cover their total production costs. Offers with the lowest strike price would be awarded with a CfD. The respective producers receive the difference between the strike price and the market prices if the market price for fossil fuel is below the strike price. If the fossil fuel price is above their strike prices, they need to refund the difference to the government. However, since production costs of e-fuels are far away from market prices (Figure 37, p. 130), refunding would not occur in the next 10 or 20 years at all.¹⁰¹

¹⁰⁰ It could also be 10, 15 or 20 years. In the case of longer terms, the investment in the system can be refinanced through a larger production volume, with the result that the subsidy should initially be lower. In the case of dynamic technological development, however, if the running times are longer, the price that is ultimately subsidized is too high compared to systems commissioned later. The duration of the funding is ultimately a political decision that must be specified within the framework of the stakeholder consultations.

¹⁰¹ For more background on CfD, see Box 2, p. 19.

The financial resources required to finance the subsidies can be obtained through different approaches:

- ▶ Drawing from federal budget of the government. However, this is only applicable at the beginning when the volume is still small, e.g. as long as the share of e-fuels is below 5% of total fuel sales;
- ▶ Earmarking revenues generated by economic instruments such as the Emissions Trading System of the European Union (ETS, section 5.1.3.4) and the European Energy Tax Directive (ETD, section 5.1.3.5);
- ▶ Revenues from ticket taxes (CE Delft 2017);
- ▶ Establishing a specific surcharge, which will be applied in fossil fuel sales. This approach would simultaneously contribute to finance the subsidy and to narrow the price gap between fossil and e-fuels. It would also resemble the approach applied under the EEG, under which the financial resources required to deploy renewable electricity installations are raised from electricity consumers, though with exemptions for certain sectors.

Based on the polluter pays principle, the revenues should be raised in the respective sectors. As the success of the EEG has illustrated,¹⁰² such an approach can trigger and maintain dynamics to introduce and upscale entirely new technologies, which are not yet compatible with current technologies.

¹⁰² The IEA (2013) assessed the EEG as a very effective instrument for the dissemination of renewable energies and in particular the generation of electricity by biomass, wind energy and photovoltaics. In addition, it has been successful in reducing costs. The principles of the EEG had been adopted by at least 65 countries worldwide by the beginning of 2012 (REN21 (2013)).

Box 2: Contracts for Difference (CfD)

- ▶ **Purpose:** Provide public subsidies to investors of GHG reducing technologies in a way which ensures efficient use of the subsidies while eliminating windfall profits and mitigating price risks for investors at the same time.
- ▶ Functioning
- ▶ The government (or a mandated company) calls for the delivery of climate friendly product to the market and provides subsidies for those providers/investors who can offer the product at lowest subsidy;
- ▶ Typical products are (renewable) electricity or climate-friendly steel/cement/chemicals; the production of e-fuels would be another potential application; if the product is an emission reduction through a certain technology/product, they are usually called Carbon Contracts for Difference (CCfD);
- ▶ At an auction, investors provide sealed bids in which they commit to provide a certain production capacity or producing a certain amount of the product at a price, the so-called strike price, which covers total CAPEX and OPEX over the contract period;
- ▶ Once that bid was successful, the investor receives on delivery of the product the difference between the contracted strike price and the price of the reference product, which is typically determined at a public exchange; if the price of the reference product exceeds the strike price, contractors have to pay the difference to the government.¹⁰³ In the case of e-fuels, the reference product would be the fossil fuel plus carbon costs if the application is covered by the EU ETS as is the case for aviation;
- ▶ Contract periods typically range from 15¹⁰⁴ to 20¹⁰⁵ years.

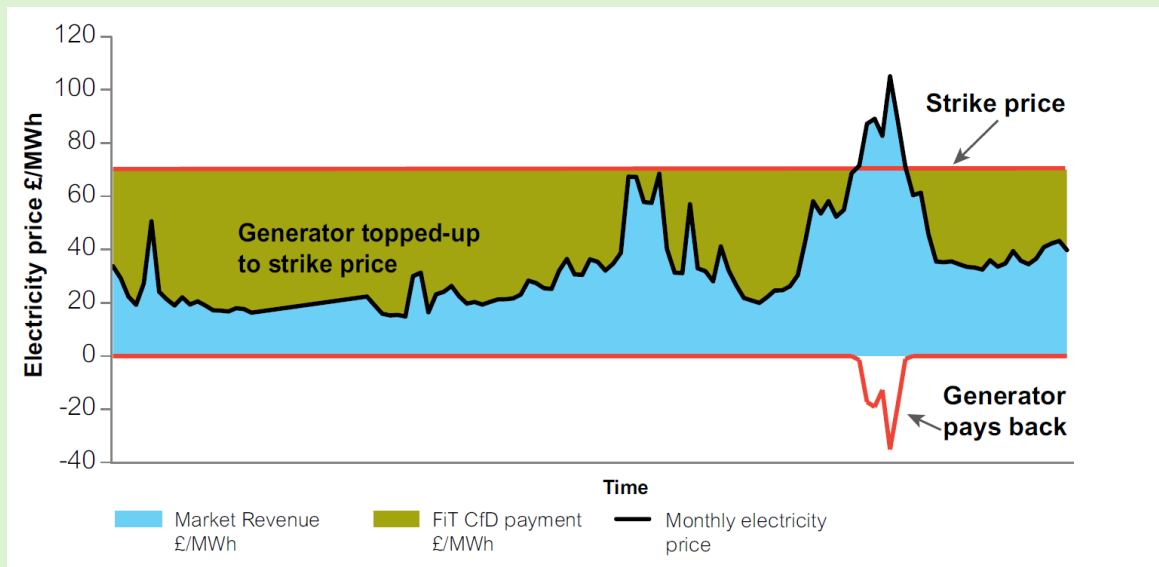
¹⁰³ Alternatively, the government may purchase the entire output and sell it at market prices to refund at least a part of the subsidy.

¹⁰⁴ <https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference>.

¹⁰⁵ https://www.diw.de/de/diw_01.c.670596.de/differenzvertraege_contracts_for_difference.html.

Box 2: Contracts for Difference (CfD)

Illustrative example for the mechanics of a CfD and resulting payments



Source: DECC 2011, p. 38

- ▶ Auctioning design
- ▶ Bid capacities/amounts could be limited to ensure that more than two e-fuel producers compete for the most efficient production technology;
- ▶ Auctions for CfD should be held frequently;
- ▶ Preferably the auctioned product volume should be synchronized with the projected increasing demand, e.g. due to a fuel mandate;
- ▶ Producers which received a CfD in earlier auctions can use subsequent auction rounds to expand their production;
- ▶ Due to 'learning by doing' and economies of scale the average strike price is likely to decline over time; competition between different e-fuel producer facilitates innovation in a similar way to the promotion of renewable electricity through feed-in tariffs.
- ▶ **Application:** UK has applied CfD since 2015 in auctioning offshore wind and nuclear power subsidies;¹⁰⁶ France, Denmark and Poland are following the UK's example.¹⁰⁷

¹⁰⁶ <https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference>.

¹⁰⁷ <https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference> (in German, behind a pay-wall).

Box 2: Contracts for Difference (CfD)

- ▶ Advantages
- ▶ Provides long-term demand and price certainty for investors (like, for example, feed-in tariffs, though without potential windfall profits);
- ▶ Provides access to long-term finance at lower cost also for SME or start-ups, which usually have higher finance costs than larger, incumbent companies; in this way, CfD provide a broader spectrum of providers and is likely to accelerate innovation in a way similar to feed-in tariffs for renewable energy;
- ▶ Payment on delivery ensures fewer investment ruins financed by public subsidies compared to pure investment subsidies; if an investor goes bust, the subsidy would have only been paid for the amount of product actually delivered;
- ▶ Payment on delivery provides incentives to run and constantly improve the installations.
- ▶ Disadvantages
- ▶ No incentives to adapt production to market signals which are transmitted via the market price;
- ▶ Requires the definition of a reference product and transparency and independency on its price formation.
- ▶ Legal aspects
- ▶ OPEX subsidies are in principle incompatible with EU state aid rules (Art 107); however, in a decision in the context of the UK's support for electricity generation from the nuclear power plant Hinkley Point C, the EU Commission made clear that OPEX subsidies in cases of CfD are equivalent to CAPEX subsidies and thus eligible,¹⁰⁸
- ▶ The Guidelines on State Aid for environmental protection and energy make clear that the subsidy may be granted for 100% of the eligible cost (instead of usual threshold of 40% or 70%), if the subsidy is allocated in a competitive and non-discriminatory bidding process.¹⁰⁹
- ▶ **In summary:** Very similar to auctioned feed-in tariffs. Advantages and disadvantages depend on the concrete implementation in terms of frequency, adjustment, retails technology-openness and organization of final delivery of the product to the market, etc.

¹⁰⁸ [Commission Decision ... Support to the Hinkley Point C Nuclear Power Station](#), particularly marginals 344-347 and 394-397.

¹⁰⁹ [Guidelines on State aid for environmental protection and energy 2014-2020](#), particularly marginals 80, 54, 43 and Annex 1.

5.1.3.4 Emissions Trading System

The main purpose of an ETS is to accomplish a certain emission level at least costs in a system perspective and to internalize at least partly the external cost of climate change caused by fossil fuels. It reduces the price difference between fossil and e-fuels. If the expected carbon prices were high enough, an ETS could basically trigger a shift from fossil to e-fuels. However, current carbon prices are required by an order of magnitude below the prices to make e-fuels competitive with fossil fuels (250 €/t compared to 25 €/t of CO₂). The European ETS Directive cannot be adjusted unilaterally by one EU Member State but only through a coordinated approach within the EU. However, in the context of the European Green Deal (EGD) an inclusion of shipping in the ETS and a strengthening of the cap and the Market Stability Reserve (MSR) is expected. These revisions would most likely result in higher carbon prices, which will, nevertheless, still not be sufficient to eliminate the price difference between fossil and e-fuels.¹¹⁰ However, even if the price difference cannot be fully eliminated, strengthening the ETS can further support the promotion of e-fuels because it reduces the price difference and diminishes the financial resources required to subsidize e-fuel production in that way. Like the approach applied under the ETS innovation fund, the ETS can also raise the revenues required to finance subsidies for increasing the market penetration of e-fuels through auctioning of all or at least a higher share of the allowances. The implementation of CORSIA, the offsetting and reduction scheme for international civil aviation, will also put an (albeit very small) price signal on carbon emissions (section 5.2.3.1).

5.1.3.5 Emission or fossil fuel tax

Emission or fossil fuel taxes pursuant to the European Energy Tax Directive (ETD) are like the ETS in many aspects: they internalize parts of the external costs of climate change induced by fossil fuels, reduce demand so that fewer fossil fuel need be replaced by e-fuels, reduce the price difference and can raise revenues required to subsidize e-fuels supply.

However, in contrast to the ETS, according to EU legislation a non-financial instrument which can be revised by qualified majority in the EU Council, changing the ETD requires unanimity, which is politically difficult to achieve and often involves a watering down of the tariffs.

Nevertheless, the Chicago Convention (ICAO 1944) allows energy taxes to be charged on routes when both countries agree to do so. A coalition of 'willing' EU Member States could be established to charge fuel taxes at least on routes among those countries. Actually, kerosene is included in the ETD, but the application of the tariffs is exempted. If the minimum tariff of 0.33 €/l were applied, it would be equivalent to a carbon price of approx. 130 €/t CO₂. Applying the German rate of 0.65 €/l would roughly double the actual costs of fossil kerosene and bring them much closer to the expected costs for generation of e-kerosene (Figure 37, p. 130).

The IMO Convention or subsequent regulation under the IMO does not explicitly exclude charging fuel taxes or levies. However, to date, no fuel taxes are applied at international level.¹¹¹ Correspondingly, tax rates for fuels used in international maritime transport are likewise not applied under the ETD.

¹¹⁰ CO₂ prices of 250 €/t would have severe consequences for industrial installations in Europe, especially if the price increases quickly. To ensure that e-fuels are competitive through a carbon price alone, it would be necessary to separate the aviation ETS from the stationary sector. In such a case, the cap could be set in a way to achieve such a CO₂ price.

¹¹¹ Along with other organisations, the International Chamber of Shipping (ICS) currently suggests to establish an International Maritime Research and Development Board (IMRB) for the promotion of e-fuels in maritime transport, which would be financed through a levy of 2 US\$/t of fuel IMO (2019).

5.1.3.6 Blending quota or fuel standard

For drop-in e-fuels, fuel suppliers would be required to blend their fossil fuel with a certain share of a compatible e-fuel. The share will continuously increase over time and by 2050 finally achieve 100%. The mandatory blending quota, also known as fuel mandate, would need to be accompanied with penalties which ensure that it is more cost-effective for the fuel suppliers to comply with the requirement.

Alternatively, it could be considered whether fuel purchasers rather than suppliers have to comply with the requirement; from an economic perspective this does not make much difference but from a transaction cost perspective it could make a difference because there are more vehicles and operators than fuel suppliers, with the result that their monitoring would induce higher implementation costs. Moreover, it could make a difference if either the purchase (suppliers) or the use (operators) of fuels is regulated, particularly in terms of evasion strategies.

If fuel suppliers are required to blend their fossil fuel, they will purchase the required amounts from e-fuel producers, which in turn can charge their higher cost because otherwise they will not be able to deliver the e-fuels. In this way, the increasing blending quota could trigger and sustain the upscaling of e-fuel production.

Fuel suppliers will pass through their higher cost for purchasing the e-fuels. As long as the blending quota is small, these additional costs will – even if the production costs of e-fuels are high – be below the variation of fossil fuel prices and not induce major evading strategies. However, once the additional costs become significant, the blending quota may induce evasion strategies to avoid these additional costs. Such evasion strategies could considerably undermine the effectiveness of the policy of the requirement. Tankering could, particularly in aviation, induce an increase of CO₂ emissions due to the extra weight of lifting some share of the fuel more than once (EUROCONTROL 2019; Melkert 2019).

The incentive for applying such strategies can be reduced/avoided if:

- ▶ the blending quota were applied globally, optionally with higher quotas for industrialized countries;
- ▶ the quota is only applied to fuel used on routes among a group of "willing countries," which introduce the policy jointly;
- ▶ the quota applies to the use rather than to the purchase of fuel;
- ▶ the production of e-fuels is subsidized in a way that makes them competitive with fossil fuels (section 5.1.3.3), with the result that fuel suppliers do not need to pass through any additional costs.

For fuels which require separate/different storage and engines/propulsion systems, such a physical blending quota is not applicable since it would require that all vehicles would need to be adjusted for being able to cope with a second fuel. Since the parallel systems would be either too small once the mandatory share exceeds their capacity or is under-utilized at beginning (while the fossil system of a dual-use ship would be under-utilized once the e-fuels share becomes larger), such an approach would induce large inefficiencies and thus increase the implementing cost of the transition. Therefore, such a physical e-fuel blending mandate is only applicable in the case of drop-in e-fuels.¹¹²

¹¹² For e-fuels such as hydrogen or ammonia, which can physically not be dropped-in, a fuel mandate could basically still be applied. However, the implementation will be more complex since it would require a certificate-based system (also called book & claim), which ensures that the mandate share of e-fuel or GHG reduction is achieved and that the additional costs

5.1.3.7 Tradeable e-fuel certificates

Under this approach, a Guarantee of Origin (GoO) would be issued for each physical unit of e-fuel stating that the e-fuel was actually produced/used in a vehicle and that it complies with certain criteria such as sustainability criteria (e.g. life-cycle CO₂ emissions reduced). Like the blending quota, fuel suppliers or purchasers would be obliged to surrender a certain amount of such GoOs. This amount could be determined as a share of the fuel used for propelling a vehicle or refer to the CO₂ emissions involved with burning the fossil fuel. As with the blending quota, the required share would increase over time to ultimately achieve 100% in 2050.

Producers of e-fuels would receive two streams of revenues to cover their production costs:

- ▶ One stream of revenue arises from selling e-fuel at a price that provides an incentive for certain vehicle operators to switch to the e-fuel, taking into account additional costs adjusting their vehicles or additional cost when investing in e-fuel ready vehicles.
- ▶ The other stream of revenue comes from selling the GoOs to those entities which need to surrender them. According to market theory, the price for GoOs would cover the difference between the price of the e-fuel and their production costs.

Issuing, trading and surrendering GoOs will certainly induce higher transaction costs than a simple blending quota for fuel suppliers. However, the advantage is that GoOs could also be applied to trigger the transition towards e-fuels if a blending quota cannot be applied because the e-fuel cannot be dropped-in but requires technological adjustments or new vehicles and infrastructure. Nevertheless, at some advanced point of the transition period, vehicles have to be drop-in-ready, or have to be phased out.

Not every vehicle would have to use the same share of e-fuels; only an average of the fleet would use the share of e-fuels equivalent to the mandatory quota. GoOs could also be used to incentivize competing e-fuels and/or engines/propulsion systems if they strictly refer to the life-cycle CO₂ emissions which they reduce.

If applied unilaterally, the GoO quota would basically provide the same incentives for evasion as a blending quota. Accordingly, these incentives can be addressed and/or mitigated through the same strategies (global application, only on routes between a coalition of the willing, subsidizing the production of e-fuels, etc., section 5.1.3.6).

5.1.4 Summary and conclusions

These considerations illustrate that none of the discussed instruments alone would achieve the goal of triggering and ensuring the transition towards post-fossil e-fuels, either because the price signals of ETS or taxes would not suffice to promote the uptake of e-fuels or because unilaterally implemented fuel mandates might induce evasion strategies which could undermine the effectiveness of the policy. Instead, an appropriate combination of different instruments will therefore be required to achieve this goal.

Some of these policies are either already applied to promote e-fuels (R&D, Real-World Laboratories, pilot projects, etc.). Others are implemented but are not focused at the promotion of e-fuels (ETS, ETD) and might need to be adjusted to promote the development and use of e-fuel. And finally, certain policies are not implemented at all and would only be introduced to spur the market penetration of e-fuel. Table 41

are shared among all covered entities. In section 5.3.1.2 (p. 196), we describe in more detail how such a technology-open e-fuel mandate could be designed and implemented.

provides an overview of the considered policy instruments and their assessment towards the criteria elaborated in section 5.1.2.

Table 41: Characteristics of policies and instruments

Policy or instrument		Research and development	Subsidies for e-fuel installations	Subsidies for e-fuel production	Emissions Trading System*	Emission or fossil fuel tax	Blending quota	Tradable e-fuel certificates
Type		Project funding	Project funding	Production subsidy	Economic incentive	Economic incentive	Regulatory standard	Regulatory standard
Policy focus	R&D	X	X					
	Production			X				
	Use				X	X	X	X
	Vehicles	x						
Barrier addressed	Infrastructure		X					
	Market failure (investment too risky)	X	X					
	Substantial OPEX			X				
	First mover disadvantage		X					
	Reducing cost differential			X	X	X	X	X
Regulatory scope		Unilateral	Unilateral	Unilateral	EU	EU	Unilateral	Unilateral
Time horizon	2022	4	4	4	1	1	1	1
	2030	2	2	3	2	2	2	2
	2040	1	1	2	3	3	3	3
	2050	0	0	1	4	4	4	4
Policy impact	Extent to which policy focus is addressed	3	3	3	2	2	3	3

Notes: *Including offset approaches such as CORSIA.

More intense green colours as well as larger digits show when a certain instrument is most effective. Scores are based on author's expert judgement.

Source: Authors' own compilation

None of the instruments directly focuses on adjusting vehicles or fuelling/bunkering infrastructure. The policies would thus need to be designed in such a way that they also provide incentives for investing in such adjustments. Nevertheless, to kick-start the transition, it would certainly be helpful to subsidize investment in pilot vehicles, fuelling/bunkering and storage facilities at ports.

Most of the instruments aim to narrow the cost difference between fossil and e-fuels while only some address other barriers. However, since the other barriers ultimately induce the price differences or can ultimately be expressed as a price difference, instruments which narrow the price difference can implicitly address other barriers as well.

Even though most of the policies can be implemented unilaterally, an EU-wide and ultimately global implementation would increase the effectiveness of the policies. Initiatives to achieve multilateral or global support for these policies should thus be initiated in parallel to the unilateral implementation of such policies.

While it is important for the effectiveness of all policies that they pursue a clear long-term perspective and aim to achieve a clear goal (100% e-fuels in 2050), it is also important that intermediate steps are agreed with a view to allowing monitoring as to whether the policy is on track or whether it needs adjustment to return to the target path.

While demand-pull instruments, which induce higher costs such as a blending quota or a quota for tradable certificates, would usually be sufficient to trigger and maintain the transition towards post-fossil e-fuels if applied globally, they will at least partially be evaded if implemented unilaterally or in a limited group of

countries. The extent to which this evasion will occur depends on how strong the incentive is and on technological opportunities for evasion and the cost of applying such strategies. Since tankering/bunkering strategies are already well-established in international transport sectors to make use of the already existing fuel price differences, it can be assumed that they will also be applied if unilateral demand-pull policies exceed a certain minimum threshold at which they may be negligible.

Strategies for overcoming this obstacle include enhancing the group of willing countries, applying the demand-pull only on routes between the group of willing countries and/or combining the demand-pull with appropriate technology-push instruments, for example with production subsidy which would reduce the price differential to a level that would eliminate the evasion incentive.

For aviation, a drop-in quota for e-kerosene could be combined with an e-fuel production subsidy, which covers the cost difference between fossil and e-kerosene to reduce incentives for evasion through tankering strategies. For shipping – where e-diesel is only one technological option among several – it would be difficult to implement a pure blending quota. However, the demand-pull could be established through a quota for tradeable certificates, which could deal with several competing e-fuels if the certificate is clearly linked to the life-cycle GHG emissions of the fuels. To avoid evasion, it also can be combined with technology push by means of subsidizing e-fuel production to levels which make e-fuels competitive with fossil fuels.

At EU level, two initiatives to incentivize the uptake of sustainable fuels including e-fuels are discussed. For aviation, the ReFuelEU Aviation initiative¹¹³ intends to accelerate the use of sustainable aviation fuels including e-kerosene in Europe. The specific design, including mandated entity, regional scope, etc. is still under discussion. However, since RED II already provides options for Member States to promote the use of sustainable aviation fuels through fuel suppliers, the initiative may mandate fuel suppliers as well.

For shipping, the FuelEU Maritime initiative¹¹⁴ aims to increase the share of sustainable alternative fuels with a basket of measures. Besides blending requirements as mentioned above, goal-based performance requirements on carbon-intensity are also considered by the EU. The latter is a tradable certificate-based low-carbon fuel standard, which would prescribe a carbon-intensity threshold of the energy used in marine operations and at berth. In contrast to the blending quota, this kind of a standard is technology-open and would not prescribe the type of fuel used for compliance. The risk of evasion might be less of an issue as the use of fuel rather than the purchase of fuel would be required to comply with the standard while being on voyage in the European Economic Area (EEA) or to an EEA port (similar to the existing SECA regulations in Europe).

5.1.5 Selection of roadmaps

We look at three potential roadmaps to promote the transition towards post-fossil e-fuels:

- ▶ e-kerosene roadmap for aviation;
- ▶ e-methanol roadmap for shipping;
- ▶ technology-open roadmap for shipping.

For aviation, synthetic kerosene from renewable sources (e-kerosene) has the potential to become the dominant fuel: it can be blended with fossil kerosene to the maximum extent as depicted in Table 18 and

¹¹³ <https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12303-Sustainable-aviation-fuels-ReFuelEU-Aviation>.

¹¹⁴ <https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-FuelEU-Maritime>.

introduced directly without the need for extensive changes in airports or aircraft. It has the same energy density as fossil kerosene and is therefore also suitable for long-distance aviation. While there are other potential technologies such as hydrogen and electric aviation, all alternatives are either still in their early development or do not have the potential to replace liquid fuels for long distances. Despite this, these alternatives can play an important role in the long term (post-2050) e.g. for shorter distances and with regard to decreasing non-CO₂ effects of aviation and should be further developed. To achieve full climate-neutrality, a mix of technological options beyond e-kerosene will be required; it currently seems clear that synthetic kerosene from renewable sources will be part of the answer to the climate challenge in aviation.

For shipping, the situation is different: there are several options for replacing fossil fuels which are being discussed and there is no clear preferred solution at the moment. For this reason, we developed two different roadmaps, one which promotes the introduction of e-methanol and the other which is technology-open, promoting e-fuels unspecifically. A technology-specific approach, in this case for e-methanol, may have the advantage of achieving the transition more quickly. Parallel developments of multiple options might be more costly and achieving defossilized shipping by 2050 could thus be even more challenging. Despite this, there are good reasons for pursuing a technology-open approach for the time being. All potential alternative fuels have specific (dis-) advantages. A technology-open approach may stimulate more innovation (Baumol 2002) and can potentially react more easily if a certain pathway proves too costly or encounters other major obstacles. The early selection of a specific technology runs the risk of not selecting the best option.

E-methanol as an alternative fuel for shipping was selected based on a multi-criteria analysis¹¹⁵ of seven alternative fuels (e-hydrogen, e-ammonia, e-methane, e-methanol, e-propane, e-DME and e-diesel). The assessment looked at environmental criteria (GHG mitigation potential, energy efficiency of production process, toxicity, flammability and explosion risk), technological readiness (production, ships, ports, drop-in potential, regulatory) and costs (fuel costs, energy density, capital costs shipside and synergies with other sectors).

- ▶ E-methane, which is a strong greenhouse gas itself, was ruled out for this analysis based on its GHG mitigation potential: unless slippage in the combustion process and leakage from tanks and methane distribution infrastructure is fully addressed, it will not lead to fully climate-neutral shipping and does not, therefore, meet the objectives of the roadmap (ICCT 2020d; thinkstep 2019; Trakakis 2018). All other alternative fuels showed similar scores related to the environmental criteria.
- ▶ E-methanol and e-diesel scored best in relation to readiness, mainly due to the limited changes required to infrastructure and ships; concerning the production, the technological readiness scored low because their production technology is still in its infancy, especially concerning direct air capture of CO₂ and also other technical issues (section 4.1). E-hydrogen and e-ammonia have the best scores for production readiness and in terms of supply side energy efficiency but would require a complete overhaul of port infrastructure and propulsion technology.
- ▶ E-diesel also scored best in relation to the cost criteria despite being the most expensive fuel. It has the same energy density as fossil fuels; therefore, no additional space needs to be taken up for the tanks and there is no need to redesign or retrofit ships. E-hydrogen and e-ammonia are the cheapest fuels per unit of energy but would require more ship volume for storage and higher capital costs for ships.

¹¹⁵ Roadmaps for achieving zero emissions, Table 50 to Table 52.

Propane and dimethyl ether (DME) scored the lowest due to relatively high fuel costs and very limited synergies with other sectors.

Overall, e-diesel scored best followed by e-methanol, e-hydrogen and e-ammonia (Roadmaps for achieving zero emissions, Table 50 to Table 52). E-propane and e-DME show no advantages compared to the other options in any dimension and e-methane is unlikely to meet the objective of fully climate-neutral maritime transport by 2050. In the Fischer-Tropsch production pathway, e-diesel could be used as drop-in fuel without major further technical requirements for ships and ports. At least initially, it could follow the development of the aviation roadmap and was therefore not assessed as a separate option. Of the remaining options, we selected e-methanol (e-MeOH) because it is an alternative fuel which has not yet been investigated in other studies at the same level of detail as e-ammonia and e-hydrogen and because it offers the advantage of blending it with fossil fuel, which may help in shifting the fuel mix slightly. E-hydrogen and e-ammonia could only be used on their own and cannot be introduced gradually on a global scale.

5.2 Roadmap aviation

The aim of the roadmap for aviation is to show a pathway that leads to a complete conversion of the global aviation industry from fossil kerosene as the main propellant to sustainable post-fossil fuels. It is based on four lines of action: 1) a domestic flagship project to quickly show the feasibility of introducing post-fossil fuels and to boost the technological development of the required processes in their early stages; 2) European action to up-scale production and deployment; 3) international cooperation to facilitate the fuel switch on a global level; and 4) technical and regulatory readiness to ensure the enabling conditions. These lines are structured along the level of implementation: from domestic action to European and international action. The fourth line – technical and regulatory readiness – lies across the other three lines and is a cross-cutting requirement. A diagram showing the elements of the roadmap and their sequence is shown at the end of this section.

5.2.1 Flagship project

The idea of a flagship project is to provide a showcase for the move to post-fossil fuels in aviation. Initially a single smaller airport such as the airport Leipzig/Halle would be supplied by a fuel blend containing increasing shares of e-kerosene.¹¹⁶ The aims of the flagship project are

- ▶ to provide a showcase for the sustainable production of e-fuels and the potential for CO₂ emission reduction in aviation;
- ▶ to gain practical experience in the real-life usage of kerosene blends containing higher shares of synthetic fuels;
- ▶ to foster demand for e-kerosene and therefore for e-kerosene production;
- ▶ to help German industry to get a leading role in an emerging market;
- ▶ to reduce the costs of e-fuels by financing the technology during the steep phase of the learning curve; and

¹¹⁶ Achieving high shares of e-fuels is easier in small(er) airports if the whole airport is supplied to avoid separate tanking infrastructure. Leipzig has a high share of long-distance flights, is supplied by train and has already participated in e-fuel pilot projects (see below).

- ▶ to act as a showcase for further action.

The main objective of the flagship project is to demonstrate that a global conversion of the aviation industry from fossil fuels to e-fuels is possible and reduces the climate impact of aviation. Any contribution to reducing CO₂ emissions depends on the production conditions of the e-fuels. It is therefore essential that the pilot also pioneers the establishment and application of sustainability criteria for the production process.

Another purpose of the flagship project is to demonstrate that high – and eventually 100% – blending quotas are feasible from a technological and safety perspective. For good reasons, the aviation sector is risk-averse related to safety aspects and a major structural change – such as exchanging the main fuel source – needs to be demonstrated and evaluated prior to a wide-scale implementation. In addition, this flagship project speeds up the development of an emerging technology still in the steep phase of the learning curve. Domestic production and supply of the required e-fuels will contribute to Germany's position as a technological leader in this field and will foster international cooperation on this issue. In a way, it aims to repeat the international success of the German energy transition (*Energiewende*) which has been a reference case for other countries for decades. Starting with small projects and initially high costs, the support scheme for renewable energies has proven that a transition from fossil/nuclear dominated electricity production is possible in a relatively short timeframe. One major success of the *Energiewende* is that it has helped to reduce the unit costs for renewables on a global scale (Oeko-Institut 2015).

To show the technical feasibility of switching to e-fuels, a significant e-kerosene share needs to be achieved through blending with a limited amount of fossil fuel. This means that it is necessary to ensure the physical supply of the mixture to aircraft; blending the same amount of e-fuels with the total kerosene demand for all aviation would not meet the goal of showing the technical feasibility of higher blending shares. For the flagship project, we propose to start with a smaller airport which would only receive the blended mix. If a very large airport were selected, it would be necessary to provide parallel infrastructure for conventional fossil and blended kerosene to ensure that high blending shares can be demonstrated despite limited initial e-kerosene production. This would require more substantial changes to management practices and potentially need new infrastructure. The same applies to airports which are supplied by pipeline, for which it would be more challenging or impossible to ensure high blending quotas if the pipeline is connected to a wider network. The airport Leipzig/Halle has a kerosene demand of about 500 000 t/year, which constitutes approx. 5% of the total kerosene supplied to aviation in Germany. Along with the maximum currently permissible blending quota of 50%, this corresponds well with the German hydrogen strategy: the strategy includes the aspirational goal of achieving a 2% share of e-fuels in aviation by 2030 (Bundesregierung 2020). The Leipzig airport is also the main hub of Deutsche Post DHL Group; DHL has committed itself to becoming carbon-neutral by 2050 and is interested in introducing sustainable e-fuels in aviation (DHL 2019). A cooperation with DHL would increase the visibility of the flagship project. An alternative option to achieving high blending quotas much more quickly would be to start with a smaller airport focused on passenger traffic only, like Weeze in western Germany. It consumes approx. 30 000 t kerosene per year, is also not connected to a pipeline but is relatively close to refineries where blending could take place. The drawback would be much lower visibility due to the size of the airport and the lack of a big international partner.

At the same time, the price differential between conventional and e-kerosene cannot be charged directly at the pump: in the integrated European aviation market, airlines could schedule their aircraft in such a way that refuelling would take place in other airports either in Germany or in neighbouring countries to avoid paying substantially higher kerosene prices at one airport. To avoid tankering behaviour, it is therefore necessary that the blended kerosene for aviation does not cost more than the fossil fuel would (including the

cost of CO₂), i.e. the price difference needs to be subsidised.¹¹⁷ To ensure that the EU's polluter pays principle (EU 2007) is followed, airlines and ultimately passengers/air cargo should pay for the additional costs. This could be achieved either by using existing or new revenues from the aviation sector such as the ticket tax and/or the auctioning of allowances in the EU ETS:

- ▶ In 2019, the revenues from the German ticket tax were € 1.2 billion (Destatis 2020). From 2020 onwards, higher rates apply; once demand for aviation has recovered from the impacts of the Covid-19 pandemic revenues are expected to increase in the future. The ticket tax only applies to passenger transport in Germany; an extension to freight transport could generate additional revenue.¹¹⁸
- ▶ Under the EU ETS, 15% of the emission allowances are currently auctioned. Germany's revenues in 2019 from these auctions amounted to approx. € 19 million (DEHSt 2020). Auctioning shares are likely to increase under the European Green Deal; if Europe goes to full auctioning, revenues will surpass € 100 million per year.

The revenues from the German ticket tax would be sufficient to finance the flagship project at Leipzig airport: Around 800 million €/year would be required to subsidize the cost difference between fossil and synthetic kerosene for a 50% blending share at current production prices in Germany of approx. 3 €/l (AVW; AEW; FE 2018). In practice, the flagship project would be less costly: Over time, production costs are expected to decrease (Figure 37, p. 130) and could already fall below 2 €/l in 2030 in Germany (Scheelhaase et al. 2019). In this case, a subsidy of € 0.5 billion would be sufficient to finance the flagship. The average e-kerosene costs in 2030 will be based on a mix of older and newer production facilities; production capacity needs to be built up over the coming 10 years to ensure the required supply for the flagship in 2030. Earlier production facilities will require a higher subsidy whereas ones entering at the end of the decade are expected to be able to produce e-kerosene at lower prices. The average price in 2030 will be a mixture of the production costs of all installations.¹¹⁹

Under the Fischer-Tropsch process, not only e-kerosene is produced but also paraffins, other liquid fuels and different gases. For all these products, there is high demand both for industrial processes as well as other transport modes. One option would be to supply the liquid products and especially e-diesel to the shipping sector to contribute to the defossilization of this transport mode as well (section 5.3). Off-road transport, heavy machinery and heavy trucks might be other potential users for e-diesel. Other instruments would be needed to bring these by-products on to the market; they would face similar cost barriers compared to the currently used fossil alternatives.

The core measure to incentivize e-kerosene production for the flagship project are guaranteed subsidies through carbon contracts for difference (Box 2). Some of the crucial elements which need to be specified in the tender are the sustainability requirements, e.g. concerning the electricity used and the source of carbon for the process, the number of years for which the price is guaranteed and the latest year by which

¹¹⁷ At the time of writing, there was no exemption for e-fuels under the EU ETS; the guidelines for estimating CO₂ emissions in the scheme were written before e-fuels played a role in aviation. It is likely that this will change in the future and that sustainable and carbon-neutral e-fuels will be treated like biofuels, i.e. the emission factor will be set to zero. In this case, subsidies will only need to cover the difference between the e-fuels and the cost of fossil fuels including the CO₂ cost under the EU ETS.

¹¹⁸ In freight transport, unilateral ticket taxes have a higher risk of evasion (i.e. using airports in neighbouring countries). Despite this, some countries like France have already implemented such a tax.

¹¹⁹ The actual subsidy could even be lower: with an emission factor of zero under the EU ETS e-fuels save airlines carbon costs. These savings should be reflected in the fuel price, i.e. the CCfD should only cover the difference between the fossil fuel price including carbon costs and the guaranteed price for the e-fuel.

delivery of the e-fuel must start. Some of these requirements will need to evolve over time to reflect the technological development, e.g. initial tenders will most likely have rather low production volumes whereas later tenders could include the obligation to use DAC as a CO₂ source. The tenders will also need to specify whether the fuels can be produced in Germany only, in the EU/EEA or also in third countries. They should be designed in such a way to ensure that more than one operator will bid successfully to avoid monopolies. At least a share of the auctions should require production in Germany and the EU: compliance with the sustainability standards can be checked more easily¹²⁰ and it will help to foster a new industry within the EU. Over time, the closing price will decrease due to the cost degression from the experiences gained in earlier installations and subsequent technological progressions. Another important reason for cost degression is the expected continued decrease in renewable electricity production costs, which constitutes the main input in monetary terms. This is another reason to start with relatively low production volumes in early auctions during the steepest phase of the learning curve: these installations will receive the highest subsidies which will lead to higher overall costs. A competitive bidding process repeated regularly will ensure that the subsidies will be kept as low as possible.¹²¹

It is necessary to guarantee that the produced fuels – mainly e-kerosene but potentially also e-diesel for support activities at the airports – will actually be delivered to the flagship airport(s) and not used for other purposes. This can be ensured by only paying the subsidy on delivery to the airport or even the aircraft and not for the production itself. For fuel suppliers, this means that they need to store and supply the blended kerosene separately from the kerosene supplied to other airports. This might require adaptations to the existing infrastructure and processes but these are minor.¹²²

Currently synthetic kerosene produced through the Fischer-Tropsch process can be blended up to 50%; e-kerosene produced through the methanol route is not yet certified. Germany will need to ensure that the necessary processes for certification are initiated on time (section 5.2.4).

After 2030 and once approval for blending shares above 50% has been achieved, the flagship project should continue by working towards 100% e-kerosene. A parallel process of introducing a mandatory blending quota at EU level would ensure that the necessary production quantities are available. The purpose would once again be to show that it is feasible to achieve a full conversion to 100%.

5.2.2 European cooperation

To achieve the goal of this roadmap, defossilized aviation by 2050, it is essential to act fast and broad at the same time. European cooperation and action are an essential step towards this direction: the EU and the 44 countries within the European Civil Aviation Conference (ECAC) have traditionally been those with the highest ambition in regulating greenhouse gas emissions from aviation. About one quarter of global scheduled aviation starts in Europe (ICAO 2019b); the EU accounts for 30% of global fuel sales to aviation and Europe for 37% (IEA 2020d).

¹²⁰ The experience from the project mechanisms under the Kyoto Protocol has shown that even independent verification of projects by accredited entities does not always ensure that sustainability requirements are met (Oeko-Institut 2016; SEI 2015). Projects in Germany and the EU can more easily be assessed than projects overseas both by authorities as well as environmental groups. Especially the first projects are likely to have a high public profile and sustainability criteria such as the electricity source will be scrutinized in detail.

¹²¹ The specific rules will also need to ensure compliance with the EU Guidelines for State Aid for environmental protection and Energy (EU 2014/C 200/01).

¹²² In 2019, a demonstration project with Leipzig airport used different multi-blends which contained at least two alternative fuels in addition to fossil Jet A 1 with high blending shares of 19-38% DBFZ (2019). It found that there is a lack of blending tanks which can be used to mix fossil with e-fuels. Ideally, blending should take place directly at the refineries both for safety reasons but also for ease of handling. It also found that all the investigated multi-blends complied with ASTM standards and could be used in aviation and airports without restrictions or further requirements.

European cooperation on sustainable aviation fuels could be based on the Renewable Energy Directive (RED): under the RED II, Member States can already account for sustainable aviation fuels if they desire to do so. To ensure a blending quota for aviation, it would be necessary to change the RED II to include an obligatory drop-in mandate for civil aviation for e-fuels only; several countries have mandates based on bio-fuels. The directive also allows to account for upstream emission reductions. Using green hydrogen in refineries as proposed in the German Hydrogen Strategy instead of hydrogen from fossil methane could reduce the GHG intensity and be an important steppingstone towards full defossilization by means of e-fuels. The EU's hydrogen strategy proposes installation of at least 6 GW of renewable hydrogen electrolyzers close to refineries by 2024 and 40 GW by 2030 (EC 2020b). The technology to do so is well-developed and could be deployed quickly, jump-starting the scale-up of a technology which will be crucial for defossilizing industry and other sectors as well. In addition to setting blending mandates or CO₂ emission intensities for fuels, sustainability criteria for e-fuels would need to be included in the RED II or its implementing provisions and need to cover inter alia requirements for electricity generation, hydrogen source, water usage, area demand and the impact on local communities (chapter 4). This should be carried out quickly to ensure that all projects meet the minimum standards from the very beginning. The RED II will be updated under the Green Deal to achieve an EU-wide greenhouse gas emission reduction of 55%. In the EU's Climate Target Plan, renewable energies will have a share of at least 38% of the gross final energy consumption by 2030 based on modelling results compared to the current target of 32% (EC 2020c).

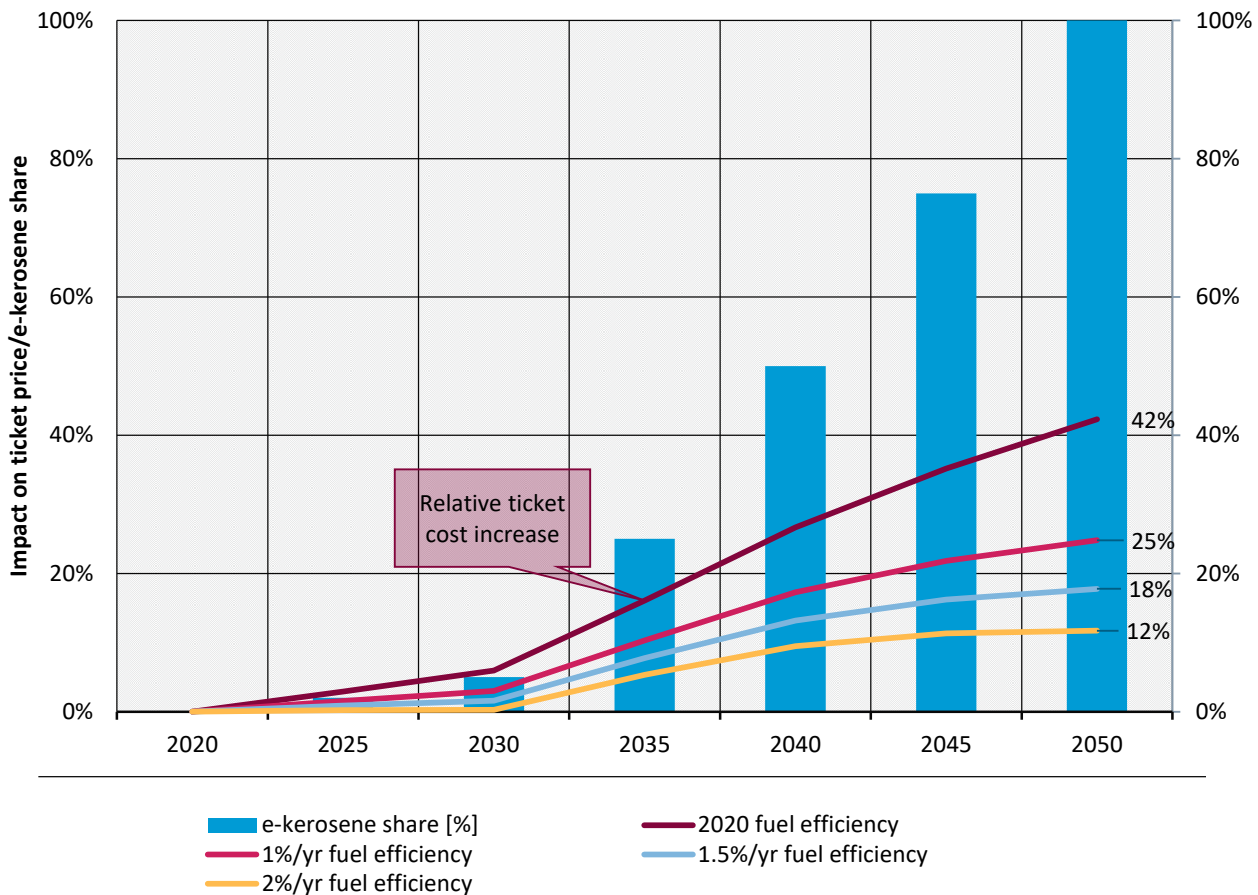
In contrast to the flagship project, the EU-wide blending quota would not need CfD auctions (Box 2) as the main policy tool. An obligatory quota with a strong enforcement scheme would be sufficient and not require any subsidies. Costs would be directly charged to airlines when refuelling. This approach was also used for biofuel quotas and removes the need for government intervention. The risk of tankering is negligible especially if the UK, Switzerland and Norway participate or introduce similar requirements. Most flights from third countries to the EU are too long to be able to avoid at least partial refuelling. Even on routes on which this would be possible (e.g. to Northern Africa), it would not lead to a distortion of competition as all airlines could apply the same behaviour. Yet, even without distortion of competition such a behaviour would increase fuel consumption and should be prevented. The evasion risk might even be higher on routes to third countries with a stop-over. If this stop-over takes place outside the EU, only the first leg of this route would fall under the quota. An alternative option would, therefore, be to charge all additional costs to intra-EU aviation at least initially. While physical separation of different blends at airports is not feasible, the additional costs could be charged only on certain routes. If necessary, it would be possible to introduce a carbon border adjustment mechanism to avoid carbon leakage. One option would be to introduce a ticket tax for flights to countries without similar regulation in the aviation sector. Another option would be to copy the flagship approach and introduce an EU-wide ticket tax to finance subsidies for e-fuel uptake.

Charging airlines directly when refuelling ensures that the climate impact of flying is included in the ticket price and provides an even stronger incentive for energy efficiency compared to the subsidised approach in the flagship project. In line with the increasing share of e-fuels for all aviation, the subsidies in the flagship project need to be reduced; airlines should not pay less than at other airports.

Typically, fuel costs make up about 20% to 30% of the ticket costs depending on the airline type (full-service carrier or low-cost carrier). Figure 43 shows the typical impact of gradually introducing a blending quota from 0% to 100% between 2020 and 2050 on ticket prices. Assuming a fuel cost share of 25%, which is an average across airline types and over distances, the impact of 100% e-kerosene would be a ticket price

increase by 42% in 2050.¹²³ This calculation is based on the current fuel consumption, i.e. the current energy efficiency of the aviation sector. Assuming that the ICAO goal of improving fuel efficiency by 2%/year is achieved (ICAO 2019a),¹²⁴ the energy demand per passenger would decrease by 45% between 2020 and 2050.¹²⁵ The resulting ticket price increase would only be 12%. An annual efficiency improvement of 1%, which is closer to historic rates, would lead to a ticket price increase of 25% up to 2050 with 100% e-kerosene. Such an increase in ticket costs, while noticeable, would be well inside of ticket price changes in the past decades.¹²⁶

Figure 43: Impact of a gradually increasing blending quota on ticket prices under different assumptions for energy efficiency improvements up to 2050



Notes: For this illustration, fuels costs constitute 25% of the ticket price; all other ticket price components have been held constant. For e-fuel costs we assume a price of 2.10 €/l in 2020 declining to 1.40 €/l in 2050.

Source: Authors' own compilation

¹²³ The calculations assume constant costs for all factors not related to the fuel. Fossil fuel prices and costs for e-kerosene are taken from Figure 37.

¹²⁴ According ICCT (2020a), fuel efficiency per tonne-kilometre increased in the decades since 1990 on average by 0.8%, 0.6% and 1.5% per year. That resulted in a decrease of CO₂ emissions by 1.0%, 0.5% and 1.0% per year.

¹²⁵ Increasing energy efficiency is a pre-condition for achieving climate-neutral aviation due to the high demand for e-fuels (section 5.1.1).

¹²⁶ For example, average ticket prices for domestic aviation in the US fell by 50% between 1980 and 2010 Thompson (28 Feb 2013).

5.2.3 International cooperation

5.2.3.1 ICAO

On an international level, the process towards achieving carbon neutral aviation by 2050 needs to be strengthened. The aim of the process is to establish a common vision with targets, a strategy to achieve this vision and ultimately to set concrete milestones and criteria. Ideally, this process would take place within ICAO to ensure that all countries participate. With a view to 2050, the Second ICAO Conference on Aviation and Alternative Fuels endorsed the ‘2050 ICAO Vision for Sustainable Aviation Fuels’. This vision is seen “as a living inspirational path” and calls for a “significant proportion” of sustainable aviation fuels by 2050 (ICAO 2017a). The vision recognises the need for sustainability requirements for SAF, the role of e-kerosene and promotes cooperation – issues strongly pushed by the EU and Germany in the preparation of the vision. In a parallel process, the ICAO Council is exploring the feasibility of setting a long-term global aspirational goal. Both the 2050 vision and a long-term goal could be natural starting points for further promotion of the complete substitution of fossil fuels with e-fuels within ICAO.

At the same time, the deliberations on climate protection in ICAO have been very slow in the past and lacked the necessary urgency in light of the climate crisis.¹²⁷ In 2010, ICAO adopted a global aspirational goal of carbon-neutral growth by 2020, which is implemented by means of a basket of measures including the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA puts a price on CO₂ emissions, but the price is expected to be so low that it will have little impact on ticket prices, fuel efficiency or the uptake of alternative fuels. The measures to achieve the 2020 aspirational goal have the potential to contribute towards the defossilization of the aviation sector, but it is unlikely that they will lead to a relevant uptake of e-kerosene by themselves if not strengthened substantially. In respect to the time left before 2050, this is unlikely to be sufficient to meet the climate goals of the Paris Agreement.

In the near term (by 2030), the main role of ICAO will likely be to enable the transition towards sustainable e-kerosene. This means continuing the process towards setting the long-term aspirational goal. Equally importantly, ICAO should continue to promote e-fuels through its bodies, forums, outreach actions and other activities. It is important that the current focus of SAF will shift from biofuels to electricity-based fuels to be able to meet the expected energy demand in the coming decades; the potential for sustainable biomass is not sufficient, when other uses are also taken into account. Introducing a mandatory quota for e-fuels under CORSIA could have the highest impacts and help foster production on a global scale. This would require substantial changes to CORSIA and would likely be difficult to agree. ICAO should also help facilitate the process to adopt any necessary changes to regulations and technical documents which might be required to achieve 100% blending quantities. In the medium term, the role of ICAO with regard to introducing e-fuels on a global scale should be more proactive: individual countries or groups of countries (see below) will most likely become the fast and early movers required to advance the practical aspects of e-kerosene production. While these first movers will be crucial to speed up the entire process, the ultimate goal of the roadmap – fossil-free fuels by 2050 on a global scale – can only be achieved if all countries participate eventually.

ICAO should also focus its work on non-CO₂ effects from aviation, mainly cloud formation. Due to these effects the total impact of aviation on global warming is about three times higher than the effect of CO₂ alone (Lee et al. 2020). E-fuels have the potential of decreasing the non-CO₂ impacts, partially because they contain almost no sulphur and therefore produce less soot when used. Despite this, aviation-induced cloud

¹²⁷ Both ICAO and UNFCCC are UN organisations consisting of the same members – national governments. In theory, this should ensure a consistent approach on joint issues between these two bodies. In practice, the different objectives of these organisations and their composition – mainly transport ministries for ICAO and environment ministries for UNFCCC – have resulted in a clear ambition gap with regards to climate targets.

formation is still possible due to the additional water introduced in the atmosphere by burning carbon-based fuel. As a first step, a detailed reporting mechanism for non-CO₂ effects would greatly increase knowledge about this issue and constitute the foundation for more specific policies and measures.

5.2.3.2 Sustainable e-kerosene alliance

International cooperation can help to meet the e-fuel demand for the German flagship project and a European blending quota and pave the way towards a global transition. An ideal location for producing e-kerosene for export to other countries would need to have excellent conditions for additional renewable electricity, a sustainable water supply, a supply for renewable CO₂, stable political conditions and already infrastructure to export the fuels (chapter 4). The price of e-fuels depends on the price for renewable electricity to a large extent. While at least some pilot installations should be built in Germany to gather experience and show technological leadership, other countries are better suited for large-scale industrial plants due to more favourable conditions for large-scale renewable electricity generation. Such power plants will require massive investment sums and can only be profitable if there is some kind of guarantee that they will be able to sell the produced e-kerosene above production costs. For a host country, there are numerous benefits: a large industrial installation will generate qualified jobs, it can contribute to the diversification of the national economy and interact positively with the electricity production and water supply for the local population. If several countries that are interested in purchasing e-fuels act together, they can profit from economies of scale, speed up the technological development and reduce the individual risk.

In Europe, Norway (hydro power), Scotland (offshore wind) and Spain (solar and wind) could be partners for early cooperation. Countries such as Morocco or Qatar in the MENA region are also promising candidates in the medium term and are also geographically close. Morocco has domestic demand for green hydrogen for its ammonia production facility and expressed interest in cooperating on e-fuels (Solarify.eu 2019). At the same time, countries in the MENA region will need to prioritize decarbonization of their national electricity supply before they become large-scale exporters of e-fuels. In this case, a first and quick step could be to have a plant producing green hydrogen, although the product should initially not be dedicated to aviation. Working with an oil exporting country has the potential to support the necessary transition towards a defossilized economy and could make use of the existing infrastructure for transporting and exporting fuels. At the same time, some additional safeguards might be needed to avoid unintended effects like prolonging the lifetime of the fossil fuel industry. It seems likely that countries such as Austria, Denmark, Finland, France, Germany, Luxembourg, Spain, Sweden and Norway would be interested in purchasing these fuels (The Luxembourg Government 2021). The Sustainable e-Kerosene Alliance (SeKA) will bring interested countries together.¹²⁸ Its tasks are to agree minimum sustainability criteria and foster the development of industrial installations in participating countries.

The financial support policies could be similar to the ones discussed for the German flagship project. In addition, it might be necessary for the governments to guarantee credit lines or investments. An alternative approach would be to use tradeable e-fuel certificates. The advantage of using certificates is that the physical quantities would not need to be physically transported to each involved end user. Instead, a certificate of origin is issued for each quantity of e-kerosene that is produced. This certificate can then be sold and the buyer has the right to account this quantity in its carbon balance. Overall, using certificates instead of bringing the fuels to the buyer is likely to reduce emissions from transport. Such an approach requires a strong certification and tracking system which ensures that no more certificates are issued than e-fuels produced and that no certificate is counted twice.

¹²⁸ For more details on how the SeKA would fit into an international strategy for the promotion of synthetic e-fuel in all hard-to-abate sectors, see UBA (2021).

The SeKA should be initiated as quickly as possible. In a first step, it could start as a bilateral project, but it would be better to agree the sustainability criteria for e-fuels from the start between a group of interested countries unless this is already specified in a revised RED II or delegated act. The alliance could also go beyond Europe and include other partners, e.g. from OECD countries.

5.2.4 Technological and regulatory readiness

Before new synthetic fuels can be used for commercial aviation, they need to be certified by ASTM International. Currently some synthetic fuels are already certified with blending limits of 10% or 50% depending on the process used (Kharina 2018), while other synthetic e-fuels are not yet ASTM-certified. kerosene derived via the Fischer-Tropsch process is certified up to 50%; e-kerosene produced via the methanol route is not yet certified at all. The requirements for new fuels depend on the similarity of the technical production process compared to already certified processes. For completely new processes, 900 000 l of the new fuel need to be supplied for testing. Processes which are very similar to already approved processes need less than 500 l for testing and approval; for a third group of processes – which are somewhat similar to approved ones but still significantly different – around 38 000 l are required. The methanol route is similar to the already certified process that converts alcohols to synthetic kerosene and is therefore expected to not require a full certification process. No alternative fuel has been certified beyond 50% blending quota until now.

To open up the methanol route for aviation, the certification process should be initiated quickly. Assuming that the intermediate process could be used and with production costs of 2.50 €/l producing the required quantities would cost approx. € 100 000. These costs could either be paid by a company intending to produce methanol-based kerosene or by a governmental institution. The capital costs associated with a methanol production facility are the higher barrier for investors. For the aviation sector, pursuing the methanol route is primarily a back-up option: if the technical problems of scaling the Fischer-Tropsch process and especially the reverse water gas shift reaction (section 4.1.1) should prove unsurmountable, there would be an alternative that is ready-for-use. In addition, it is not yet clear whether one route should prove to be more economical than the other. Even if aviation is not to be a consumer of e-methanol in the future, building up e-methanol production capacities is necessary to achieve economy-wide climate-neutrality: it could be used in the shipping sector (section 5.3.1) and is an important feedstock for several chemical processes; Germany alone produced 1.4 million t in 2019 (Destatis 2019). It is therefore essential that this route is developed further and should be supported by governments in the form of R&D support.

Another required ASTM certification relates to co-processing. There are two ways to produce a blended fuel:

- ▶ production of e-kerosene and subsequent blending with fossil kerosene; and
- ▶ production of synthetic crude oil which is then used as feedstock together with fossil crude oil in refineries.

Beyond the flagship project and similar demonstration projects, e-kerosene will not be the direct output of the e-fuel production facilities. Instead, these facilities will produce a synthetic crude oil (syncrude) using renewable electricity and a CO₂ supply. This syncrude will then be processed further with fossil crude oil in refineries. The relationship between syncrude and fossil crude feedstock determines the blending share of the final product. The advantage of this approach is that the e-fuel production requires less steps and is a generic output, which can then be further processed in the existing infrastructure. So far, ASTM has only certified a co-processing quantity of 5% syncrude for kerosene production. To go to higher blending shares, it is therefore necessary to initiate the approval process for higher co-processing quantities. This certification should be initiated quickly, well before EU-wide blending mandates reach five percent. Due to the

geographic distribution of refineries and future syncrude production facilities, it might be more efficient to have higher blending shares in some refineries and lower shares in other.

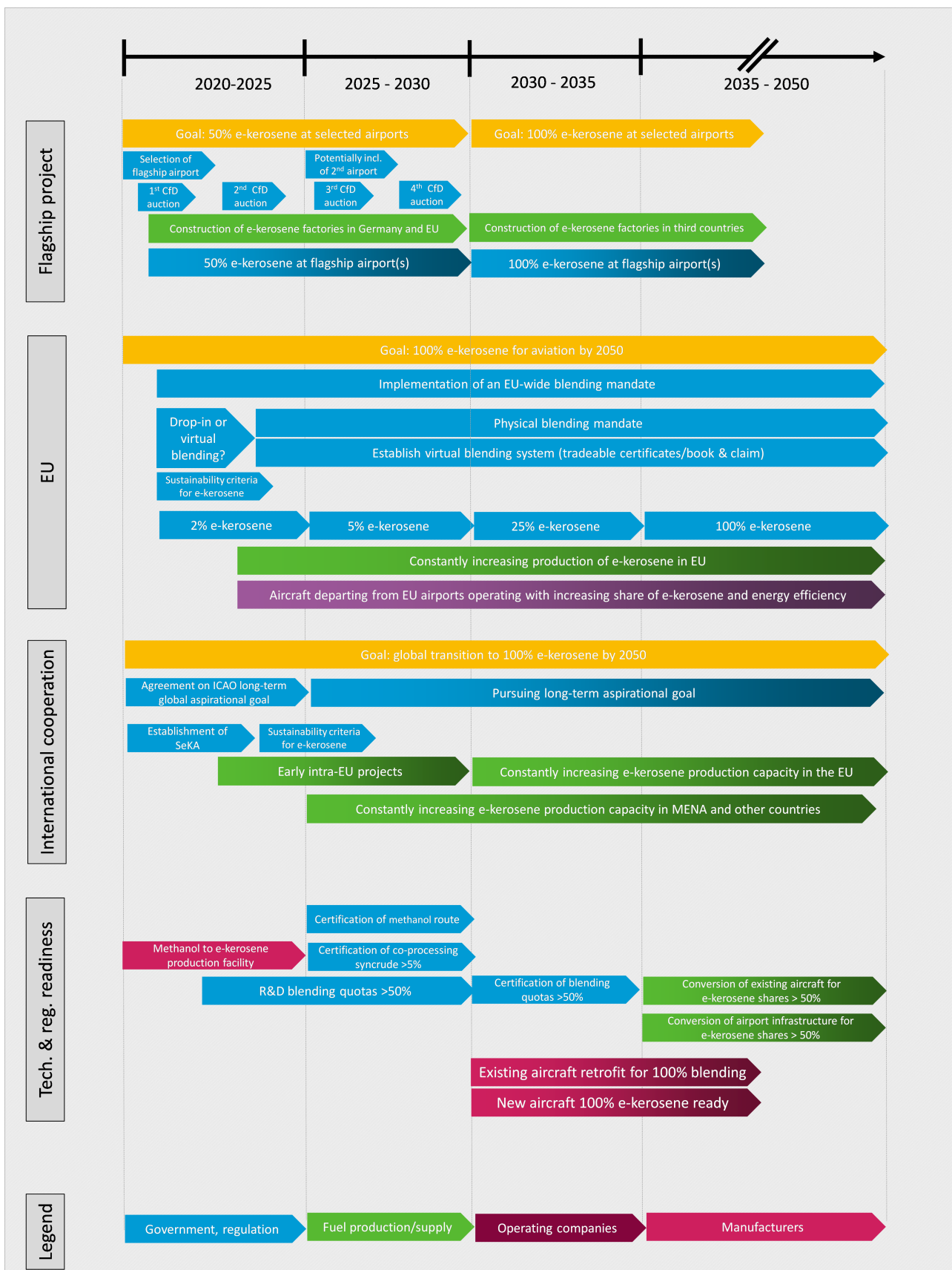
In the medium term, it is necessary to achieve certification for one or more e-fuels to be used as the sole energy carrier, i.e. certification of blending quotas of up to 100%. To date, no synthetic fuel has received this certification and it is unknown how long the process will take. It will take at least two decades before global e-kerosene production capacities are large enough for the production to surpass half of the energy demand from European aviation, i.e. when it would be necessary to go beyond 50% blend-in quotas; thus, there is no urgency to achieve the certification soon. Despite this, the process should be started soon as moving beyond 50% might require changes to the airplanes as well, e.g. other seals with the right properties for the slightly different fuel composition. The certification and necessary changes to aircraft might also be different for the Fischer-Tropsch and the e-methanol route. One important step will be small-scale demonstration flights and projects. To achieve defossilization by 2050, all planes need to be able to use 100% synthetic fuels at some point after 2040. This could require retrofitting/conversion of existing engines aircraft and airport infrastructure, e.g. along with installing new engines and additional requirements for new aircraft. Ideally, it would be possible to gain approval for 0-100% blending shares – in which case, there would not be any issues related to different blending shares at different airports, which is quite likely especially for intercontinental flights with potentially very different mandates between origin and destination. This would also be relevant if some airports in Europe already go beyond a 50% share, whereas others are still below that threshold. If such a broad approval is not possible, it might be necessary to have an intermediary approval for mid-range of blending shares, e.g. 25-75%. This would enable the aviation sector to gradually replace/upgrade their fleet in line with the regional and global development.

Some changes to the ground infrastructure and processes will also be required; sufficient time should be allowed for these changes. Blending should already take place in the refinery (DBFZ 2019) and blending tanks might be required. As long as blending quotas remain below 50%, no changes are required at the airports or to the aircraft; this leaves more than enough time to prepare the infrastructure for higher blending shares if necessary once ASTM approval has been achieved and blending shares are increasing significantly. By 2040, all airports should be able to go beyond 50% blending quotas in line with the requirements for aviation; if necessary, this should be ensured through appropriate regulation.

5.2.5 Overview

Figure 44 provides an overview of the suggested initiatives and activities discussed above and enhances the picture by some activities not explicitly mentioned above. It distinguishes between the different types of stakeholders involved: governments, which establish the legal regulation for ensuring the implementation of the necessary activities by fuel producers and suppliers and by aircraft operators and manufacturers. Moreover, it suggests indicative targets, which eventually need to be discussed and agreed politically and an indicative schedule of when the individual steps need to be initiated and when they should be completed to achieving the goals envisaged. The start of individual arrows indicates when an initiative or activity should start with a view to fulfilment by the year when the arrow ends. The fading-in of darker colours indicates that efforts or the stringency of the intervention need to be intensified of time.

Figure 44: Aviation roadmap



Source: Authors' own compilation

The overview illustrates that on all dimensions of the roadmap (Flagship project, EU cooperation, international cooperation and readiness), the first steps have to be taken immediately. National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible. The years up to 2030 are decisive for achieving the defossilization of aviation by 2050. If appropriate policies are not ‘set on track’ by then, at least at national and European level, it will be difficult to achieve this goal.

5.3 Roadmaps shipping

Following the recognition that alternative fuels and especially e-fuels are crucial for reducing GHG emissions in shipping, there has been a proliferation of studies on the defossilization of shipping. A literature review conveys the same picture as the discussions among industry stakeholders: to date, there is no clearly preferred option among e-fuels. It is currently unclear which e-fuel(s) will be dominant in future shipping. Table 42 provides an overview of the most relevant recent studies which examine e-fuels from a shipping perspective.

Table 42: Overview of recent studies on e-fuels for maritime shipping

Study	E-fuel addressed	Method	Aspects
CE Delft; UMAS; LR; Oeko-Institut (2019)	Hydrogen, ammonia, methanol	Literature	Vessel and fuel systems, fuel availability
DNV GL (2020)	Hydrogen, ammonia, methanol, MGO, LNG, LPG	Scenarios, literature	Vessel and fuel systems
DNV GL (2016b)	Methanol	Literature	Vessel and fuel systems
EDF (2019)	Ammonia	Scenarios, literature, case studies	Vessel and fuel system, costs projections, fuel availability
Hansson et al. (2020)	Ammonia	Energy systems modelling	Multi-criteria decision analysis involving relevant stakeholders
ICCT (2018)	Hydrogen, ammonia	Literature	Fuel systems, cost projections
ICCT (2020c)	Hydrogen	Case study, modelling	Cargo space and port calls
ICCT (2020b)	Hydrogen	Case study, modelling	Refuelling infrastructure
IRENA (2019)	Hydrogen, ammonia, methanol	Literature	Cost projections
KR (2020)	Ammonia	Scenarios, literature	Vessel and fuel systems
LR; UMAS (2019)	Hydrogen, ammonia, methanol, MGO	Scenarios, literature	Cost projections
LR; UMAS (2020)	Hydrogen, ammonia, methanol, LNG	Case study	Cost comparison based on price projection scenarios
Korberg et al. (2021)	Methanol, DME, diesel, LNG, ammonia, hydrogen	Case study	Cost comparison based on price projection scenarios

Source: Authors' own compilation

These studies use a variety of terms and definitions in relation to marine e-fuels and apply diverging criteria to discuss the alternatives. They are not, therefore, directly comparable. However, while it appears that there is consensus across the studies on hydrogen as the basis for all derivatives, the direct application of hydrogen itself in shipping is still debated, particularly for larger ships. Methanol and ammonia seem to be the most promising options to date. Methodologically, the studies focus on developing scenarios up to 2050 and evaluating the different fuel options regarding appropriate onboard system, storage and

handling. These kinds of studies help to elevate some of the technical issues and provide an indication of the potential future amounts of fuel needed. However, there is not yet a clear consensus on whether one of the potential alternatives might emerge as a dominant fuel or whether several alternatives would emerge in parallel.

Moreover, there is a lack of studies that investigate policy instruments and strategies which target e-fuels specifically and give an indication how regulatory certainty could be established. As elaborated in the introduction to chapter 5, we assess a methanol roadmap and a technology-open roadmap as examples in this study. They should serve as blueprints for decision-makers to explore whether a fuel-specific or technology-open approach is more promising in terms of accelerating the uptake of e-fuels in maritime transport.

5.3.1 E-methanol roadmap

Methanol (MeOH) is one of the simplest e-fuel to handle since it is liquid at atmospheric conditions. Fossil methanol is one of the top five most-traded chemicals used to make adhesives, paints, LCD screens, silicones, pharmaceuticals and in the automotive industries. Its synthesis is more energy-efficient than the production of other synthetic hydrocarbons and further optimizing its production is simpler. There are a few obstacles to scaling-up, with the result that it is attractive as a transport and marine fuel especially as it induces much lower NO_x, PM and soot emissions than fossil marine fuel. It is also a hydrogen carrier comprising 40% more H₂ than liquid hydrogen per unit of volume and needs only about as much energy per unit to synthesis as that required to store hydrogen.

Production methods mostly produce crude methanol which contains some gases and water, so distillation is needed to achieve the chemical industry's requirement of 99% purity, potentially much less purity is required when using as a marine fuel.

Toxicity

Methanol is toxic and, if swallowed, results in death in 10 to 48 hours. The cure is straightforward; ethanol administered intravenously. Good fuel piping etc. onboard minimizes accidental ingestion and adding an extremely bitter-tasting benzoate such as Bitrex stops people drinking it accidentally. Inhaling or skin/eye contact should be avoided but is not as dangerous unless exposure occurs for a few hours. Toxicity is comparable to, or lesser than, gasoline or diesel.

As a marine fuel, the advantages of methanol are linked to its safety characteristics and far lower pollutant emissions compared to fossil bunker fuels. Methanol is infinitely miscible in water and dilutes rapidly so dangerous concentrations are hardly ever reached. Lethal concentrations for marine life of methanol are 240 times higher than for diesel and 1 900 times higher than for gasoline. Double hulls or bottoms can potentially be modified to store it.

Methanol as a marine fuel

Initially alternative marine fuel work focused on LNG which must be converted to a liquified gas for onboard storage, thus significantly affecting ship design or retrofits. Methanol can be made from natural gas and is a liquid at atmospheric conditions, with the result that it is much safer to use onboard than LNG since it avoids the complications of cryogenic storage of a gas. While its (net) volumetric lower heating value is approx. 23% lower (15.9 vs. 20.5 MJ/l) than LNG, methanol is more easily stored onboard because it is liquid at atmospheric conditions. Importantly, the flashpoint of methanol (12°C), though below the SOLAS threshold of 60°C, is much higher than that of LNG (-58°C). Its flammability index is much closer to diesel and, in a pool fire, methanol is vastly safer than either gases or liquid hydrocarbons. Due to its low cetane number, a small amount diesel as pilot fuel is required for the use in ICEs (FCBI energy 2015).

Methanol also has potential as an energy carrier for fuel-cell-powered ships. The liquid methanol would be reformed onboard to generate hydrogen or be used directly in a methanol fuel cell. Methanol reforms at a sufficiently low temperature that, even at low engine loads capturing this exhaust heat, represents a significant opportunity to harness waste heat recovery in internal combustion engines.

Several studies conclude that blending methanol with diesel fuels is possible although at low levels unless emulsifiers are added, which would increase costs (Verhelst et al. 2019; Methanol Institute 2007). However, there are already more than 10 methanol powered ships in operation, either specific new builds for methanol use or dual fuel engine conversions for operation either on methanol or conventional fuel (Methanol Institute 2020a; IRENA 2019; Paulauskiene et al. 2019). On such ships, fossil methanol originating from natural gas can be blended with e-methanol from renewable electricity. Since well-to-tank GHG emissions of methanol produced from natural gas are slightly higher than corresponding emissions from MGO and VLSFO (DNV GL 2016b), using fossil methanol instead of e-methanol on converted ships would result in even higher GHG emissions. However, using e-methanol in ships currently using fossil methanol would deliver even higher GHG reductions than in blends with oil-based fossil fuels.

Handling and storage

Methanol has a lower energy density than conventional fuels so requires more storage volume per energy unit, which will vary per ship type and by whether a new build or retrofit. Protective cofferdams are needed between onboard tanks. Existing fuel and ballast tanks can also be converted along with the space between double hulls as methanol spills are not very contentious due to its infinite and environmentally-safe miscibility with water. Instead of increasing tank size, ships can bunker more often as ferries and other short sea shipping vessels already do. Methanol produced from natural gas is in wide use globally, so port handling is not an issue. To date, methanol has usually been bunkered by trucks with pumps built in containers on the quay or from methanol hubs via barges, rail or tank trucks. At some European ports, methanol is one of the leading chemicals by volume handled and current practices and safety precautions build on long experience. Currently it is already available at 88 of the world largest ports (Methanol Institute 2020a). Estimated maintenance costs are similar or possibly lower for methanol-fuelled ships with other operational costs that are comparable, although experience remains limited.

5.3.1.1 National activities

Lighthouse project

The goal is to achieve a certain level of adoption of renewable sourced e-methanol from shipping calling at German ports on both new build and existing ships through fuel blending, conversion to dual fuel engines or to fuel cells with a view to demonstrating that the technology works with e-MeOH. There are already more than 10 ships globally operating with MeOH (Methanol Institute 2020a), such that it can be considered as a proven technology. The purpose of the lighthouse project would be to prove that e-MeOH can replace both fossil MeOH and other fossil fuels and to kick start to the building of e-methanol production sites in Germany.¹²⁹

By 2025, there should be ships capable of operating on at least 50% e-MeOH with a view to operating with 100% e-MeOH can be demonstrated by 2030, at the latest.¹³⁰ This would involve selected ships calling at German ports and decisions as to who pays the CAPEX for ship conversions and new builds as well as for

¹²⁹ A first pilot project to produce e-MeOH is already operating at RWE's power plant in Niederaussem/Germany. It applies the emission-to-liquid (ETL) technology developed by Carbon Recycling International (CRI), based in Iceland. However, both the electricity and the CO₂ input are from fossil sources, with the result that the output cannot be regarded as post-fossil fuel. The project has nevertheless demonstrated that post-fossil e-MeOH could be produced using this technology on an industrial scale if the inputs are from post-fossil sources (i-deals (2016); CRI (2020)). Further project could build on the experience gained there.

¹³⁰ A.P. Møller - Mærsk aims at operating a 2 000 TEU container ship with e-MeOH by 2023, but admits that sourcing the fuel in the amounts required will be a significant challenge, <https://www.maersk.com/news/articles/2021/02/17/maersk-first-carbon-neutral-liner-vessel-by-2023>.

the methanol production facilities and for meeting the additional fuel OPEX in comparison to conventional fuels.

The lighthouse project could involve non-commercial shipping where bunkering is from German ports only, e.g. coastal naval or coast guard vessels, government shipping and research vessels. Germany could also take a lead in Europe by requiring the progressive conversion of government and/or research ships to undergo engine conversion to methanol in addition to the switch to e-methanol propulsion as soon as possible.

Similar to the project initiated by Danish companies at Copenhagen Airport,¹³¹ a joint venture could be encouraged that is located in one of the major ports and involving German shipowners aiming at constructing e-methanol powered new builds and engine conversions of existing ships, manufacturers of e-MeOH production installations and operators of these facilities.

Currently, MeOH is an input for several products of the chemical industry such as formaldehyde or acetic acid. Since this MeOH has been generated from fossil sources to date (roughly 60% as a co-product of the refinery process and 40% through reformation of methane), the fossil MeOH inputs need to be replaced by non-fossil inputs sooner than later. Therefore, further synergies might be mobilized if incumbent producers and/or consumers of fossil MeOH are joining the lighthouse project.

Possibilities include ferry engine conversions or new builds for longer routes for which battery propulsion alone is insufficient or joint venture projects with other shipping companies in neighbouring countries, e.g. Scandinavia, where shipping has similar geographic operational profiles.

All options have advantages and disadvantages. Lessons learned from inland shipping cannot directly be transferred to maritime shipping, while lessons from ferries or cruise liners may not be applicable to other segments of shipping. This applies to government-owned ships as well. However, their advantage is that most of them usually bunker in their home port. Such a lighthouse project should, therefore, be established in one port where several government ships such as research or coast guard vessels are based.

Since MeOH can be used in different types of ICE, many existing ships could be converted to dual fuel engines so that MeOH can basically be used in all ship categories (Verbiest und Janvier 2019). The costs of converting existing ships include modification of engine, onboard fuel system and associated safety systems and are estimated to amount to 300 €/kW engine capacity, i.e. comparable to costs of adding a scrubber. For converting an existing ship to LNG dual fuel capacity, the costs would amount to 1 000 €/kW (Methanol Institute 2015; EMSA 2015). However, through the implementation of the lighthouse project, it would also be possible to enhance the knowledge on CAPEX and OPEX involved in converting to e-MeOH. It is important to note that conversion to dual fuel engine capability, e.g. with the Stena Germanica, preserves the ability to switch to methanol propulsion from Marine Gasoil (MGO) fossil propulsion.

To seed the project and provide ongoing support, some level of involvement funded by the German government will be needed, motivated by general defossilization, green stimulus and advanced technology objectives. Funding could also come from German revenues, should the shipping sector be included in the EU ETS, from the innovation fund of the EU ETS or, alternatively, from the EU Maritime Decarbonisation Fund as suggested by the EP (2020), provided that the lighthouse project is eligible for support from this fund. Calls for applications or auctioning subsidies to fund CAPEX for engine conversions or new builds could be considered along with similar OPEX instruments for the supply of e-methanol over a pre-determined

¹³¹ Danish companies join forces on an ambitious sustainable fuel project, <https://www.dfds.com/en/about/media/news/danish-companies-join-forces-on-an-ambitious-sustainable-fuel-project>.

period, particularly if such initiatives were able to trigger joint ventures between shipping companies and fuel suppliers.

The lighthouse project could build on several research projects, both nationally and EU-funded, for methanol-fuelled ships that have been initiated in recent years. They are led by the engine manufacturers MAN and Wärtsilä, universities in Scandinavia and Benelux and include a number of ship conversions, notably the Swedish 1 200 capacity ferry, Stena Germanica (Stena Line 2015). Other projects such as Spireth,¹³² Fastwater,¹³³ LeanShips¹³⁴ and North-CCU-hub¹³⁵ established large coalitions involving commercial organisations such as SSPA AB,¹³⁶ Lloyd's Register, Engie SA,¹³⁷ Antwerp and Rotterdam ports and a range of technical universities in northern Europe. Proman and Engie SA are now starting a project to build the world's largest green hydrogen to renewable methanol facility in the Port of Antwerp.¹³⁸ Ship methanol research projects are also now underway in China, Singapore and India, which present opportunities for more distant collaboration.¹³⁹

In order to accelerate work on both national and EU levels, German industry supported by national project funding should step up efforts to forge partnerships with existing and new research and industrial groups in neighbouring countries and concentrate in particular on identifying outstanding issues requiring further R&D, engine or infrastructure work, etc. Cooperation with the European Commission and other relevant EU bodies including EMSA and the Joint Research Centre in Ispra to address these outstanding issues should be stepped up.

E-methanol mandate

With a view to further accelerating the uptake of e-methanol in Germany, it could be considered to establish a fuel mandate for e-methanol as elaborated in more detail as promotion activity at the European level below (section 5.3.1.2). However, since establishing such an instrument at national level would be cumbersome, the volume of the ship fuel market in Germany would be too small to trigger significant demand dynamics for e-methanol. Moreover, the potential for evasion – if implemented at national rather than European level – would be larger. Hence, this approach should not be pursued further. Instead, the German government should actively support the European Commission's FuelEU Maritime initiative,¹⁴⁰ which aims at accelerating the uptake of post-fossil fuels including through a fuel mandate.

5.3.1.2 European cooperation

The goal at EU level is to develop and implement an EU-wide demand-pull policy (i.e. going beyond R&D and trigger learning by deployment) which ensures the accelerated uptake of e-MeOH across EU ports and

¹³² SPIRETH - Methanol as marine fuel, <https://www.sspa.se/how/research/spireth-methanol-marine-fuel>.

¹³³ FASTWATER, FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel: Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up, <https://www.fastwater.eu/>.

¹³⁴ LeanShips, Low Energy And Near to zero emissions Ships, <https://www.leanships-project.eu/home/>.

¹³⁵ North-CCU-hub, Towards a climate-neutral economy in North Sea Ports, <https://northccuhub.eu/>.

¹³⁶ Statens Skeppsprovsnings Anstalt, Göteborg, <https://www.sspa.se>.

¹³⁷ Known up to 2015 as GDF Suez, <https://www.engie.com>.

¹³⁸ Port of Antwerp turns to biomethanol, <https://www.engie.com/en/port-antwerp-biomethanol>.

¹³⁹ DNV GL, May 2020, Methanol as a potential alternative fuel for shipping, <https://www.dnvgl.com/maritime/advisory/afi-update/Methanol-as-a-potential-alternative-fuel-for-shipping-A-brief-talk-with-Chris-Chatterton.html>; SAFETY4SEA, 11/12/2018, India starts project to promote methanol as marine fuel, <https://safety4sea.com/india-starts-project-to-promote-methanol-as-marine-fuel/>.

¹⁴⁰ <https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-FuelEU-Maritime>.

sets Europe on a path to the full phase-out of fossil fuels for shipping in Europe and/or by European ships/operators by 2050.

Incentives for conversion to or new build of methanol ships

Building on the German lighthouse project, the EU could agree to a requirement progressively implemented for government and/or research ships to undergo engine conversion to operate on e-methanol. This initiative could be extended as sufficient fuel becomes available to additional classes or categories of ships.

In addition, incentives should be provided for the introduction of new build e-methanol ships or engine conversions of existing vessels with 5% MGO/VLSFO diesel for ignition. Such ships would comply with Sulphur Emission Control Area (SECA) and Nitrous Oxide Emission Control Area (NECA) requirements as well as the global 0.5% sulphur cap. Dual fuel conversion costs for existing ships are on a par with scrubber/SCR installation costs while the additional CAPEX for a new build dual fuel engine methanol powered ship is around US\$ 10 million for a 10 000 kW engine (Lindstad 2020). EMSA (2015) estimates that new builds would face investment costs of 815 US\$/kW of engine capacity on average while retrofitting would require an investment of 392 US\$/kW.

These ships would be initially propelled by methanol produced from natural gas. Methanol produced from natural gas has at times been cheaper than fossil marine fuels. Today, methanol as a ship fuel produced from natural gas is priced in Rotterdam about on a par with VLSFO (section 5.3.1). Methanol-propelled ships would be subject to the same mandate requiring the progressive blending of e-methanol but with natural gas methanol.

E-methanol mandate

EU action, unless in relation to financial instruments such as taxes or levies, require decisions by qualified majority vote in Council preferably agreeing regulations implemented directly and uniformly across the EU27 Member States. Under the European Green Deal, the European Commission plans to include shipping into the EU ETS. The EP (2020) suggests that this should be carried out during the revision of the shipping Monitoring Reporting and Verification (MRV) Regulation (EU 2015/757) by creating an Ocean Fund as an alternative to ships' participation in the trading allowances.¹⁴¹ The establishment of such a fund would be a first step "to make ships more energy-efficient and to support investment in innovative technologies and infrastructure, such as alternative fuel and green ports".¹⁴²

However, neither the Ocean Fund nor the ETS alone will currently or projected future allowance prices be sufficient to drive the level of change needed to meet 2030 or 2050 reduction targets. A separate policy in addition to ETS or fund will be required to achieve defossilization of maritime transport. Accordingly, the European Commission aims to accelerate the uptake of post-fossil fuels through a set of policies potentially including a fuel mandate (FuelEU Maritime¹⁴³). A comparatively simple way to provide incentives for increasing the uptake of e-methanol would be through a physical drop-in mandate similar to the approach

¹⁴¹ Amendments adopted by the European Parliament on 16/09/2020 on the proposal for a regulation of the European Parliament and of the Council amending Regulation (EU) 2015/757 in order to take appropriate account of the global data collection system for ship fuel oil consumption data (COM(2019)0038 – C8-0043/2019 – 2019/0017(COD)), https://www.europarl.europa.eu/doceo/document/TA-9-2020-0219_EN.pdf.

¹⁴² Shipping industry must contribute to climate-neutrality, say MEPs, 07/07/2020, <https://www.europarl.europa.eu/news/en/press-room/20200703IPR82633/shipping-industry-must-contribute-to-climate-neutrality-say-meps>.

¹⁴³ <https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-FuelEU-Maritime>.

for e-kerosene in aviation (section 5.2.2). This would require that e-methanol can be blended with the currently predominantly used diesel fuels – MGO/VLSFO (HFO, RFO, MFO, etc.).

The blending of currently used fossil fuels with MeOH is basically possible, at least at lower shares. However, the question remains as to whether the blending of higher shares is possible (section 5.3.1). These considerations suggest that it would currently be too early to pursue a “simple” physical drop-in e-methanol fuel mandate approach across Europe. Further technical research would need to be conducted to provide the required certainty. However, if it were possible to conclude later that physical drop-in, also in larger shares, is feasible, it would be attractive to implement a policy based on a physical drop-in mandate for e-methanol. The policy design would be quite similar in terms of obliged entity, quantitative metrics of the mandate, eligible fuels, etc. to the drop-in approach for aviation (section 5.2.2). Each entity falling under the scope of the instrument would be required to comply with the same share of e-methanol, which would increase over time until it reaches 100% in 2050.¹⁴⁴ The blending of e-diesel (a co-product of PTL processes including for aviation) should not be excluded from such a physical blending mandate – as it is 100% post-fossil like e-methanol and a completely drop-in fuel. But e-diesel would be unlikely to prove commercially attractive as e-methanol production costs are lower.

A low-level e-methanol blending mandate could serve as a ‘no regrets’ initiative while giving Europe an early start by establishing one feasible route for the transition to 100% e-methanol powered ships. Since a low-level blending mandate would be needed for a completely drop-in fuel requiring no onboard or shore-side bunkering practices changes, it would be reversible to the extent that existing ships could quickly change away from blending drop-in e-methanol if a superior approach later becomes available. In the meantime, by passing on higher fuel costs to ship owners/operators and ultimately consumers, progress along the pricing, fuel-mixing and scaling-up of clean e-fuel production can be achieved. We do not, however, elaborate further on this approach but focus rather on how the mandate would need to be designed if it turns out that the physical drop-in of e-methanol is not possible.

If physical drop-in is not feasible, the minimum quota cannot be achieved by each entity but needs to be achieved across the average of the covered entities within a certain monitoring period, e.g. one year (virtual blending).¹⁴⁵ In this case, some ships would be converted to dual fuel engines or methanol only new builds which could significantly overachieve the mandated share. Many ships, especially the older ones, may just continue to sail on marine diesel and physically not comply with the mandate. On average, the mandated share could still be achieved, provided that the requirements established through the mandate provides the appropriate incentives.

To ensure this, the mandate would need to be established based on a book and claim system (Pechstein et al. 2020) with e-methanol certificates. The certificates would be issued to suppliers of eligible e-methanol. They would be certified by accredited third party verifiers, which testify that the e-methanol is compliant with requirements similar to requirements of the RED for biofuels, which take into account all upstream GHG emissions and other environmental impacts.¹⁴⁶ The mandate to surrender such certificates could be

¹⁴⁴ An estimate of the volumes of e-fuels and renewable electricity required to produce these amounts is provided in section 5.1.1 (Table 40).

¹⁴⁵ The design elements of such a virtual mandate would need to be discussed in more detail. The quota could, for example, be accounted in physical volumes (mass or energy) in terms of GHG reduction compared to a reference fuel. Potential entities to be required complying with the mandate could, for example, be the fuel producers, the fuel consumers (shipping companies) or the fuel suppliers. All options have specific advantages and disadvantages, which need to be spelled out once an agreement on the overall design is achieved.

¹⁴⁶ The sustainability criteria for the production of e-fuels and the methodology for calculating GHG reductions of e-fuels are to be elaborated by 31/12/2021 through two delegated acts pursuant to Art. 27 (3) and Art. 28 (5) respectively of RED II (OJ, L 328, 21.12.2018).

linked to different activities, mainly selling, purchasing or using fuel for maritime transport. Covered entities would be required to surrender a share of e-methanol certificates for each unit of fuel which increases over the years. Linking the mandate to selling fuel would be similar to the approach of the RED II, according to which fuel suppliers are also the entity responsible for complying with the directive. Alternatively, the mandate could be linked to the demand of fuel for maritime transport so that shipping companies or ship operators would need to surrender the certificates. One disadvantage of the latter option would be that it involves more entities, with the result that MRV would induce higher transactions costs. However, both approaches have the disadvantage that they provide the incentive to evade the requirement through bunkering beyond the EU.¹⁴⁷ The third approach could overcome this disadvantage since it links the requirement of surrendering e-MeOH certificates to using fuels on routes to or from EU ports. It could be based on the EU's MRV regulation under which CO₂ emissions are calculated from the fuel used on these routes.¹⁴⁸ Ship operators or shipping companies could not evade the costs by simply bunkering outside the EU. Since the approach is similar to SECAs and NECAs, it could be called a Low GHG Emission Control Area (LECA).

Politically, it would still need to be discussed whether the fuel used on both inbound and outbound routes to ports outside the EU are covered by the mandate or whether only a share of the fuel used on these routes are covered (e.g. 50%). If all outbound and inbound journeys were included, the incentive for e-methanol production would also be larger than under the supply or demand approach.

The mandated entity would need to purchase certificates from e-MeOH producers, which would sell these certificates at a price that they need to finance the additional cost of e-methanol production while selling the e-methanol at a price similar to fossil fuel. In this way, the additional cost of the e-methanol production would not only be borne by those entities which actually purchase the e-methanol but by all covered entities. To achieve the goal of 100% in 2050, the shares to be achieved through this mandate would need to increase steeply, e.g. from 2% by 2025 to 5% and 33% by 2030 and 2035 respectively and to 100% by 2050.

To ensure that at least some entities convert ships which can use e-methanol, the price of certificates may need to be so high that e-methanol can be offered even at a lower price than fossil fuel. The price difference would refinance the investment required to adjust existing technology or the additional cost for e-methanol ships in the case of new builds. If the requirement was suitably enforced, market incentives should – according to economic theory – ensure that sufficient entities embark on e-methanol technology. However, such steps involve high technological risks, which in the early phase of a new technology usually cannot be provided by market incentives alone. Therefore, it would significantly facilitate the transition if investments in adjusting existing technology or additional cost for new technology are at least partly covered by subsidies.

Another way to facilitate the transitional period would be to subsidize the production of e-methanol. This would be an industrial policy strategy to promote becoming a first mover and frontrunner in a promising and forward-looking technology with a high potential of avoiding GHG emissions in the future rather than a GHG reduction contribution today (similar to the promotion of renewable electricity generation by wind and solar in the early years of this century).

¹⁴⁷ T&E (2020) assesses the risk of evasion for including maritime shipping in the EU ETS and concludes that at current allowance prices the risks are small. This is because the number of ports with directly competing ports beyond the EEA territory is small and because port calls induce additional cost. However, with increasing allowance prices the evasion incentives would become stronger so that evasion could result in significant carbon leakage unless addressed through introducing that port calls require genuine business activity such as unloading or loading a certain share of cargo or passengers.

¹⁴⁸ The EU Data Collection Systems (DCS) is implemented through the so-called MRV regulation (2015/757), which basically includes emissions on journeys to and from EEA ports of all ships larger than 5 000 gross tonnage. For the revision of the regulation, the EP suggests to also include ships between 400 and 5 000 gross tonnage (footnote 142).

5.3.1.3 International cooperation

Discussion at the IMO is focused on achieving the targets agreed in April 2018 to reduce annual GHG emissions of shipping by at least 50% in 2050 relative to 2008 and to improve the GHG intensity (CO₂ emissions per transport work) of shipping by at least 40% in 2030 relative to 2008 and pursue efforts to improve it by 70% by 2050 (IMO 2018). The initial focus is on which immediate policies could be agreed in the short term i.e. by 2023. At MEPC 75 in autumn 2020, new short-term measures were approved with the view of adopting these amendments to the MARPOL convention at the MEPC session in summer 2021 (IMO 2020b):

- ▶ The Energy Efficiency Index for Existing Ships (EEXI) will require every operator to improve the technical energy efficiency of existing ships in order to catch up with a new ship of the same type and dead-weight.
- ▶ A regulation on operational carbon intensity management which requires a linear reduction of in-service carbon intensity of a ship between 2023 and 2030 (LR 2020). Ships will be rated based on a Carbon Intensity Indicator (CII). The rating will be documented in the existing Ship Energy Efficiency Management Plan (SEEMP).

These two goal-based measures will improve the energy efficiency of ships and complement the existing EEDI from 2023 onwards (LR 2020). Little concrete discussion has yet been held on specific policies for the medium and the long term that will transition the sector to cleaner fuels, like a market-based policy.

To what extent are efforts to defossilize shipping best implemented globally via agreement at the IMO? There are strong arguments for the IMO to set suitable global regulations on fuels and environmental standards on all aspects of fuel safety from ship construction to onboard procedures for handling, equipment etc. and for shoreside bunkering procedures etc. to reach this goal. Agreement and implementation at the IMO through international legal instruments ensure a level and safe playing field for all. But, to what extent do policies for driving the uptake of clean fuels need a global approach? This has been a long-debated issue in the context of aviation and is worthy of debate for shipping especially as the climate crisis deepens. Fuel blending mandates for example might be far easier to agree and implement initially for select geographic regions. This concept is in fact already in place with regional implementation of SECAs and NECAs.

In addition to an initiative in Europe, a shift to methanol or a blending requirement could be considered in other regions with high bunkering demand like Singapore. Implementing such a policy for Chinese ports could be relatively straightforward given the local availability of methanol and pressing air quality problems. The greatest potential for developing methanol powered shipping outside Europe is therefore China, which is the world's largest methanol producer by far and also dominates demand globally. Methanol from coal gasification has been used for many years in the manufacture of chemicals but also as a fuel in industrial boilers, passenger vehicles, and heavy-duty trucks where prices including for DME are significantly lower than gasoline (Methanol Institute 2016). China now imports methanol from the US, which is a cheaper producer. Chinese investors are involved in locally controversial plans together with Hafnia, one of the largest oil product tanker companies, to build a shale gas methanol plant at Kalama port in Washington state to supply the Chinese market.¹⁴⁹ Australia is an obvious potential source of green hydrogen¹⁵⁰ and

¹⁴⁹ The Maritime Executive, 17/09.2020, Controversial Kalama Methanol Plant Secures Investment from Hafnia, <https://www.maritime-executive.com/article/controversial-kalama-methanol-plant-secures-investment-from-hafnia>.

¹⁵⁰ Xinhua, 22/06/2019, Plans announced for world's largest solar farm in Central Australia, http://www.xinhuanet.com/english/2019-06/22/c_138164116.htm.

also has abundant natural resources including gas. It must be considered an interesting location for future methanol or e-methanol production.

To accelerate the establishment of e-MeOH as the dominant fuel for maritime transport, the EU could initiate a Global Supply and Demand Partnership (GSDP) with like-minded countries, which see the need to start the uptake of one e-fuel rather soon than later, since the time to achieve defossilization is too short for a time-consuming competition period, which eventually may identify a potentially only somewhat better e-fuel option. This partnership would involve countries with key shipping fleets and countries which could supply either the technology for the transition (ships, engines, e-MeOH production facilities, etc.) or have natural resources to produce and supply the global market with e-MeOH. It could start with a small number of key countries but may be enhanced once the partnership has developed some global impact, fostering the interest of other countries to join the partnership.

However, a blending mandate would be most effective if it would be applied globally and therefore established under the IMO. Since this process for adopting such mandate at global level would likely be more time-consuming before it becomes effective than establishing a mandate in a group of proactive countries or regions, the mandated rate would need to increase steeper to reach 100% in 2050.

A proposal brought forward ICS et al. at IMO (2019) to establish an International Maritime Research and Development Board (IMRB) would include imposing a 2 US\$/t levy on all marine fuel purchases worldwide to create a global R&D fund. Such a R&D fund has merits although it remains unclear how the funds would be disbursed, where the work would be done and on what projects and will inevitably be subject to considerable political discussion. In order to kickstart global moves towards the uptake of clean marine fuels such as e-methanol, some of the proceeds from such an R&D fund could be earmarked to accelerating work on needed regulatory rules for e-methanol as a ship fuel.¹⁵¹

A mandate for blending e-methanol with MGO/VLSFO as proposed for Europe could also be envisaged at the global level or in additional geographic regions. It could be implemented through MARPOL while fuel blending safety and environmental specifications could be developed under the International Convention for the Safety of Life at Sea (SOLAS). Starting at a low – say 2% – level, such a mandate would most easily be implemented first at the major bunkering hubs with e-methanol production being ramped up there first to meet bunkering hub requirements. A 2% blending requirement would have a limited impact on fuel price and therefore evasion strategies would be limited.¹⁵² Successful implementation could then encourage a wider selection of bunkering ports to join in.

5.3.1.4 Overview

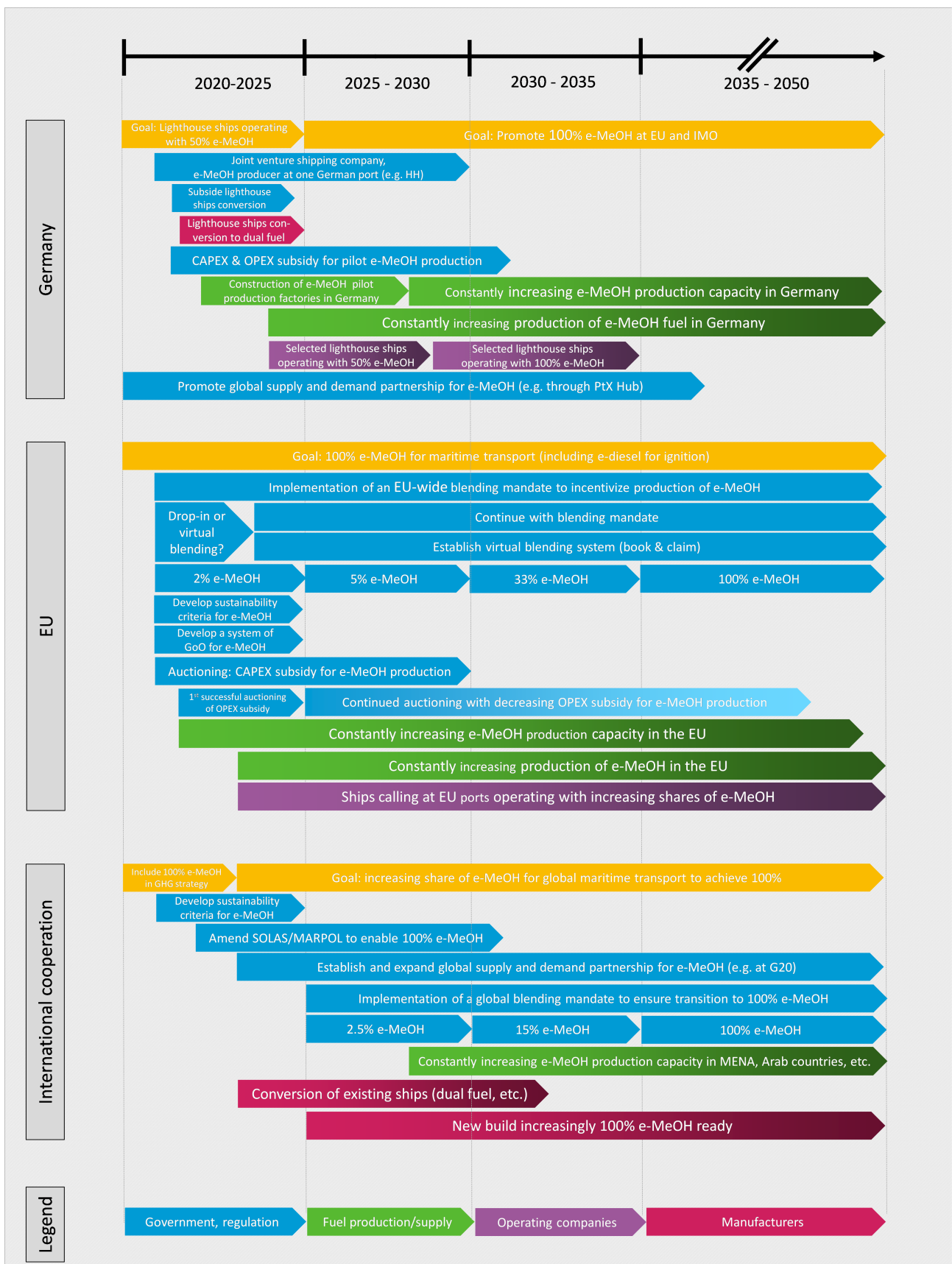
Figure 45 provides an overview of the suggested initiatives and activities discussed above and enhances the picture by some activities not explicitly mentioned above. It distinguishes between different types of stakeholders involved: governments which establish the legal regulation for ensuring the implementation of the necessary activities; fuel producers and suppliers which invest in production facilities and supply infrastructure and operate them; shipping companies which operate the ships; and manufacturers, which provide new-build or adjust existing vehicles. Moreover, it suggests indicative targets, which eventually need to be discussed and agreed politically and an indicative schedule of when the individual steps need to be initiated and when they should be completed to achieving the goals envisaged. The start of individual arrows

¹⁵¹ There are already Interim Guidelines for using methanol as a fuel in maritime transport: IMO (2020b).

¹⁵² Similar to the consideration for aviation (section 5.2.2), the additional cost would on average across total fuel consumption be small as long as the mandated shares are small. However, with increasing shares the incentive increases as well. To mitigate the incentives, e-fuels might need to be, at least initially, subsidised until a global fuel mandate is implemented under the IMO.

indicates when an initiative or activity should be commenced with a view to being accomplished by the year when the arrow ends. Fading in of darker colours indicates that efforts or the stringency of the intervention need to be intensified over time.

Figure 45: E-MeOH roadmap



Source: Authors' own compilation

The overview illustrates that at all regulatory levels (Germany, EU, International), the first steps have to be taken immediately. National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible. The years up to 2025 are decisive for achieving defossilization of maritime shipping by 2050. If appropriate policies are not 'set on track' by then, at least at national and European level, it will be difficult to achieve this goal.

5.3.2 Technology-open roadmap

The specific challenge of maritime shipping is that – different to aviation – one dominant e-fuel has not yet emerged. While the roadmap sketched in the previous section is based on the assumption that technological developments, which involve infrastructure decisions with regard to global fuel storage and supply capacities, need clear political guidance based on long-term targets, the roadmap sketched below trusts in market forces to guide involved companies taking the right long-term decision. It also requires long-term target setting by governments and regulators, but the policies applied are less guiding and more in the style of guard-rails. The activities and policies to accelerate the uptake of e-fuels are not necessarily fundamentally different but have often just a different focus.

5.3.2.1 National activities

The long-term goal is to facilitate the transition from the use of fossil towards post-fossil fuels for ships calling at German ports. To demonstrate the feasibility of this transition, Germany could initiate a lighthouse project in which such e-fuels are produced and used with a view to gaining further experience and identify advantages and disadvantages of the different fuel options from practical experience. For this purpose, Germany would leverage its resources, know-how and influence to accelerate R&D and pilot projects to identify the most promising maritime e-fuels, the optimal production pathways and geographic locations and accelerates deployment by incentivising new builds and ship conversions while deepening cooperation with prospective producing countries, forging industry and political support coalitions with neighbours and leading on developing EU/global policies.

In order to harness and incentivize German industrial and technical know-how on shipping and e-fuel pathways, the government could launch competitive tenders for the construction of new builds and ship engine conversions in order to assess operational performance of the different fuel options and quantify well-to-wake emissions. Building on Germany's strong history and capacities in maritime technologies and its clear focus on promoting e-fuels and openly sharing the findings to create a shipping defossilization knowledge and deployment hub, the following activities could be initiated:

- ▶ Fund comparative studies to quantify and assess the impacts – timelines, price, etc. – of competing demands for e-fuels from the aviation and shipping sector taking into account overall feedstock limitations, the practicability of enforcing sustainability criteria, financial and cost constraints between the two sectors and the need for transition fuels.
- ▶ Provide financial and technical support to assist German ship owners to establish cooperative e-fuel ventures with similarly interested counterparts in neighbouring countries. Cooperation could involve ship trials on Baltic or North Sea shipping routes.
- ▶ Provide financial support for pilot production facilities with a view to facilitating improving e-fuel production processes through 'learning by doing'.
- ▶ Initiate competitive tenders to investigate and compare the different technology pathways with incentives for early results and successful deployment, while at the same time making sure that know-how

and results are shared in regular progress reviews in order to accelerate the learning process for all and to allow for dynamic course changes as needed as technological knowledge improves.

Focus should be on the early implementation including battery electric propulsion or other pathways which can start to achieve emissions reductions well before 2030 within the German coastal and EU regions; therefore, ferries, roll-on/roll-off ships and service vessels should be addressed initially. The assessment of e-fuel options for ocean going vessels – hydrogen, ammonia, methanol, etc. – should initially concentrate more on optimal fuel production pathways and timelines and less on deployment until the perspectives in terms of dominant shipping fuels are clearer.

At the same time, the German government should aim to accelerate the uptake of e-fuels through the promotion of a global supply and demand partnership, potentially through the PtX Hub.¹⁵³ The partnership would aim at agreeing on a joint strategy for defossilizing maritime transport. A small group with key shipping and e-fuel supply countries is likely to be more effective than aiming to involve as many countries as possible.

5.3.2.2 European cooperation

The EU's intention to include shipping in the ETS is only a first step and it will be critical that good cooperation can be maintained with the IMO in order to foster efforts for further initiatives in other regions. However, inclusion in the ETS will not provide sufficient incentives to drive the transition towards post-fossil fuels in maritime transport (section 5.1.3.4). The EU therefore needs to establish a policy which ensures the accelerated uptake of e-fuels in shipping¹⁵⁴ and at the same time use this initiative to trigger and promote the application of these fuels globally. Since a dominant e-fuel is not currently in sight, the EU would need to initiate a process which facilitates the further technological development of the most promising e-fuel options with a view to increasing continuously the share of post-fossil fuels in total fuel consumption of maritime shipping and finally achieving a 100% share in 2050.

Establishing an alternative compliance mechanism for ships participating directly in the ETS through creation of an Ocean Fund (section 5.3.1.2), based on emissions reported under the MRV scope, would not only reduce administrative burden but also help win industry support by ensuring that the revenues raised can be used directly in-sector on defossilization initiatives. However, even with ETS ambition being raised to achieve an EU-wide reduction in net GHG emissions of at least 55% by 2030, compared to 1990 levels, allowance prices are unlikely to rise in the next few years to levels required for fostering the transition towards post-fossil fuels in maritime transport. Additional policies would be required if shipping is also to meet the same revised 2030 EU reduction targets as other sectors.

Europe should therefore introduce a GHG intensity reduction policy which applies to all ships within the EU MRV scope that requires them to achieve not only the IMO's interim 2030 global target of a 40% reduction in ship GHG intensity agreed in 2018, but also the EU-wide net reduction in GHGs of at least 55% by 2030. This requirement would provide a strong push for post-fossil fuels since such a reduction cannot be achieved by increasing technological or operational efficiency but only through increasing the uptake of post-fossil fuels.

Such a policy is within the EU's legal remit. The MRV regulation (EU 2015/757) covers only large ships above 5 000 gross tonnage – around 55% of all ships calling at EEA ports – and about 90% of all CO₂ emissions

¹⁵³ <https://ptx-hub.org/>.

¹⁵⁴ Under the FuelEU Maritime initiative, the European Commission aims at accelerating the uptake of post-fossil fuels through a basket of measures potentially including a fuel mandate (<https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-FuelEU-Maritime>).

within the regulation's geographic scope. Military vessels, naval auxiliaries, fish-catching or fish-processing ships are excluded. Based on the report for 2018 and 2019, EC (2020a) concludes that the large majority of ships inspected by EU port authorities carried a valid document of Compliance. Around two-thirds of ships reporting in 2018 were flagged in non-EU states with having more than half ownership by entities based in the EU and around half of these being European companies.

Retrofits and newly designed ships, ready to use post-fossil fuels will be needed to trigger the required supply chain and bunkering infrastructure changes. The transition to compliance should be accelerated through incentives and subsidies to frontrunner shipping companies and individual ship owners who take these initial steps towards defossilization. These incentives could be financed by ETS revenues, the Ocean Fund or potentially from budgets raised through abolishing the exemption of fossil fuels for maritime transport under the Energy Tax Directive (ETD).

Compliance to such a GHG intensity policy would not be based on fuel mandate to be achieved by each ship when operating within the MRV scope. To provide flexibility in terms of which e-fuel should be applied an e-fuel certificate system with GoEs should be established. It would be similar to the one described above in the e-MeOH roadmap (section 5.3.1.2) and would certify the life cycle emission reduction of each e-fuel.

The baseline of the GHG intensity standard would be set at the average GHG intensity of traffic covered under the MRV regulations in 2018 and 2019. From there, the standard might start with a -2% reduction in 2022, increase to -10% (2025) and -40% (2030) and finally reach -100% in 2050. The standard would be technology-open and allow shipping companies to focus on efficiency improvements and/or e-fuels.¹⁵⁵ However, due to the steep decline of the standard, efficiency improvements will quickly not suffice to comply with the standard so that applying post-fossil e-fuels would become a more and more attractive option.

Ships with emission below the baseline would initially comply automatically with the standard. To avoid a complex trading of over-achievement between ship operators in the initial years, 'excess reductions' could be banked and used to comply with the standard in later years when the actual emissions are already above the threshold. However, due to the steep decline of the emission threshold ship operators would rather sooner than later need to implement reduction measures. To comply with the requirements, they can reduce emissions through technical and operational measures such as increasing engine efficiency or slow steaming. In addition, they could surrender GoOs, which would offset emissions above the threshold. As described in more detail in the e-MeOH roadmap (section 5.3.1.2), these GoOs would need to be purchased from e-fuel producers, which would use the revenues to finance the share of their total production costs, which exceeds the market price for fossil shipping fuel. Different to the e-MeOH roadmap, GoOs from all types of e-fuels would be eligible for compliance with the standard.

To ensure that the GoOs provide the required incentives, two certificates would be issued for each unit of e-fuel produced. One of the certificates accompanies the e-fuel with no additional cost and certifies which emissions factor needs to be applied in the monitoring of emissions. Shipping operators who use e-fuels will be able to reduce their monitored emissions. Shipping operators who continue sailing on fossil fuels will need to purchase the second certificate to offset their emissions exceeding the actual standard and thus contribute appropriately to finance the additional costs for accelerating the uptake of e-fuels. This would increase the cost – but not the price – of fossil fuel. Since shipping operators who use e-fuels do not bear the extra cost of GoOs, they can use this difference to finance additional costs for making their ships e-fuel ready.

¹⁵⁵ The standard could for example be measured in *Annual average CO₂ emissions per transport work (mass) [g CO₂ / m tonnes · n miles]* since this figure is available for more than 80% of the ships covered by the MRV regulation.

It would be advisable to involve the European Maritime Safety Agency (EMSA) in devising procedures for the progressive blending of e-fuels with existing fossil marine fuels. EMSA's capacities in such technical evaluation of future post-fossil marine fuels should be assessed and strengthened as necessary so that an European centre of technical excellence, combined with regulatory and certifying authority, can work alongside and help drive industry, class societies and ports etc. in developing policies to bring future e-fuels such as e-methanol to market.

5.3.2.3 International cooperation

The key to finally defossilizing shipping via e-fuels and ships that can burn them is to make sure that the global shipping community adopts standards on clean fuels and their technical aspects that will enable their global deployment. The IMO has the advantage, unlike ICAO, of a maritime pollution convention (MARPOL) that has binding and enforceable provisions on all ships. MARPOL is supplemented by Paris MoU¹⁵⁶ on port state control and other Memorandums of Understanding (MoU) around the world covering European and American waters. Nevertheless, global defossilization of shipping will depend on the actions of frontrunners leading to the progressive adoption of mandatory abatement policies and practices, also because about 18% of global ship fuel burnt is associated with domestic shipping (IMO 2020a).

Technical standards

To ensure global applicability, the IMO must play the central role in developing and setting global industry standards for the safety, handling, bunkering and onboard use and deployment of future post-fossil fuels and work collaboratively with states and the ISO on setting fuel specifications. This will constitute a complex and very heavy technical and scientific workload for the secretariat, for members states and for observers to build on existing and potentially new conventions. This regulatory work is essential but requires time¹⁵⁷ and must not, therefore, be delayed by indecision over the relative merits of different e-fuel options.

Many studies and projects will need to be undertaken that require IMO members to make special contributions financially, in human resources and R&D know-how. This work must start as soon as possible and proceed in tandem with advances in the understanding and development of the different fuel pathways. A major issue will be the extent to which attention is focused on sustainable biofuels rather than e-fuels where the regulatory challenges are likely to be larger. To ensure defossilization of the maritime sector, it is therefore important to establish regulations limiting the use of advanced biofuels to those sourcing from feedstocks with no risks of indirect land use change (ILUC).

A key element in assessing the relative merits of different post-fossil fuel options for the shipping industry and planning for their production will be the different safety, handling, production standards and certification requirements that will be specific to each fuel type and their blends. To ensure an accelerated uptake world-wide, it will be essential that the required regulations are agreed under SOLAS and MARPOL so that ships travelling anywhere will be required to observe minimum standards and to adhere to local regulations that will have been introduced based on global standards.

¹⁵⁶ Paris MoU on Port State Control (PSC), <https://www.parismou.org/>.

¹⁵⁷ The IMO's Maritime Safety Committee (MSC) has, for example, been working for several years before the interim guidelines for the Safety of Ships using methyl or ethyl alcohol as fuel had been adopted in December 2020 (IMO 2020b).

Implementing strategies

Debate at the IMO on GHG reduction policies started well over a decade ago. Carbon pricing in its various forms, energy efficiency or GHG efficiency policies as well as fuel mandates are under consideration. The latest suggestion aims at establishing an International Maritime Research and Development Board (IMRB), i.e. a global fuel levy to finance R&D (IMO 2019). Agreeing to such a levy would be an important start. However, given Common but Differentiated Responsibilities (CBDR) under the UNFCCC and global south concerns over economic impacts, it is hard to see a global consensus being reached in the foreseeable future on any policies which significantly raise fossil fuel prices or touch on the use of revenues.

Incremental action starting at regional level such as Europe and then extending first to other regions may well prove to be the most effective pathway to the sector's eventual defossilization. Such EU moves will be important in gaining acceptance that regional approaches are the most likely way to advance defossilization. European frontrunner action on ship air pollution in the Baltic Sea in the 90s led to the IMO adopting the emission control area concept. The 2016 IMO review confirming implementation of the global sulphur cap in 2020 was very controversial and in the end only adopted because of the European Parliament's insistence in 2012 that the cap would be applied within the EU in 2020 irrespective of any IMO decision. Similarly has the adoption of the EU MRV regulation for GHG emissions from shipping (EU 2015/757) most likely contributed to accelerate the adoption of the IMO's Data Collection System (IMO 2016).

Active pursuit of the most promising options at European level can therefore exercise a major influence on regulatory decisions under the IMO. EU Member States along with some other states remain the largest bloc of the 88 signatories to MARPOL Annex VI today. The GHG intensity standard for shipping to complementing the EEDI (section 5.3.1.3) may contribute to global change. Discussion in this direction is just starting with a focus on mandating the construction of zero emissions vessels from 2030. Europe has the technical and regulatory know-how to take the lead on this. While all the principal shipbuilders are now in Asia, the European maritime technology sector already produces around half of the world's maritime equipment each year, and specializes in high-end, complex and technologically-advanced ship types and systems (cruise ships, ferries, offshore vessels and installations, propulsion systems, radars, piloting systems etc.) and in advanced 'blue economy' technologies (EPSC 2019). As with the development of fuel technology, decisions and commercial direction will be driven by a few key players.

Low GHG emission control areas (LECAs), as suggested in section 5.3.1.2, have the potential to develop regionally, possibly featuring different and competing technologies depending also on the availability and cost of renewable electrolysis in different geographies. That could lead – or oblige – states to agree green technology shipping routes and install supporting port infrastructure by ship type as necessary, possibly starting between China, Singapore and Europe. After China, Singapore is the biggest bunkering hub in the world and has enormous economic stakes in shipping's future.

The technology-open approach will, therefore, likely lead to a variety of e-fuels and solutions well before a potential dominance of one e-fuel becomes apparent. This would likely add to cost due to infrastructure overlap and to the importance of pursuing accelerated action to identify and rule out suboptimal pathways and dead ends as quickly as possible. In this respect, plotting shipping's course is far more daunting than that for aviation. Stepped-up EU and national approaches on technology options can make an important and necessary contribution. In addition, given the role of shipping companies like Mærsk and CMA in

Europe and the container sector's importance to shipping and its industry body, the World Shipping Council (WSC), it would make sense to foster closer collaboration.¹⁵⁸

To establish such cooperation, the EU could initiate a Sustainable e-fuel Alliance for Maritime Shipping (SeAMS) which aims to identify and agree, sooner than later, on the most promising e-fuels which would drive the transition to post-fossil maritime shipping.¹⁵⁹ This partnership would build on existing initiatives such as the Getting to Zero Coalition¹⁶⁰ and involve countries with key shipping fleets and countries, which could supply either the technology for the transition (ships, engines, e-fuel production facilities, etc.) or have natural resources to produce and supply the global market with e-fuels. It could start with a small number of key countries but may be enhanced once the partnership has developed some global impact, fostering the interest of other countries in joining the partnership.

5.3.2.4 Overview

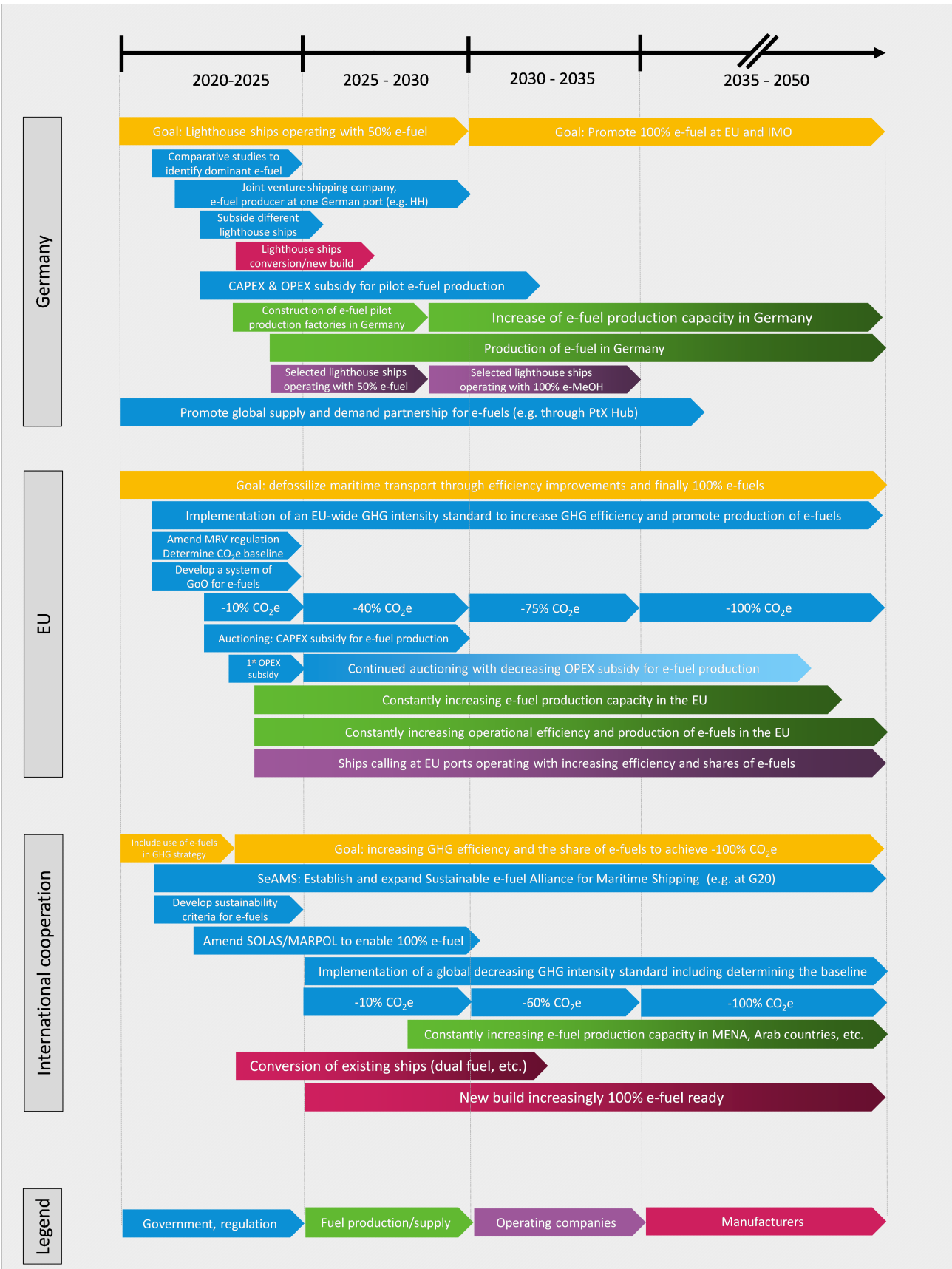
Figure 46 provides an overview of the suggested initiatives and activities discussed above and enhances the picture by some activities not explicitly mentioned above. It distinguishes between different types of stakeholders involved: governments which establish the legal regulation for ensuring the implementation of the necessary activities; fuel producers and suppliers which invest in production facilities and supply infrastructure and operate them; shipping companies which operate the ships; and manufacturers which provide new-build or adjust existing vehicles. Moreover, it suggests indicative targets, which eventually need to be discussed and agreed politically, and an indicative schedule of when the individual steps need to be initiated and when they should be completed to achieving the goals envisaged. The start of individual arrows indicates when an initiative or activity should be commenced with a view to being accomplished by the year when the arrow ends. The darkening colour indicates that efforts or the stringency of the intervention need to be intensified of time.

¹⁵⁸ One initiative in this direction is the 2020 established Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, which aims at "decarbonization of the maritime industry", <https://zerocarbonshipping.com/>.

¹⁵⁹ For more details on how the SeAMS would fit into an international strategy for the promotion of synthetic e-fuel in all hard-to-abate sectors, see UBA (2021).

¹⁶⁰ The Getting to Zero Coalition was founded in 2018, involves 140 companies and is supported by several governments and the IMO, <https://www.globalmaritimeforum.org/getting-to-zero-coalition/>.

Figure 46: Technology-open roadmap



Source: Authors' own compilation

The overview to some extent resembles the e-MeOH roadmap (Figure 45). This is mainly because it covers the same regulatory levels and stakeholders. However, there are significant differences, mainly in terms of the policies applied to achieve the defossilization of maritime shipping by 2050. While the e-MeOH roadmap focuses on the transition to post-fossil fuels through a blending mandate, the technology-open roadmap provides room for different e-fuel types and efficiency improvements at the same time. Even though the determination of which of the e-fuel(s) is or are more efficient than others may take longer, the regulatory decisions to provide the guidance and incentives to identify the most efficient option to promote their accelerated uptake need to be taken rather sooner than later. Again, the years up to 2025 are therefore decisive for achieving defossilization of maritime shipping by 2050. If appropriate policies are not "set on track" by then, at least at national and European level, it will be difficult to achieve that goal.

5.4 Comparison

In contrast to aviation, for which e-kerosene is seen by almost all stakeholders as the fuel of the future, a dominant e-fuel has not yet emerged for maritime shipping. On the contrary, several promising fuels are being considered, some of which are even to be used in different propulsion systems. All options have certain advantages and disadvantages, including readiness of the production technology, GHG reduction potential, costs, overall conversion efficiency, handling, safety, environmental risks, re-use of existing infrastructure, etc. E-methanol is technologically advanced and would require comparatively little changes of vehicle and supply infrastructure but is likely to be more expensive since its production requires non-fossil CO₂ as input. E-hydrogen and e-ammonia are carbon-free and are thus possible long-term favourites with their development depending on resolving not inconsiderable storage and onboard handling issues. In addition, the development of all e-fuels significantly depends on reductions in green hydrogen production costs. It is therefore currently impossible to predict which of these technological options is the most efficient.

The (neo-)classical approach in such situations is to promote research, development and deployment in a technology-open manner. The distributed swarm intelligence of researcher and entrepreneurs will – guided by market forces – identify the most efficient option, provided that the regulatory guard rails and targets to be achieved are clearly spelled out. In addition, other conditions such as fair competition without dominating market power of individual competitors and transparent information while protecting intellectual property need, among other aspects, to be ensured for identifying the most efficient technological option.

While ensuring such conditions at a national level is challenging but possible, it can hardly be ensured at a global level on which no overarching sovereign can take care of them, but countries have to agree to ensuring them in mutual consent. There are several examples of market forces not having provided the technologically most efficient option, the most prominent of which is the QWERTY keyboard design for typewriters (David 1986) and the VHS standard for video recorders (Cusumano et al. 1992). It can therefore certainly be questioned whether market forces alone can deliver the most efficient technology.

Despite this general question, the time span required to identify the most efficient solution is often ignored. This may not be a problem in the context of, for example, consumer good standards. However, in the context of GHG reduction technologies, the time span is one of the most important dimensions which needs to be considered, particularly if global infrastructures are affected.

The different e-fuel types require different infrastructures and handling protocols, both in ports and on the vessels. Storage and bunker infrastructure for ammonia, hydrogen and LNG are significantly different to existing infrastructure for fossil fuel and, in addition, cannot be converted easily from one e-fuel to another. At the same time, increasing effort is being put into identifying pathways such as dual fuel and hybrid engine technology that can enable flexibility to accommodate different future options as knowledge and experience develops.

Under a technology-open approach, more than one infrastructure needs to be developed in the pilot phase, to test the practical feasibility of the e-fuel. The approach may thus result in two situations:

- ▶ In the first case, one of the e-fuels or a small subset may after several years of road testing develop as clearly superior to the other options and emerge as the dominant e-fuel. The infrastructures for the other options will need to be written off as sunk cost. The amount of these sunk costs is likely to be lower the earlier the dominant e-fuel emerges and to be higher the more options initially compete to become the dominant e-fuel.
- ▶ In the second case, none of the options will emerge as a clearly dominating e-fuel. The number of e-fuels competing will decrease over time, but two or three fuels will remain, which turn out to perform best in reality. In this case, the potential cost reduction due to economies of scale will be much lower, as the capacity for scaling has to be shared by the two or three remaining e-fuels. The foregone cost reduction will, in turn, depend on the number of e-fuels that remain in the competition, which is expected to be higher the more e-fuel options that entered competition at the beginning.

Even if the technology-open approach would finally identify the most efficient e-fuel so that scaling up can focus on one technology, the scaling-up needs to be implemented much more steeply to arrive at 100% in 2050 because identifying the optimal e-fuel is likely to be more time-consuming than agreeing on a technology specific approach, with the result that scaling-up can only start later. Since GHG emissions are accumulating in the atmosphere, the technology-open approach may need to arrive even before 2050 with 100% e-fuel to be on par with the accumulated emissions under the technology-specific approach, which might have started scaling-up several years earlier.

However, a technology-specific approach has downsides as well, particularly if there are high risks that the technology faces fundamental challenges which would postpone or hinder scaling up. Deciding which of the two approaches is more appropriate for maritime shipping is thus not easy. Several aspects should be considered before answering this question:

- ▶ Infrastructure dependency: The more competing technologies require specific (global) infrastructures, the more a coordinated, technology-specific approach seems to be appropriate. An e-fuel that is produced with different technologies which, however, deliver the same product requires less specific transport, storage and bunkering infrastructure than two or more e-fuels with considerably different characteristics.¹⁶¹ With regard to identifying the most appropriate e-fuel for shipping, competition may thus do more harm than good because this decision has a much stronger impact on the required developments of global supply and storage infrastructures.

¹⁶¹ This can be illustrated by an example from the aviation sector: For the generation of e-kerosene there are basically two routes, the 'traditional' Fischer-Tropsch (FT) and the methanol route. Currently the FT route seems more advanced than the methanol route. However, there are technological challenges in the FT route such as the water-gas-shift reaction, which are not fully prepared for scaling up. Since both approaches produce the same product in the end, they can be fed into the same infrastructure. Pursuing a technology-open approach in promoting the generation of e-kerosene would thus not cause any significant sunk costs in infrastructure. It may even produce no sunk cost at all because both routes may be basically profitable though at different profit rates. For selecting the most efficient e-kerosene production route technological competition will promote later scaling up, also because there may be some learning spillovers between both routes.

- ▶ **Path dependency:** Are there certain bifurcations, which mean that changing to the other path would be almost impossible or extremely expensive? Since the bunker technologies for the different e-fuels under consideration for shipping are significantly different in terms of temperature, pressure and space required, this is certainly the case. This also speaks for choosing the preferred type of e-fuel early on.
- ▶ **Level of globalization:** Certain technology decisions depend on the preferences of local consumer or local endowments with resources including human capital and knowledge. In this case, competing technologies which deliver similar consumer products or services will be quite helpful because the competition helps to identify the undisclosed preferences taking into account the actual level of endowments. However, for technologies which are globally so connected and intertwined as maritime shipping, local preferences are rather a hindrance for the quick uptake required to achieve full defossilization of the shipping sector by 2050.
- ▶ **Efficiency versus efficacy:** The quasi mantra of neo-classical economics since Adam Smith's book on *The Wealth of Nations* (1776) is that the division of labour and competition at the level of individuals results in increasing wealth for all. Interestingly, there is little empirical evidence that market forces really deliver more long-term efficiency for entire nations in comparison to other governing approaches. However, while previous technological changes contributed to increasing the wealth of individuals, the technological change required for achieving global defossilization needs to be accomplished to prevent a drastic decline of global wealth due to global warming in a limited window of remaining time. Whether increasing the wealth of individuals is achieved this year or a decade later is not irrelevant but does not have such existential implications as not defossilizing the economy, so that tipping points are triggered which lead to irreversible climate dynamics. Against this background, it seems to be more important that technological developments effectively achieve the defossilization goals than that the technological transition is achieved with highest efficiency. This does not mean that efficiency is irrelevant. On the contrary, if two processes currently deliver the same output in a more climate-friendly way than existing technologies and one is even more climate-efficient than the other, the more efficient process should clearly be promoted. However, if one process currently delivered this output in a more climate-friendly way while the other was not yet available but may deliver the output in a more climate-friendly way at some point in the future, the one delivering the product right now should currently be clearly preferred over the one that may deliver in the future. In the context of climate mitigation, the focus on efficiency via market forces must currently be balanced with a strong focus on GHG reduction efficacy through long-term planning by governments.
- ▶ **Decision of other countries:** In the past, many technological path decisions depended on the decisions of certain frontrunner countries, not always because the technology was most developed but because governments have taken clearly-guided decisions, with the result that the technology was promoted in the country. California has often set environmental standards for cars (unleaded gasoline, catalysers, etc.), which were later taken over by other countries. More recently, China has established such a global standard by clearly promoting battery-electric cars of other propulsion systems for cars (IEA 2020a). Germany has also been a frontrunner in terms of the promotion of renewable energy through feed-in tariffs in 2000 (IRENA 2015), which has been adopted by many other countries since then. It is therefore advisable that developments in this policy field in other countries are monitored and a coordinated

decision among more proactive countries is potentially initiated rather than trusting in markets forces to identify the most efficient technological e-fuel option at some point in the future.

These aspects are partly overlapping and cannot be fully distinguished. However, they provide some justification of pursuing a technology-specific approach rather than a technology-open one: Most importantly, the limited time frame for transition towards post-fossil fuels, but also the infrastructure dependency of each e-fuel type and the global nature of maritime shipping suggest that it would be wiser to focus on one e-fuel early on rather than promoting the technological competition for further years.

But how should such a technology specific approach be designed? In principle this is illustrated in the e-MeOH roadmap (section 5.3.1). What would be the most appropriate e-fuel for such a technology specific approach? This study was not designed to identify the most appropriate e-fuel for a technology-specific approach. The selections of one e-fuel for elaborating two different roadmaps for maritime shipping took into account advantages and disadvantages of the considered e-fuels but also included deliberations on the extent to which the individual fuels were already promoted by certain stakeholders of the sector. The selection process was based on a heuristic approach, which consolidated the expert knowledge of the involved researchers (section 5.1.5). However, it was not based on comprehensive scenario-based approach which aims to quantify the advantages and disadvantages of individual e-fuels, including cost projections for e-fuels, vessels and infrastructure as well as global resource availability and infrastructure requirements. Before deciding on the most appropriate e-fuel type to be promoted, a coalition of countries willing to pursue a technology-specific roadmap should be forged.

A ‘Sustainable e-fuel Alliance for Maritime Shipping’ (SeAMS) may be such a coalition of the willing countries (section 5.3.2.3). It should be large enough to be considered as a frontrunner and members should be ready to openly consider pros and cons of individual e-fuels with a view to reaching a common agreement on one of these e-fuels as the one that should be jointly promoted. The potential core candidates of such a coalition would comprise some EU countries or the EU as whole, the USA and Canada plus some south Asian countries, such as China,¹⁶² Singapore or Indonesia, since this would cover one of the globally busiest trade routes and therefore traffic-significant enough to make some impact. The SeAMS may be rounded off by countries which are potential candidates for generating the e-fuel in the future. Potential candidates from the southern hemisphere are countries such Argentina, Australia, Brazil or Chile plus some Arab countries (Saudi Arabia, Qatar, etc.) or countries from the MENA region such as Morocco. Other willing countries may join the coalition at any time if they agree with the principles and the goals. However, starting with a smaller core group of countries may be more effective than aiming at enlarging the coalition quickly.

In addition to governments, this coalition should involve stakeholders from the shipping sector, including operators and manufacturers, and e-fuel suppliers and producers. It would be important to ensure that representatives of incumbent companies are sufficiently balanced with representatives from start-ups and newcomers. In addition, the coalition should involve research entities, customers of maritime shipping services and NGOs, to reflect all social perspectives in the coalition.

Once the core of the SeAMS has been forged, it should commission the above-mentioned scenario-based study for determining the most appropriate e-fuel for maritime shipping. Forging the coalitions, agreeing on terms of references for the study, conducting the study and finally agreeing on the most appropriate e-fuel will take time. However, the earlier this process can be accomplished, the quicker the transition to

¹⁶² The Maritime Executive, 14/07/2020, Comprehensive Study of Methanol as Marine Fuel Launching in China, <https://www.maritime-executive.com/article/comprehensive-study-of-methanol-as-marine-fuel-launching-in-china>.

post-fossil fuels can be triggered. The coalition should aim to accomplish this process as soon as possible, preferably by 2023 so that these assessments can still be considered in IMO discussions on the GHG reduction strategy to be adopted in that year. However, even if it achieved this goal only in 2025, it would be much quicker than the process which can be expected towards promoting post-fossil fuels under the IMO.¹⁶³

5.5 Conclusions

In summary, we can conclude that there is currently a challenging dilemma for policy makers. The transition towards defossilizing maritime transport should, on the one hand, be accomplished by 2050. However, there is no dominant e-fuel or a limited number of feasible e-fuels in sight. On the contrary, for certain options such as e-ammonia or e-hydrogen tests have just begun and it may take until 2025 to prove the practical feasibility as post-fossil fuel for trans ocean-going vessels.

Each of the more promising e-fuel options has considerable challenges and it is uncertain which of those can be addressed sooner than later:

- ▶ E-methanol is relatively easy to handle and store, would require retrofitting existing infrastructure and vehicles but would allow a continued use of existing technology. However, non-fossil CO₂, for example from DAC, is required for producing it; however, it is uncertain whether DAC will be available at scale and at competitive costs.
- ▶ E-ammonia does not require CO₂ but nitrogen, which can comparatively easy be sourced from ambient air. However, it is toxic and more difficult to handle and would thus require more fundamental changes in existing infrastructure and vehicles, which would also result in higher losses of capacity. Moreover, ship engines running on ammonia are not yet available.
- ▶ E-hydrogen is likely to be the cheapest option in the long term. However, it has similar challenges as e-ammonia in terms of infrastructure and vehicles and it may take even longer to solve the technical issues.
- ▶ E-diesel is likely to remain by far the most expensive e-fuel in terms of production costs since it involves additional transformation steps, which reduce the overall WTT efficiency. However, if synergies with other sectors – particularly aviation – could be mobilized, the cost difference might be further reduced.

While developing two or several e-fuel options in parallel may be expensive, either due to sunk costs or due to economies of scale that have to be foregone, it could be considered whether they could be developed in a consecutive manner. E-hydrogen might have the best long-term perspectives but would be too late available in the necessary amounts. E-methanol or e-ammonia might be available earlier, meaning that they can be pursued as a limited 'bridge' from fossil shipping fuels to e-hydrogen.

¹⁶³ Forbes, 21/10/2020, Sort Your Ships Out: "The European Union has already expressed its lack of confidence in the IMO and are moving forward with a proposal to include shipping in its carbon trading markets, as well as introducing a higher set of emission standards, called Emission Control Areas. This raises the possibility that other regions may do the same, given the weak leadership of the IMO on climate and environmental issues, and this could eventually lead to the breakup of the IMO in favor of more responsive, regional shipping regulatory organizations." https://www.forbes.com/sites/nishandegnarain/2020/10/21/sort-your-ships-out-protestors-denounce-un-shipping-agency-over-climate-failure/?fbclid=IwAR2jWCD32JambGxBnJpaCZ_ZSjw3qBvspWTak4DUb1LMN45VM61diiAvTtc#33b3d5d64d68.

Any decision to accelerate the transition to post-fossil fuels in maritime transport is, obviously, facing stronger uncertainties than for other sectors. Aware of these uncertainties, the following activities seem nevertheless sensible:

- ▶ At EU level, a technology-open e-fuel mandate based on GoO should be implemented as soon as possible for a limited period, e.g. up to 2030. The main purpose of this mandate is to provide incentives for pilot projects including vessels, bunkering infrastructure and e-fuel production to prove their practical feasibility and with a view to identifying one or a limited number of dominant e-fuels by 2030, at the latest. In addition, this approach would already establish the administration required to promote the uptake of the dominant fuel(s) after that technology-open period. E-diesel and e-LNG are likely to be available earlier than other shipping e-fuels. To ensure that other e-fuels are also employed for proving their practical feasibility, their pilot projects need to be subsidized.
- ▶ At national level, this identification process should be supported through lighthouse projects which allow 'learning by doing' and illustrate the practical feasibility of e-fuels.
- ▶ At multilateral level, the above-mentioned SeAMS to coordinate activities for promoting the increased uptake of e-fuels in maritime shipping should be initiated. One of the first joint efforts of this alliance should be conducting a comparative scenario analysis of the most promising e-fuel options for shipping, which aims to identify the dominant fuel(s) for shipping as soon as possible.
- ▶ On the one hand, e-fuel generation involves several transformation, storage and transportation processes. As a first step, all e-fuels require the generation of e-hydrogen from renewable energies. Promoting the expansion of electrolyser and renewable electricity generation capacities can thus be considered a no-regret strategy for the promotion of any e-fuel for maritime transport. Fortunately, many countries have already implemented policies for the promotion of renewable electricity since many years and more recently also developed strategies for the generation of e-hydrogen. However, given the enormous amount of capacity required to accomplish the transition, such strategies need to be strengthened continuously.
- ▶ On the other hand, e-fuels potentially to be used in maritime transport may also be used in other sectors either as a fuel or as an input for industrial production processes: e-hydrogen for steel production or for heavy road transport and e-ammonia or e-methanol as in inputs for products of the chemical industry. The promotion of these e-fuels may thus mobilize synergies between maritime shipping and these sectors, since they need to be decarbonized as well. However, these synergies may turn into conflicts if the supply of these e-fuels does not keep pace with aggregated demand from all sectors.

For the transition of maritime transport towards post-fossil fuels, the main goal for the next period is to limit the number of e-fuels applied in this sector. Unless such a dominant fuel or fuels is or are supported by a critical mass of countries, it will hardly be possible to trigger the economies of scale dynamics required to accomplish the transition.

These recommendations might be perceived as contradicting the previous pledge for a focusing on the promotion of one e-fuel rather than waiting until market dynamics crowd out less competitive fuels. However, this requires that the selected e-fuel is promoted by a critical mass of countries and stakeholders. During the phase, which is required to join these forces and agree on the e-fuel of the future, market dynamics may contribute to further identify technological and economic challenges of the individual e-fuel options.

Even though the identification process may situate maritime as a latecomer in comparison to other sectors, the sector may profit from development in processes required the production of the dominant e-fuel(s) achieved already in other sectors.

6 Conclusions

With the adoption of the Paris Agreement, Parties agreed to reduce greenhouse gas emissions so that the global temperature increase remains well below 2°C and, if possible, below 1.5°C compared to pre-industrial levels. Parties agreed to balance anthropogenic GHG emissions and sinks with a view to achieving climate neutrality as soon as possible in the second half of this century. Since emissions from aviation and maritime transport are clearly anthropogenic, they fall under the objectives of the Paris Agreement even without being explicitly mentioned. Achieving climate neutrality in both sectors will not be possible without climate-neutral alternatives to the fossil fuels used today.

Climate neutrality of air and sea transport can thus only succeed through the use of post-fossil fuels, which are produced from renewable electricity in such a way that they do not result in any or very low GHG emission during their entire lifecycle from well to wing/wake. In this study we developed political options (roadmaps) for a climate-neutral energy supply for aviation and maritime transport based on synthetic electro-fuels (e-fuels) produced from renewable electricity by 2050. In addition, policy instruments and technological measures are proposed which aim to bring e-fuels to market maturity.

Truly sustainably-produced biofuels can certainly contribute to the reduction of GHG emissions in aviation and maritime transport. However, given the limited availability and the competing demand from other sectors for these fuels and in accordance with the terms of references for this study, we have focused on e-fuels and considered biofuels only if they directly interfere with e-fuels (conflicts/synergies).

Future trends and scenarios

As a basis for these roadmaps, we assessed the amounts of post-fossil fuels which will be required to defossilize both sectors. In 2020, aviation and maritime shipping consumed approx. 27 EJ overall. Depending on which projections materialize, the combined demand of both sectors could grow by 45% (low scenario) or more than double until 2050 (high scenario). The corresponding CO₂ emissions of aviation and shipping accounted for approx. 6% of global CO₂ emissions from fuel combustion in 2018. Aviation and shipping emissions projected for 2050 would amount to 8.5 to 12.6% of the global CO₂ emissions for 2018.

Based on these projections, we estimated the amount of renewable electricity required to produce the e-fuels for these demands. In 2018, the total global renewable electricity generation amounted to 6.7 PWh. Currently, each of the sectors would require the total global renewable electricity generation if their energy demand were to be supplied by post-fossil e-fuels only. Assuming the average growth rates for wind and photovoltaics of the last 5 years, all additional renewable capacity added in the next 10 years would be required to supply the projected energy demand of both sectors with e-fuels in 2050.

Assuming, for example, a blending quota of 2% e-fuels in shipping and aviation at the EU level in 2030, 67 TWh renewable electricity would be required to generate e-kerosene while 36 TWh would be needed to produce the e-fuels for the shipping sector. The equivalent figures for Germany amount to 12 TWh and 2 TWh, respectively – independently of what e-fuel(s) are ultimately used in the shipping sector.

Political fields of action

Research has revealed that limited availability and high costs compared to conventional fossil fuels are the main barriers to the use of synthetic fuels in the air transport sector, while technological and certification issues seem to be of lower relevance.

In the aviation sector, different types of policies to support the use of e-fuels could be applied; these include mandatory and gradually increasing blending quotas, green certificates or subsidies similar to feed-in tariffs for renewable energy. All these policies would avoid a costly duplication of infrastructures in fuel distribution. It seems more efficient to apply policies at the fuel provision rather than at the airline level to reduce transaction costs and the risk of a delayed implementation caused by lobbying.

In the maritime shipping sector, as in the aviation sector, currently no e-fuels are used. Existing environmental policy incentives are by no means sufficient to stimulate the use and the supply of these fuels. However, for maritime transport there is, in contrast to the aviation sector, a whole range of potential e-fuel options under discussion.

E-diesel seems to be an obvious choice since it is fully compatible with the current system. However, e-diesel is likely to be the most expensive of the potential options to produce and it would not be the obvious choice when it comes to fuel cell application.

Various non-diesel fuel options are being discussed for maritime shipping since the sector is looking for alternative fuels due to stricter air pollution regulations and because fuel cells are regarded as a potential future alternative for the internal combustion engine. These fuel options are, as fossil variants, developed to very different degrees for their use in maritime shipping. It is not currently clear which of the fuel options will prevail. This will highly depend on the price of these fuels and whether some options prove to be technically superior to others. Moreover, the optimal solution might also vary between ship types and their activities.

Policies and actions to eliminate specific barriers to the supply and use of post-fossil fuels in shipping could therefore be of a more generic nature. Or, since the uncertainty itself can be a major barrier to the uptake and supply of post-fossil fuels in maritime shipping, policies and actions could be aimed at reducing the uncertainty by either quickly excluding comparatively inferior options and/or by stimulating the development of flexible options, both for ships and for fuel suppliers.

Post-fossil energy supply options

In principle, it is possible to produce e-fuels in such a way that facilitates the complete transition to post-fossil energy supply in aviation and maritime transport. In addition to using additional renewable electricity for producing them, the CO₂ required for producing hydrocarbons such as e-methanol or e-diesel needs to come from non-fossil sources, too. To ensure both, the development of technologies such as direct air capture (DAC) need to be accelerated while the upstream emissions of renewable electricity generation must go down to zero in the long term.

During the transition of the global energy systems, fossil sources still contribute to electricity generation. The emerging demand for CO₂ as a feedstock for fuel production must not prevent the reduction of CO₂ emissions from industrial point sources. Stringent sustainability and climate regulations covering the entire lifecycle of e-fuels are thus needed to ensure that the use of e-fuels during the transition phase contributes to absolute GHG reduction.

Among the different e-fuels, e-hydrogen and e-ammonia have the highest well-to-tank conversion efficiency. E-methanol, e-LNG and e-DME have higher conversion losses but are more efficient in production than e-kerosene or e-diesel. Since efficiency has a direct impact on the electricity demand for e-fuel production, a similar ranking results for the comparison of the production costs and land used for e-fuel production. From a purely fuel production perspective, ammonia and hydrogen therefore have advantages over other e-fuels but face challenges in terms of risk, handling or infrastructure.

E-fuels will not be available in relevant quantities soon. Scaling up and automation of electrolysers production and the further development of certain processes such as the reverse water-gas-shift-reaction in the e-fuel production process chain are technological challenges. While e-hydrogen and e-ammonia could be produced on an industrial scale relatively soon, the commissioning of the first large-scale industrial plants for other carbon-based e-fuels may take longer.

Today the production costs of e-fuels are significantly higher than those of fossil fuels and, even if this spread narrows, the costs of e-fuels will remain higher in the longer term. Policy instruments which promote their use in aviation and maritime transport are therefore needed. The extent to which the costs of e-

fuels decline depends above all on the costs of renewable electricity, the investment costs for electrolyzers and the costs of financing the investments. Long-term projections of future production costs differ significantly, making it very difficult to draw conclusions here. However, countries or regions with low generation costs for renewable electricity, sufficient availability of land and water and reliable political governance conditions can provide e-fuels at lower costs. Accordingly, imports from such regions to Germany and the EU are likely to achieve a considerable scale in the longer term.

Roadmaps for achieving zero emissions

The roadmaps illustrate pathways that enable the transition of global aviation and maritime transport from fossil to sustainable post-fossil fuels. Since e-kerosene is very likely to be the dominant e-fuel for long-haul aviation, we have provided only one roadmap for this sector. For maritime transport, the situation is more complex. Several e-fuel are candidates to become the dominant fuel in the future and different fuels might prevail in parallel. All candidates have distinct advantages and disadvantages without one option being clearly the best. We therefore described two roadmaps: one which focuses on the promotion of one of the potential candidates and one which pursues a technology-open approach.

All roadmaps include sections on actions to be initiated and implemented in Germany and mainly focus on demonstration of the technological feasibility of the transition based on lighthouse or pilot projects. Since the promotion of the accelerated uptake of these e-fuels can hardly be done by one country but requires a larger market, our assessment of activities to be initiated and implemented at European level focuses on policy instruments which could trigger and sustain the transition towards post-fossil fuels. Ultimately the transition can only be achieved if e-fuels are used and supplied globally. Quite naturally ICAO and IMO could play a pivotal role in this context. However, experience with greenhouse gas reduction policies in both organizations suggests that consensus-based decision making could take more time than is available to complete the transition by 2050 as assumed in this study. At global level we therefore look at initiatives of smaller groups of countries which could operate as frontrunners to promote the use of e-fuels while the focus under ICAO and IMO should be put on expanding the fuel standards for vehicles and infrastructure to ensure that e-fuels can be used.

- ▶ **Germany:** For aviation, we suggest establishing Leipzig as a flagship airport for e-kerosene and describe how 50% and 100% e-kerosene could be provided by 2030 and 2035, respectively. Under the e-methanol roadmap for maritime transport, we suggest initiating and subsidizing a joint venture of shipping companies, fuel producers and a German port (e.g. Hamburg) to both enable further ships for the use of e-methanol and to construct facilities for the production of e-methanol. Under a technology-open roadmap, a similar joint venture would be initiated, however, which focuses on identifying the most promising e-fuel for deep sea shipping rather than on scaling up production and use of a certain e-fuel.
- ▶ **European Union:** To accelerate the uptake of e-kerosene at EU level, we assess a physical drop-in mandate (fuel standard), discuss advantages and disadvantages of the instrument and estimate the short-term price impact on flight tickets. As for aviation, a blending mandate for maritime transport with constantly increasing shares of e-methanol should be implemented. However, since physical drop-in to fossil fuels such as HFO or VLSFO may be feasible only up to limited shares, the mandate might need to be implemented as a book and claim system based on guarantee of origin certificates. Under the technology-open roadmap, we also suggest that a fuel mandate should be established. However, to enable the use of different e-fuels with the mandate, its monitoring needs to be based on the well-to-wake GHG reduction of each fuel rather than on physical units of the fuel. Similar to the fuel-specific approach, a system of reduction certificates that are tradable among the covered entities would need to be designed and established for implementing this mandate.

- **International cooperation:** Under ICAO, Germany and EU Member States should concentrate on the further development of the fuel standards (SARPs) to ensure that e-kerosene can be used in larger quantities as soon as possible. At the same time, a Sustainable e-Kerosene Alliance (SeKA) should be pursued as a potential frontrunner for promoting the use of e-kerosene. At IMO, priority should be given to amending SOLAS and MARPOL so that 100% e-fuels can be used as soon as possible. Moreover, Germany should, along with other interested countries, foster the establishment of a Sustainable e-fuel Alliance for Maritime Shipping (SeAMS) with the aim of identifying and agreeing upon, sooner rather than later, the most promising e-fuels for driving the transition to post-fossil maritime shipping. In addition, Germany and the EU should initiate a Global Supply and Demand Partnership (GSDP) with like-minded e-fuel supply and demand countries with a view to facilitating and accelerating the uptake of e-fuels in both aviation and maritime transport.

In contrast to aviation, where e-kerosene is seen by almost all stakeholders as the e-fuel of the future, one e-fuel has not emerged as the dominant fuel for the future for the maritime shipping to date. The comparison of the shipping roadmaps reveals that a technology-open approach might deliver the most cost-efficient e-fuel(s) but could involve a further delay of GHG reductions and higher costs overall due to sunk cost of investments in those e-fuels which are eliminated in the competition and due to small economies of scale if more than one e-fuel emerges as the dominant fuel(s). Deciding which of the two approaches is more appropriate is thus not clear-cut. However, for sectors which are as globally connected and intertwined as international transport, local preferences are rather a hindrance for the accelerated uptake of e-fuel required to achieve full defossilization by 2050. The limited time span that remains for the transition towards post-fossil fuels, but also the infrastructure dependency of each e-fuel type and the global nature of international transport therefore suggest that it would be wiser to focus on one e-fuel early on rather than promoting technological competition for further years.

In summary, we can conclude that there is currently a challenging dilemma for policy makers. On the one hand, the transition towards defossilizing international transport should be accomplished by 2050, requiring that the right decisions are made sooner rather than later. Particularly for shipping, on the other hand, there is no dominant e-fuel or a limited number of feasible e-fuels in sight. For the transition towards post-fossil fuels, the main goal for the years ahead is therefore to limit the number of e-fuels pursued. Unless a dominant fuel or fuels are supported by a critical mass of countries, it will hardly be possible to trigger the economies-of-scale dynamics required to accomplish the transition.

Recommendations

Mitigating climate change and achieving the global temperature goals agreed in the Paris Agreement requires GHG reduction efforts in all sectors, including aviation and maritime transport. In addition to significantly increasing technological and operational efficiency and reducing demand for these transport services through modal shift or more local production and consumption, the substitution of fossil fuels by sustainably generated e-fuels plays a pivotal role in achieving this goal. However, since their technology has not matured yet with costs that are currently higher than fossil fuels by a factor of 3 to 4, triggering and implementing the transition to 100% e-fuels is a complex and challenging task.

In this study, we developed and assessed roadmaps for achieving defossilization of aviation and maritime transport through the transition to sustainably generated post-fossil e-fuels. The roadmaps involve activities at different regulatory levels (Germany, EU, International) and by differently affected stakeholders (operators, fuel producers/suppliers, manufacturers). Moreover, we analyzed the suitability of policy instruments for achieving this goal.

Given the complexity, it should be noted that the three roadmaps described are only some of the multitude of potential roadmaps in practice. Every activity outlined could certainly be varied, thereby changing the

composition of the roadmap. However, despite this limitation, the roadmaps allow interlinkages to be identified between the activities of different actors at different regulatory levels.

In terms of e-fuel supply, there are significant differences between aviation and maritime transport: While e-kerosene is widely accepted as future fuel for aviation, such a dominant fuel has not yet emerged for maritime transport. Against this background, our main recommendations are:

- ▶ Coordination of policy initiatives at global level would be most effective to achieve defossilization of both sectors. However, achieving sufficiently ambitious agreements at IMO and ICAO would likely take more time than is available to achieve the temperature goals of the Paris Agreement.
- ▶ Forerunner activities at national (Germany) or regional (Europe) level are likely to accelerate the progress at international level.
- ▶ Implementing ‘lighthouse projects’ which demonstrate the practical feasibility of fully deploying e-fuels can trigger the transition on a larger level.
- ▶ For aviation, a drop-in fuel mandate at European level is a viable option which would trigger and ensure the increased uptake of e-kerosene in one of the major global aviation markets. However, possible competitive impacts of such a mandate have to be taken into account.
- ▶ For shipping, it is too early to identify the dominant e-fuel(s). The main goal of a transition strategy should therefore be to reduce the number of potential options, preferably to one dominant e-fuel. At EU level, this process can be supported by a technology-open e-fuel mandate, which should be converted as soon as possible into a specific mandate for one e-fuel.
- ▶ Hydrogen is a no-regret option for all e-fuels and synergies might emerge in the upscaling of e-fuel production for aviation and shipping, for instance if intermediate or by-products of e-kerosene production would also be used for generating e-fuels for the shipping sector.
- ▶ To trigger technological learning in the production of e-fuels, the deployment of these fuels will need to be subsidized early on. This will facilitate the scaling-up of generation capacities and reduce production costs. Since all potential e-fuels for aviation and maritime transport are also used as fuels or raw material in other sectors, their defossilization will be required anyway, making the fostering of such a transition a no regret policy. Hence, the defossilization concepts of other sectors should ideally be interlinked with the aviation and shipping roadmaps in order to generate an optimized general concept. This could apportion the costs of conversion to all sectors as they face the challenge of defossilization in parallel.
- ▶ As long as policies to increase the uptake of e-fuels are not applied at global level, subsidies for e-fuel production or consumption will be required to ensure a more level playing field with fossil fuels used elsewhere.
- ▶ Progress on mitigation policies at international level is usually slow. Efforts to establish policies for accelerating the uptake of e-fuels under ICAO and IMO including e-fuel mandates and market-based policies, therefore, need to be intensified immediately. In addition, processes need to be initiated to ensure that global fuel safety standards are further developed for enabling the use of e-fuels.

- ▶ A strategic partnership between a critical mass of key countries and actors should be initiated. Such an initiative could start with a small number of countries with a significant market share in aviation or shipping, which are likely to agree on a common strategy, potentially accompanied by future e-fuel supply countries. Other countries could join the initiative later, provided that they agree with the principles and goals of the initiative. For shipping, the main goal of such an initiative would be to agree on dominant e-fuels and preferably only one as soon as possible and no later than 2025.

Our assessment also shows that the first steps must be taken immediately at all regulatory levels. National governments need to ensure that the policies which provide incentives and guidance to investors and operators are adopted as soon as possible and actively support policy initiatives at European and international level. The years up to 2025 are decisive for achieving defossilization of aviation and maritime transport. If appropriate policies are not set in place by then, at least at national and European level, it will be difficult to achieve the goal of defossilization by 2050.

7 References

- 50 Hertz; Amprion; TenneT; TransnetBW (2019). Netzentwicklungsplan Strom 2030, Version 2019. Zweiter Entwurf. 50 Hertz; Amprion; TenneT; TransnetBW, 15 Apr 2019.
- ABF - A Barrel Full (2014). European Refineries. A Barrel Full, 2014. Online available at <http://abarrelfull.wikidot.com/european-refineries>, last accessed on 4 Mar 2019.
- Air Liquide (2019): Gas Encyclopedia. Online available at <https://encyclopedia.airliquide.com/>.
- Airbus (2019). Global Market Forecast, Cities, Airports & Aircraft 2019-2038. Airbus, 2019. Online available at <https://www.airbus.com/content/dam/corporate-topics/strategy/global-market-forecast/GMF-2019-2038-Airbus-Commercial-Aircraft-book.pdf>, last accessed on 31 Jan 2021.
- Alfa Laval; Hafnia; Haldor Topsoe; Vestas; Siemens Gamesa (2020): Ammonfuel - an industrial view of ammonia as a marine fuel, 2020. Online available at <https://hafniabw.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf>, last accessed on 16 Feb 2021.
- ASTM International (2019a): ASTM D1655 - 18b, Standard Specification for Aviation Turbine Fuels, 2019a. Online available at ASTM D1655 - 18b, Standard Specification for Aviation Turbine Fuels.
- ASTM International (2019b): Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, 2019b. Online available at <https://www.astm.org/Standards/D7566.htm>.
- ATAG - Air Transport Action Group (2020a). Tracking Aviation Efficiency, How is the aviation sector performing in its drive to improve fuel efficiency, in line with its short-term goal?. Air Transport Action Group, 2020. Online available at https://aviationbenefits.org/media/167219/fact-sheet_3_tracking-aviation-efficiency_3.pdf, last accessed on 6 Apr 2021.
- ATAG - Air Transport Action Group (2020b). Waypoint 2050, Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency. Air Transport Action Group, 2020. Online available at https://aviationbenefits.org/media/167187/w2050_full.pdf, last accessed on 6 Apr 2021.
- Austin (2017): In Depth: Methanol Is Ready for Use as Marine Fuel, 2017. Online available at <https://worldmaritimeneews.com/archives/249601/interview-methanol-is-ready-for-use-as-marine-fuel/>.
- Aviation Jet Fuel Information (2019): Aviation Turbine Fuel (Jet Fuel), 2019. Online available at <http://www.csgnetwork.com/jet-fuel.html>.
- AVW - Agora Verkehrswende; AEW - Agora Energiewende (2018). Die zukünftigen Kosten strombasierter synthetischer Brennstoffe, Schlussfolgerungen aus Sicht von Agora Verkehrswende und Agora Energiewende. Agora Verkehrswende; Agora Energiewende. Berlin, 2018.
- AVW - Agora Verkehrswende; AEW - Agora Energiewende; FE - frontier economics (2018). Die zukünftigen Kosten strombasierter synthetischer Brennstoffe. Agora Verkehrswende; Agora Energiewende; frontier economics. Berlin, 2018. Online available at https://www.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynCost-Studie_WEB.pdf, last accessed on 16 May 2021.
- AZoCleantech (2018): Using Dimethyl Ether as Fuel for heat, Transportation and Electricity, 2018. Online available at <https://www.azocleantech.com/article.aspx?ArticleID=713>.
- Baumol, W. J. (2002): The free-market innovation machine: Analyzing the growth miracle of capitalism: Princeton university press.
- BCG - The Boston Consulting Group; Prognos (2018): Gerbert, P.; Herhold, P.; Buchardt, J.; Schönberger, S.; Rechenmacher, F.; Krichner, A.; Kemmler, A.; Wünsch, M. Klimapfade für Deutschland. The Boston Consulting Group; Prognos. Berlin, Basel, Hamburg, München, 2018.
- BEIS - Departement for Business, Energy and Industrial Strategy (ed.) (2018): Derwent, R. G. Hydrogen for heating: atmospheric impacts, A literature review (BEIS Research Paper Number 2018: no. 21), 2018. Online available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760538/Hydrogen_atmospheric_impact_report.pdf.
- Berti, A. (2018): Renewable jet fuels: how to handle the heavy costs, 2018. Online available at <https://www.airport-technology.com/features/renewable-jet-fuels-how-to-handle-the-heavy-costs/>.

- BMW (2018): EEG in Zahlen, Vergütung, Differenzkosten und EEG-Umlage 2000 bis 2019, 2018. Online available at <https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/eeg-in-zahlen-pdf.pdf%3Fblob%3DpublicationFile>, last accessed on 4 Mar 2019.
- Boundy, B.; Diegel, S. W.; Wright, L.; Davis, S. C. (2011): Biomass Energy Data Handbook, Section: Appendix A Lower and Higher Heating Values of Gas, Liquid and Solid Fuels, 2011, last accessed on 1 Feb 2021.
- BP - British Petroleum (2019): Energy Outlook, British Petroleum. Online available at <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf>, last accessed on 8 May 2020.
- Brown, T. (2018): Pilot project: an ammonia tanker fueled by its own cargo, 2018. Online available at <http://www.ammoniaenergy.org/pilot-project-an-ammonia-tanker-fueled-by-its-own-cargo/>.
- Brown, T. (2019): MAN Energy Solutions: an ammonia engine for the maritime sector, 2019. Online available at <http://www.ammoniaenergy.org/man-energy-solutions-an-ammonia-engine-for-the-maritime-sector/>.
- Brynnolf, S.; Taljegard, M.; Grahn, M.; Hansson, J. (2017): Electrofuels for the transport sector: A review of production costs. Göteborg, 2017.
- Bundesregierung (2020): Die Nationale Wasserstoffstrategie, Schlüsselement der Energiewende. Online available at <https://www.bmbf.de/files/die-nationale-wasserstoffstrategie.pdf>, last accessed on 26 Jun 2020.
- BW LPG (2021). Sustainability Report. BW LPG, 2021. Online available at <https://www.bwlp.com/docs/default-source/financial-reports/4-bw-lpg-sustainability-report-2020.pdf>, last accessed on 9 Apr 2021.
- Carbon Recycling International (2013): First Commercial Plant, Carbon Recycling International. Online available at https://web.archive.org/web/20130703233732/http://cri.is/index.php?option=com_content&view=article&id=14&Itemid=8&lang=en, last accessed on 16 Apr 2019.
- Cardona, C. A.; Sanchez, O. J.; Gutierrez, L. F. (2010): Process Synthesis for Fuel Ethanol Production: CRC Press. Online available at https://books.google.nl/books?id=5RTOBQAAQBAJ&pg=PA7&lpg=PA7&dq=0.794+at+15%C2%B0C+density+ethanol&source=bl&ots=-bLJ7ZYg0Y&sig=ACfU3U2svWoa0jeNIA_bHolqVFyGXavXpw&hl=nl&sa=X&ved=2ahUKewiyvYqrmrma-hUE3KQKHZ3uD-sQ6AEwD3oECA0QAQ#v=onepage&q=0.794%20at%2015%C2%B0C%20density%20ethanol&f=true.
- CE Delft (2017): Faber, J.; Smeets, E. M. Overheidsmaatregelen biokerosine: mogelijkheden om de vraag naar biokerosine te stimuleren en de effecten op de luchtvaart en de economie. CE Delft, 2017. Online available at <https://www.ce.nl/publicaties/download/2348>.
- CE Delft; DLR; Fearnley Consultants; Narture Associates; MMU; MARINTEK; Northon Rose; Oeko-Institut; Öko-Recherche (2009): Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport. In collaboration with Faber, J.; Markowska, A.; Nelissen, D.; Davidson, M.; Eyring, V. et al., 2009. Online available at <https://www.cedelft.eu/en/publications/download/825>, last accessed on 1 Feb 2021.
- CE Delft; Lee, D. S. (2017): Reduction of GHG emissions from ships: Update of maritime greenhouse gas emissions projections – Full report, Submitted by BIMCO (No. MEPC 71/INF.34). Online available at <https://www.cedelft.eu/en/publications/download/2445>, last updated on 2017, last accessed on 19 Oct 2018.
- CE Delft; Lee, D. S. (2019): Update of maritime greenhouse gas emission projections, 2019. Online available at <https://www.cedelft.eu/en/publications/download/2698>, last accessed on 31 Jan 2021.
- CE Delft; UMAS - University Maritime Advisory Services; LR - Lloyd's Register; Oeko-Institut (2019). Study on methods and considerations for the determination of greenhouse gas emission reduction targets for international shipping. CE Delft; University Maritime Advisory Services; Lloyd's Register; Oeko-Institut, 2019. Online available at <https://www.cedelft.eu/en/publications/download/2735>.
- Cerology (2018): Malins, C. What role for electromethane and electroammonia technologies in European transport's low carbon future?. Cerology, 2018. Online available at https://www.transportenvironment.org/sites/te/files/publications/2018_06_Cerology_What-role-electromethane-and-electroammonia_June2018.pdf.

- Chemistry (2020): Alkanes- Saturated Hydrocarbons, Chemistry. Online available at [https://batch.libretexts.org/print/url=https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_A_Molecular_Approach_\(Tro\)/21%3A_Organic_Chemistry/21.04%3A_Alkanes- Saturated_Hydrocarbons.pdf](https://batch.libretexts.org/print/url=https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_A_Molecular_Approach_(Tro)/21%3A_Organic_Chemistry/21.04%3A_Alkanes- Saturated_Hydrocarbons.pdf), last updated on 28 Mar 2021, last accessed on 9 Apr 2021.
- C-job (2018): Ammonia as ship's fuel: C-Job's future-proof way of thinking, 2018. Online available at <https://c-job.com/ammonia-as-ships-fuel-c-jobs-future-proof-way-of-thinking/>.
- Clariant (2019): Welcome at Clariant in Romania, Bine ați venit la Clariant în România. Commercial-Scale Flagship Plant for the Production of Cellulosic Ethanol, Clariant. Online available at <https://www.clariant.com/en/Company/Contacts-and-Locations/Key-Sites/Romania>, last accessed on 15 Dec 2019.
- ClassNK (2018). Alternative Fuels and Energy Efficiency for the Shipping Industry, An overview of LNG, LPG and Methanol Fuelled Ships. ClassNK, 2018. Online available at <https://gmn.imo.org/wp-content/uploads/2018/01/AnnexV-2-5-Alternative-Fuels-and-Energy-Efficiency.pdf>.
- Commercial Aviation Alternative Fuels Initiative (2013): ASTM D4054 Users' Guide, 2013. Online available at http://www.caafi.org/resources/pdf/d4054_users_guide_v6_2.pdf.
- CRI - Carbon Recycling International (2020): Projects: Emissions-to-Liquids Technology, Carbon Recycling International. Online available at <https://www.carbonrecycling.is/projects#projects-mefco2>, last updated on 25 Dec 2020, last accessed on 25 Dec 2020.
- Crop Energies GmbH (2019): Zeitz, Deutschland: Die effizienteste Bioethanolanlage Europas, Crop Energies GmbH. Online available at <http://www.cropenergies.com/de/Unternehmen/Standorte/Zeitz/>, last accessed on 15 Dec 2019.
- CTH - Chalmers University of Technology; IVL - Swedish Environmental Research Institute (2017): Brynolf, S.; Taljegard, M.; Grahn, M.; Hansson, J. Electrofuels for the transport sector: A review of production costs. Chalmers University of Technology; Swedish Environmental Research Institute. Göteborg, 2017.
- Cusumano, M. A.; Mylonadis, Y.; Rosenbloom, R. S. (1992): Strategic Maneuvering and Mass-Market Dynamics: The Triumph of VHS over Beta. In: *Business History Review* 66 (1), pp. 51–94. Online available at https://EconPapers.repec.org/RePEc:cup:buhirw:v:66:y:1992:i:01:p:51-94_06.
- CUT - Chalmers University of Technology (2014): Ali Brohi, E. Ammonia as fuel for internal combustion engines?, An evaluation of the feasibility of using nitrogen-based fuels in ICE. Chalmers University of Technology. Gothenburg, 2014. Online available at <http://publications.lib.chalmers.se/records/fulltext/207145/207145.pdf>, last accessed on 4 Mar 2019.
- David, P. A. (1986): Understanding the economics of QWERTY: The necessity of history. In: *Economic History and the modern economics*, pp. 30–49.
- DBFZ - Deutsches Biomasseforschungszentrum (2019): Bullerdiek, N.; Buse, J.; Dögnitz, N.; Feige, A.; Halling, A.-M.; Hauschild, S.; Hawighorst, P.; Kaltschmitt, M. Einsatz von Multiblend JET A-1 in der Praxis, Zusammenfassung der Ergebnisse aus dem Modellvorhaben der Mobilitäts- und Kraftstoffstrategie. Deutsches Biomasseforschungszentrum, 2019. Online available at https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/demo-spk-endbericht.pdf?__blob=publicationFile, last accessed on 23 Oct 2020.
- DBFZ - Deutsches Biomasseforschungszentrum; dena - Deutsche Energie-Agentur; IWES - Fraunhofer Institut für Windenergie und Energiesystemtechnik (2017): Daniel-Gromke, J.; Rensberg, N.; Denysenko, V.; Trommler, M.; Reinholz, T.; Völler, K.; Beil, M.; Beyrich, W. Anlagenbestand Biogas und Biomethan – Biogaserzeugung und -nutzung in Deutschland (DBFZ-Report, 30). Deutsches Biomasseforschungszentrum; Deutsche Energie-Agentur; Fraunhofer Institut für Windenergie und Energiesystemtechnik, 2017.
- DECC - Department of Energy & Climate Change (2011). Planning our electric future, A white paper for secure, affordable and low-carbon electricity. Department of Energy & Climate Change, 2011. Online available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48129/2176-emr-white-paper.pdf, last accessed on 31 Mar 2021.
- DECHEMA - Gesellschaft für Chemische Technik und Biotechnologie e.V. (ed.) (2019). Optionen für ein nachhaltiges Energiesystem mit Power-to-X Technologien, Nachhaltigkeitseffekte - Potenziale Entwicklungsmöglichkeiten. 2. Roadmap des Kopernikus-Projektes „Power-to-X“: Flexible Nutzung erneuerbarer Ressourcen (P2X), 2019.

- DEHSt - Deutsche Emissionshandelsstelle im Umweltbundesamt (2020): Versteigerung. Online available at <https://www.dehst.de/DE/Europaeischer-Emissionshandel/Emissionshandel-verstehen/Versteigerung/versteigerung-node.html>, last updated on 20 May 2020, last accessed on 22 Oct 2020.
- dena - Deutsche Energie-Agentur GmbH; LBST - Ludwig-Bölkow-Systemtechnik GmbH (2017): Siegemund, S.; Trommler, M.; Kolb, O.; Zinnecker, V.; Schmidt, P.; Weindorf, W.; Zittel, W.; Raksha, T.; Zerhusen, J. E-Fuels Study: The potential of electricity-based fuels for low-emission transport in the EU, An expertise by LBST and dena. Deutsche Energie-Agentur GmbH; Ludwig-Bölkow-Systemtechnik GmbH. Verband der Automobilindustrie (ed.). Berlin, 2017.
- Destatis - Statistisches Bundesamt (2019): Vierteljährliche Produktionserhebung i.Verarb.Gew., 42131-0003. Online available at <https://www-genesis.destatis.de/genesis/online#astructure>, last updated on 25 Oct 2020, last accessed on 25 Oct 2020.
- Destatis - Statistisches Bundesamt (2020): 1,2 Milliarden Euro Luftverkehr-steuer im Jahr 2019 angemeldet. Online available at <https://www.destatis.de/DE/Themen/Staat/Steuern/Weitere-Steuern/luftverkehrsteuer.html>, last updated on 22 Apr 2020, last accessed on 22 Oct 2020.
- DHL - Deutsche Post DHL Group (2019): White Paper: Sustainable fuels for logistics, Status. Opportunities. Solutions., 17 Oct 2019. Online available at <https://www.dpdhl.com/content/dam/dpdhl/en/media-center/responsibility/dpdhl-whitepaper-sustainable-fuels-for-logistics.pdf>, last accessed on 22 Nov 2020.
- Dieterich, V.; Buttler, A.; Hanel, A.; Spliethoff, H.; Fendt, S. (2020): Power-to-liquid via synthesis of methanol, DME or Fischer-Tropsch-fuels: a review. In: *Energy Environmental Science* (13), pp. 3207–3252.
- DIW Econ; LBST; MKmetric; TU Darmstadt; UNICONSULT; Waldeck RA (2015): Grundlagenermittlung für ein Luftverkehrskonzept der Bundesregierung. Online available at <http://www.fluglaerm-rhein-main.de/wp-content/uploads/2016/03/2015-11-BundesVerkehrsministerium-Grundlagen-Luftverkehrskonzept.pdf>, last accessed on 8 May 2020.
- DNV GL (2015): The fuel trilemma, 2015. Online available at <https://safety4sea.com/wp-content/uploads/2015/06/DNV-GL-Position-Paper-on-Fuel-Trilemma.pdf>.
- DNV GL (2016a). Methanol as marine fuel, Environmental benefits, technology readiness, and economic feasibility. DNV GL, 2016.
- DNV GL (2016b). Methanol as marine fuel, Environmental benefits, technology readiness, and economic feasibility. DNV GL, 2016. Online available at http://www.imo.org/fr/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Report_Methanol_21.01.2016.pdf, last accessed on 12 Sep 2020.
- DNV GL (2017a). Low Carbon Shipping Towards 2050. DNV GL, 2017. Online available at C:\Users\m.cames\Documents\Download\DNV_GL_Low_Carbon_Shipping_Towards_2050.pdf, last accessed on 15 May 2021.
- DNV GL (2017b): LPG as a marine fuel, 2017.
- DNV GL (2017c): Maritime forecast to 2050, Energy Transition Outlook 2017, 2017. Online available at <https://eto.dnvgl.com/2017/maritime>, last accessed on 28 Sep 2018.
- DNV GL (2017d): Study on the use of fuel cells in shipping, 2017.
- DNV GL (2018): Langfeldt, L. Maritime Fuel Cell Applications, Technologies and ongoing developments. DNV GL, 2018.
- DNV GL (2018a): Assessment of selected alternative fuels and technologies Assessment of selected alternative fuels and technologies, 2018a.
- DNV GL (2018b): Maritime fuel cell applications, 2018b.
- DNV GL (2019): Comparison of Alternative Marine Fuels, 2019. Online available at https://sea-Ing.org/wp-content/uploads/2020/04/Alternative-Marine-Fuels-Study_final_report_25.09.19.pdf.
- DNV GL (2020). Maritime Forecast to 2050, Energy Transition Outlook 2020. DNV GL, 2020. Online available at https://brandcentral.dnvgl.com/dloriginal/gallery/10651/files/original/b3002f4841aa463abdd4a9b469b1ed08.pdf?f=DNVGL_2020_Maritime_Forecast_to_2050_WEB.pdf, last accessed on 24 Oct 2020.
- Dow (2020). L3G 06.05.C.10 - Industrieel reinigen, Bijlage 8 Ignition Energy. Dow, 2020. Online available at <https://nl.dow.com/content/dam/corp/documents/ehs/779-07309-06-l3g-06-05-c-10-industrieel-reinigen-bijlage-8-ignition-energy.pdf>, last accessed on 9 Apr 2021.

- DUT - Delft University of Technology (ed.) (2019): Vries, N. de. Safe and effective application of ammonia as a marine fuel, 2019. Online available at <https://repository.tudelft.nl/islandora/object/uuid%3Abe8cbe0a-28ec-4bd9-8ad0-648de04649b8>.
- E4tech; Element Energy (2014): Bertuccioli, L.; Chan, A.; Hart, D.; Lehner, F.; Madden, B.; Standen, E. Development of Water Electrolysis in the European Union. E4tech; Element Energy. Fuel Cells and Hydrogen Joint Undertaking (ed.). Lausanne, 2014.
- EASA - European Union Aviation Safety Agency (2019). European Aviation Environmental Report. European Union Aviation Safety Agency, 2019. Online available at https://www.easa.europa.eu/eaer/system/files/usr_uploaded/219473_EASA_EAER_2019_WEB_HI-RES_190311.pdf, last accessed on 31 Jan 2021.
- EC - European Commission (2018): European Commission. A Clean Planet for all – A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, In-depth analysis in support of the commission; Communication COM (2018) 773. European Commission, 2018. Online available at https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf, last accessed on 3 May 2021.
- EC - European Commission (2020a). 2019 Annual Report on CO₂ Emissions from Maritime Transport (SWD(2020) 82 final). European Commission. Brussels, 2020. Online available at https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/swd_2020_82_en.pdf, last accessed on 20 Oct 2020.
- EC - European Commission (2020b): A hydrogen strategy for a climate-neutral Europe (COM(2020) 301 final), 8 Jul 2020. Online available at https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf, last accessed on 24 Oct 2020.
- EC - European Commission (2020c): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions, Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. COM(2020) 562 final, 17 Sep 2020. Online available at https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf.
- ECHA (2018a): Ammonia Substance information, 2018. Online available at <https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.014.225>.
- ECHA (2018b): Fuel oil, residual Substance information, 2018. Online available at <https://echa.europa.eu/nl/substance-information/-/substanceinfo/100.064.230>.
- ECHA (2018c): Methanol Substance information, 2018. Online available at <https://echa.europa.eu/substance-information/-/substanceinfo/100.000.599>.
- Ecofys; eclareon; ISI - Fraunhofer Institut für System- und Innovationsforschung; NTUA - National Technical University of Athens; LEI - Lithuanian Energy Institute; TU Wien (2016): Noothout, P.; Jager, D. de; Tesniere, L.; van Rooijen, S.; Karypidis, N.; Brückmann, R.; Jirous, F.; Breitschopf, B.; Angelopoulos, D.; Doukas, H.; Konstantinavičiūtė, I.; Resch, G. The impact of risks in renewable energy investments and the role of smart policies. Project Acronym: DiaCore. Ecofys; eclareon; Fraunhofer Institut für System- und Innovationsforschung; National Technical University of Athens; Lithuanian Energy Institute; TU Wien, 2016.
- Ecoinvent Centre (2018). ecoinvent database v3.5. Ecoinvent Centre. Ecoinvent Centre (ed.), 2018.
- EDF - Environmental Defense Fund (2019): Ash, N.; Scarbrough, T. Sailing on Solar, Could green ammonia decarbonise international shipping?. Environmental Defense Fund, 2019. Online available at <https://europe.edf.org/file/399/download?token=agUEb-KeQ>, last accessed on 24 Oct 2020.
- EEIT - Escola Europea - Intermodal Transport (2018). From LNG to Hydrogen?, Pitfalls and Possibilities. Escola Europea - Intermodal Transport, 2018. Online available at <https://escolaeuropea.eu/news/environmental-news/from-lng-to-hydrogen-pitfalls-and-possibilities/>.
- Embraer (2018): Market Outlook 2018-2037., 2018. Online available at https://www.embraermarketoutlook2019.com/wp-content/uploads/2018/07/Embraer_MarketOutlookBook_2018_DownloadablePDF_A4.pdf.
- EMSA - European Maritime Safety Agency (2017): Ellis, J.; Tanneberger, K. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. European Maritime Safety Agency, 2017. Online available at <http://www.emsa.europa.eu/publications/download/4142/2726/23.html>, last accessed on 1 Feb 2021.

- EMSA (2015): Ellis, J.; Tanneberger, K. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. EMSA, 2015. Online available at <http://www.emsa.europa.eu/emsa-documents/latest/download/4142/2726/23.html>, last accessed on 23 Oct 2020.
- EP - European Parliament (2020). Global data collection system for ship fuel oil consumption data ***I - P9_TA(2020)0219, Amendments adopted by the European Parliament on 16 September 2020 on the proposal for a regulation of the European Parliament and of the Council amending Regulation (EU) 2015/757 in order to take appropriate account of the global data collection system for ship fuel oil consumption data (COM(2019)0038 - C8-0043/2019 -2019/0017(COD)). Ordinary legislative procedure: first reading. European Parliament, 2020. Online available at https://www.europarl.europa.eu/doceo/document/TA-9-2020-0219_EN.pdf, last accessed on 15 Jan 2021.
- EPSC - European Political Strategy Centre (2019): Clean Transport at Sea, Setting a Course for European Leadership. In: *EPSC Strategic Notes* (32). Online available at <https://op.europa.eu/o/opportal-service/download-handler?identifier=02cc57f8-4e14-11ea-aece-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar&part=>, last accessed on 25 Oct 2020.
- EU - European Union (2007): Consolidated Reader-Friendly Edition of the Treaty on European Union (TEU) and the Treaty on the Functioning of the European Union (TFEU) as amended by the Treaty of Lisbon (2007).
- EU (2019): EU SCIENCE HUB, The European Commission's science and knowledge service, Renewable Energy – Recast to 2030 (RED II), 2019. Online available at <https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii>.
- EUROCONTROL (2018): European Aviation in 2040. Challenges of Growth., 2018. Online available at <https://www.eurocontrol.int/sites/default/files/content/documents/official-documents/reports/challenges-of-growth-2018.pdf>.
- EUROCONTROL (2019). Fuel Tankering, economic benefits and environmental impact. EUROCONTROL, 2019. Online available at https://www.eurocontrol.int/archive_download/all/node/11476/eurocontrol-think-paper-1-fuel-tankering.pdf, last accessed on 18 Oct 2020.
- Fasihi, M.; Bogdanov, D.; Breyer, C. (2016): Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, 10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, Düsseldorf, Germany. In: *Energy Procedia* (99), pp. 243–268, last accessed on 5 Dec 2018.
- Fasihi, M.; Efimova, O.; Breyer, C. (2019): Techno-economic assessment of CO₂ direct air capture plants. In: *Journal of Cleaner Production* 224, pp. 957–980. DOI: 10.1016/j.jclepro.2019.03.086.
- FCBI energy (2015): Anderson, K.; Márquez Salazar, C. Methanol as a marine fuel. FCBI energy, 2015. Online available at <http://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf>, last accessed on 1 Feb 2021.
- FCH - Fuel Cells and Hydrogen (2019): Launch of Refhyne, world's largest electrolysis plant in Rhineland refinery, Fuel Cells and Hydrogen. Online available at <https://www.fch.europa.eu/news/launch-refhyne-worlds-largest-electrolysis-plant-rhineland-refinery>, last updated on 4 Mar 2019, last accessed on 4 Mar 2019.
- FE - frontier economics (2018): Perner, J.; Bothe, D. International aspects of a power-to-x roadmap, A report prepared for the World Energy Council Germany. frontier economics. The Weltenergieerat - Deutschland e.V. (ed.), 2018. Online available at <https://www.frontier-economics.com/media/2642/frontier-int-ptx-roadmap-stc-12-10-18-final-report.pdf>, last accessed on 1 Feb 2021.
- FE - frontier economics; AEW - Agora Energiewende; AVW - Agora Verkehrswende (2017). PtG/PtL calculator: An interactive tool to determine the cost of Power-to-Gas (methane) and Power-to-Liquid, Model version: 1.0. frontier economics; Agora Energiewende; Agora Verkehrswende, 2017.
- Ferjan, K. (2013): IATA Airline Operational Cost Task Force (AOCTF), 2013. Online available at https://www.iata.org/whatwedo/workgroups/Documents/acc-2013-gva/0930-1015_AOCTF_FY2012_Report_FERJAN.pdf.
- Flightpath 2020 (2018): Importance of appropriate support for Sustainable Renewable Aviation Fuels, 2018. Online available at https://www.biofuelsflightpath.eu/images/pdf/Flightpath_support_to_IATA_letter_RED_II.pdf.
- FVV - Forschungsvereinigung Verbrennungskraftmaschinen; LBST - Ludwig-Bölkow-Systemtechnik GmbH (2013): Albrecht, U.; Schmidt, P.; Weindorf, W.; Wurster, R.; Zittel, W. Zukünftige Kraftstoffe für Verbrennungsmotoren und Gasturbinen, Eine

- Expertise für die Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV). Forschungsvereinigung Verbrennungskraftmaschinen; Ludwig-Bölkow-Systemtechnik GmbH. Frankfurt am Main, 2013.
- Ganley, J. C. (2006): Intermediate Temperature Direct Ammonia Fuel Cells, 2006.
- Gelhausen, M. C.; Berster, P.; Wilken, D. (2019): Airport capacity constraints and strategies for mitigation, A global perspective: Academic Press.
- GloMeep (2018): Waste heat recovery systems, 2018. Online available at <https://glomeep.imo.org/technology/waste-heat-recovery-systems/>.
- GMM - Green Maritime Methanol (2020): Green Maritime Methanol consortium starts engine test programme, Green Maritime Methanol. Online available at <https://greenmaritimethanol.nl/green-maritime-methanol-consortium-starts-engine-test-programme/>, last accessed on 1 Feb 2021.
- Graham, J.; Rahmes, T.; Kay, M.; Belières, J.-P.; Kinder, J.; Millet, S.; Ray, J.; Vannice, W.; Trela, J. (2013): Impact of SPK Fuels and Fuel Blends on Non-Metallic Materials Used in Commercial Aircraft Fuel Systems, 2013. Online available at https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/clean/reports/media/Impact_of_Alternative_Jet_Fuel_and_Fuel_Blends.pdf.
- Grahn, M.; Sprei, F. (2015): Future alternative transportation fuels, A synthesis report from literature reviews on fuel properties, combustion engine performance and environmental effects, 2015. Online available at http://publications.lib.chalmers.se/records/fulltext/218580/local_218580.pdf, last accessed on 1 Feb 2021.
- Grimme, W.; Jung, M. (2018): Towards more sustainability? – The development of aviation emissions from Germany between 1995 and 2016, Proceedings of the 22nd ATRS World Conference, Seoul, DLR - Deutsches Zentrum für Luft- und Raumfahrt, last updated on 2018.
- Grünewald, M. (2018): Power to Gas für Augsburg - a Showcase. Clean Air Tech Day. MAN Diesel & Turbo SE. Augsburg, 6 May 2018.
- Hansson, J.; Brynolf, S.; Fridell, E.; Lehtveer, M. (2020): The Potential Role of Ammonia as Marine Fuel, Based on Energy Systems Modeling and Multi-Criteria Decision Analysis. In: *Sustainability* 12 (8), p. 3265. DOI: 10.3390/su12083265.
- Hansson, J.; Mansson, S.; Brynolf, S.; Grahn, M. (2019): Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. In: *Biomass and Bioenergy* (126), pp. 159–173, last accessed on 21 Dec 2019.
- Hepting, M.; Pak, H.; Grimme, W.; Dahlmann, K.; Jung, M.; Wilken, D. (2020): Climate impact of German air traffic: A scenario approach. In: *Transportation Research Part D: Transport and Environment* 85, p. 102467. DOI: 10.1016/j.trd.2020.102467.
- Holen, G.; Bruknapp, R. (2019): 100% Carbon Neutral, Disrupt or be disrupted. Kraftstoffe der Zukunft - 16. Internationaler Fachkongress für erneuerbare Mobilität. Nordic Blue Crude. Berlin, 22 Jan 2019.
- Horvath, S.; Fasihi, M.; Breyer, C. (2018): Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. In: *Energy Conversion and Management* (164), pp. 230–241.
- HSE - Health and safety executive (2010): Pritchard, D. K.; Ratigan, W. M. Hazards of liquid hydrogen, Position paper. Health and safety executive, 2010. Online available at <https://www.hse.gov.uk/research/rrpdf/rr769.pdf>, last accessed on 1 Feb 2021.
- Hydrogen Europe, 2. (2018): Hydrogen transport & distribution, 2018. Online available at <https://hydrogeneurope.eu/hydrogen-transport-distribution>.
- IATA - International Air Transport Association (2020). Passenger Forecast Infographic. International Air Transport Association, 2020. Online available at <https://www.iata.org/contentassets/e938e150c0f547449c1093239597cc18/pax-forecast-infographic-2020-final.pdf>, last accessed on 31 Jan 2021.
- IATA (2015): IATA Guidance Material for Sustainable Aviation Fuel Management, 2nd edition, 2015. Online available at <https://www.iata.org/whatwedo/environment/Documents/IATA%20Guidance%20Material%20for%20SAF.pdf>.
- IBIA (2018): ISO to develop standard for methyl ethyl alcohol fuels, 2018. Online available at <https://ibia.net/iso-to-develop-standard-for-methyl-ethyl-alcohol-fuels/>.

- ICAO - International Civil Aviation Organization (1944). Convention on International Civil Aviation done at Chicago on the 7th day of December 1944. International Civil Aviation Organization. Montreal, 1944. Online available at https://www.icao.int/publications/documents/7300_orig.pdf, last accessed on 14 Jan 2021.
- ICAO - International Civil Aviation Organization (2016). On Board, A Sustainable Future. International Civil Aviation Organization, 2016. Online available at https://www.icao.int/environmental-protection/Documents/ICAOEnvironmentalBrochure_Web.pdf, last accessed on 28 Sep 2018.
- ICAO - International Civil Aviation Organization (2017a): 2050 ICAO Vision for Sustainable Aviation Fuels. Online available at <https://www.icao.int/environmental-protection/GFAAF/Pages/ICAO-Vision.aspx>, last updated on 23 Jun 2020.000Z, last accessed on 23 Jun 2020.
- ICAO - International Civil Aviation Organization (2017b): Doc 10075 - Assembly Resolutions in Force (as of 6 October 2016), International Civil Aviation Organization. Online available at https://www.icao.int/Meetings/a39/Documents/Resolutions/10075_en.pdf, last updated on 2017, last accessed on 15 May 2018.
- ICAO - International Civil Aviation Organization (2018). Long-Term Traffic Forecasts, Paenger and Cargo. International Civil Aviation Organization, 2018. Online available at https://www.icao.int/sustainability/Documents/LTF_Charts-Results_2018edition.pdf, last accessed on 31 Jan 2021.
- ICAO - International Civil Aviation Organization (2019a). Resolution A40-18: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change, 40th session of the ICAO Assembly. International Civil Aviation Organization, 2019. Online available at https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-18_Climate_Change.pdf, last accessed on 7 Apr 2021.
- ICAO - International Civil Aviation Organization (2019b): Presentation of 2018 Air Transport statistical results, 2019. Online available at https://www.icao.int/annual-report-2018/Documents/Annual.Report.2018_Air%20Transport%20Statistics.pdf, last accessed on 19 Jun 2020.
- ICAO - International Civil Aviation Organization (2020a). Effects of Novel Coronavirus (COVID-19) on Civil Aviation Economic Impact Analysis. International Civil Aviation Organization. Montreal, 2020. Online available at <https://www.icao.int/sustainability/Documents/COVID-19/ICAO%20COVID%202020%2011%2018%20Economic%20Impact.pdf>, last accessed on 31 Jan 2021.
- ICAO - International Civil Aviation Organization (2020b): Global Framework for Aviation Alternative Fuels - Conversion processes, International Civil Aviation Organization. Online available at C:\Users\m.cames\Documents\Download\ICAO (2020) Conversion Processes.pdf, last accessed on 9 Apr 2021.
- ICCT - International Council on Clean Transportation (2018): Hall, D.; Pavlenko, N.; Lutsey, N. Beyond road vehicles: Survey of zero-emission technology options across the transport sector (Working Paper, 2018-11). International Council on Clean Transportation, 18 Jul 2018. Online available at https://www.theicct.org/sites/default/files/publications/Beyond_Road_ZEV_Working_Paper_20180718.pdf, last accessed on 1 Oct 2018.
- ICCT - International Council on Clean Transportation (2019): Searle, S.; Pavlenko, N.; Kharina, A.; Giuntoli, J. Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities International Council on Clean Transportation, briefing,. International Council on Clean Transportation, 2019. Online available at https://www.theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.
- ICCT - International Council on Clean Transportation (2020a). Fuel burn of new commercial jet aircraft: 1960 to 2019. International Council on Clean Transportation, 2020. Online available at <https://theicct.org/sites/default/files/publications/Aircraft-fuel-burn-trends-sept2020.pdf>, last accessed on 6 Nov 2020.
- ICCT - International Council on Clean Transportation (2020b): Georgeff, E.; Mao, X.; Rutherford, D.; Osipova, L. Liquid hydrogen refueling infrastructure to support a zero-emission US–China container shipping corridor (2020-24). International Council on Clean Transportation, 2020. Online available at <https://theicct.org/sites/default/files/publications/ZEV-port-infra-hydrogren-oct2020-v2.pdf>, last accessed on 11 Apr 2021.
- ICCT - International Council on Clean Transportation (2020c): Mao, X.; Rutherford, D.; Osipova, L.; Comer, B. Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?. International

- Council on Clean Transportation, 2020. Online available at <https://theicct.org/sites/default/files/publications/Zero-emission-container-corridor-hydrogen-3.5.2020.pdf>, last accessed on 11 Apr 2021.
- ICCT - International Council on Clean Transportation (2020d): Pavlenko, N.; Comer, B.; Zhou, Y.; Clark, N.; Rutherford, D. The climate implications of using LNG as a marine fuel. International Council on Clean Transportation, 2020. Online available at https://theicct.org/sites/default/files/publications/LNG%20as%20marine%20fuel%2C%20working%20paper-02_FINAL_20200416.pdf, last accessed on 9 Apr 2021.
- ICCT - International Council on Clean Transportation (2020e): Wappelhorst, S. The End of the Road? An Overview of Combustion-Engine Car Phase-Out Announcements Across Europe. International Council on Clean Transportation, 2020. Online available at <https://theicct.org/sites/default/files/publications/Combustion-engine-phase-out-briefing-may11.2020.pdf>, last accessed on 15 May 2021.
- i-deals (2016). MeFCO2 - Methanol fuel from CO2, Synthesis of methanol from captured carbon dioxide using surplus electricity. i-deals, 2016. Online available at <http://www.mefco2.eu/pdf/mefco2-teaser.pdf>, last accessed on 25 Dec 2020.
- IEA - International Energy Agency (2016). World Energy Outlook. International Energy Agency. Paris, 2016.
- IEA - International Energy Agency (2018a). World Energy Outlook. International Energy Agency. Paris, 2018. Online available at https://webstore.iea.org/download/direct/2375?fileName=World_Energy_Outlook_2018.pdf, last accessed on 31 Jan 2021.
- IEA - International Energy Agency (2019). Renewables Information Statistics. International Energy Agency, 2019.
- IEA - International Energy Agency (2020a). Global EV Outlook 2020, Entering the decade of electric drive?. International Energy Agency, 2020, last accessed on 24 Oct 2020.
- IEA - International Energy Agency (2020b). Key World Energy Statistics. International Energy Agency, 2020. Online available at https://webstore.iea.org/download/direct/4093?fileName=Key_World_Energy_Statistics_2020.pdf, last accessed on 31 Jan 2021.
- IEA - International Energy Agency (2020c): Tracking Transport, Aviation, International Energy Agency. Online available at <https://www.iea.org/reports/tracking-transport-2020>, last accessed on 31 Jan 2021.
- IEA - International Energy Agency (2020d): World energy balances, International Energy Agency, last accessed on 2020.
- IEA - International Energy Agency (2021a). CO₂ Emissions from Fuel Combustion Statistics. International Energy Agency, 2021.
- IEA - International Energy Agency (2021b): Global electrolysis capacity becoming operational annually, 2014-2023, historical and announced – Charts – Data & Statistics - IEA, International Energy Agency. Online available at <https://www.iea.org/data-and-statistics/charts/global-electrolysis-capacity-becoming-operational-annually-2014-2023-historical-and-announced>, last updated on 18 Jun 2020, last accessed on 26 Mar 2021.
- IEA (2013): Energiepolitik der IEA-Länder, Deutschland Prüfung 2013. Online available at <https://www.oecd-ilibrary.org/content/publication/9789264202139-de>, last accessed on 20 Oct 2020.
- IEA (2018b): Advanced Motor Fuels: Dimethyl ether (DME), 2018. Online available at https://www.iea-amf.org/content/fuel_information/dme.
- IEA-AMF (2009): Dimethyl ether (DME), 2009. Online available at https://www.iea-amf.org/content/fuel_information/dme.
- IFA - Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (2021): GESTIS Substance Database, Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung. Online available at <https://gestis-database.dguv.de/>, last accessed on 9 Apr 2021.
- ifeu - Institut für Energie- und Umweltforschung (2019): Fröhlich, T.; Blömer, S.; Münter, D.; Brischke, L.-A. CO₂-Quellen für die PtX-Herstellung in Deutschland - Technologien, Umweltwirkung, Verfügbarkeit (ifeu paper, 03/2019). Institut für Energie- und Umweltforschung, 2019.
- IFPRI - International Food Policy Institute (2011): Laborde, D. Assessing the Land Use Change Consequences of European Biofuel policies, Final Report. International Food Policy Institute, 2011. Online available at <http://ebrary.ifpri.org/utis/getfile/collection/p15738coll5/id/197/filename/198.pdf>.

- IIASA - International Institute for Applied Systems Analysis (2018): RCP Database (version 2.0), International Institute for Applied Systems Analysis. Online available at <http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome>, last accessed on 28 Sep 2018.
- IMO - International Maritime Organization (2009). Second IMO GHG Study 2009. International Maritime Organization. London, 2009. Online available at <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/SecondIMOGHGStudy2009.pdf>, last accessed on 28 Sep 2018.
- IMO - International Maritime Organization (2014). Reduction of GHG Emissions from Ships, Third IMO GHG Study 2014 - Final Report. International Maritime Organization, 25 Jul 2014. Online available at <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf>, last accessed on 14 May 2018.
- IMO - International Maritime Organization (2016): Resolution MEPC.278(70), Data collection system for fuel oil consumption of ships. London, 28 Oct 2016. Online available at <https://gmn.imo.org/wp-content/uploads/2017/05/MEPC-27870-Data-collection-system-for-fuel-oil-consumption-of-ships.pdf>, last accessed on 23 Oct 2017.
- IMO - International Maritime Organization (2018). Adoption of the Initial IMO on Reduction of GHG Emissions from Ships. International Maritime Organization, 2018. Online available at http://www4.unfccc.int/sites/SubmissionPortal/Documents/201804271056---IMO%20SBSTA%2048%20submission_final_200418.pdf.
- IMO - International Maritime Organization (2019): International Maritime Research and Development Board (IMRB), International Maritime Organization, last accessed on 18 Oct 2020.
- IMO - International Maritime Organization (2020a). Fourth IMO GHG Study 2020, Reduction of GHG Emissions from Ships (MEPC 75/7/15). International Maritime Organization. London, 2020. Online available at <https://docs.imo.org/Shared/Download.aspx?did=125134>, last accessed on 24 Oct 2020.
- IMO - International Maritime Organization (2020b): Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621), last accessed on 27 Dec 2020.
- IMO - International Maritime Organization (2020c): Maritime Safety Committee, 102nd session, International Maritime Organization, last updated on <https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MSC-102nd-session.aspx>, last accessed on 1 Feb 2021.
- International Renewable Energy Agency (ed.) (2018). Hydrogen from renewable power, Technology outlook for the energy transition. Abu Dhabi, 2018.
- IPBES - Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (2019). The global assessment report on biodiversity and ecosystem services, Summary for policymakers. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019. Online available at https://ipbes.net/sites/default/files/2020-02/ipbes_global_assessment_report_summary_for_policymakers_en.pdf.
- IPCC - Intergovernmental Panel on Climate Change (2014). Climate Change 2014, Summary for Policymakers. Intergovernmental Panel on Climate Change, 2014. Online available at https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf.
- IRENA - International Renewable Energy Agency (2015). REmap 2030, Renewable Energy Prospects: Germany. International Renewable Energy Agency, 2015. Online available at https://www.irena.org/documentdownloads/publications/irena_remap_germany_report_2015.pdf, last accessed on 24 Oct 2020.
- IRENA - International Renewable Energy Agency (2016). Innovation Outlook: Advanced Liquid Biofuels. International Renewable Energy Agency, 2016. Online available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf.
- IRENA (2019). Navigating the way to a renewable future: Solutions to decarbonise shipping. IRENA, 2019. Online available at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf, last accessed on 20 Oct 2020.
- ISE - Fraunhofer Institut für Solare Energiesysteme; E4tech; IPA - Fraunhofer Institut für Produktionstechnologie und Automatisierung (2018): Smolinka, T.; Wiebe, N.; Sterchele, P.; Palzer, A.; Lehner, F.; Jansen, M.; Kiemel, S.; Miehe, R.; Wahren, S.;

- Zimmermann, F. Studie IndWEde, Industrialisierung der Wasser-elektrolyse in Deutschland: -Chancen und -Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme. Fraunhofer Institut für Solare Energiesysteme; E4tech; Fraunhofer Institut für Produktionstechnologie und Automatisierung. Bundesministerium für Verkehr und digitale Infrastruktur (ed.). Berlin, 2018.
- ISO (2017). Fuel Standard for marine residual fuels (8217). ISO, 2017. Online available at <https://www.wfscorp.com/sites/default/files/ISO-8217-2017-Tables-1-and-2-1-1.pdf>, last accessed on 1 Feb 2021.
- ITM Power (2019): World's largest Hydrogen Electrolysis in Shell's Rhineland Refinery. Online available at <https://www.itm-power.com/item/38-world-s-largest-hydrogen-electrolysis-in-shell-s-rhineland-refinery>.
- IWES - Fraunhofer Institut für Windenergie und Energiesystemtechnik (2017): Pfennig, M.; Gerhardt, N.; Pape, C.; Böttger, D. Mittel- und Langfristige Potenziale von PTL und H₂-Importen aus internationalen EE-Vorzugsregionen, Teilbericht im Rahmen des Projektes: Klimawirksamkeit Elektromobilität - Entwicklungsoptionen des Straßenverkehrs unter Berücksichtigung der Rückkopplung des Energieversorgungssystems in Hinblick auf mittel- und langfristige Klimaziele. Fraunhofer Institut für Windenergie und Energiesystemtechnik. Kassel, 2017.
- JRC (2016): Alternative fuels for marine and inland waterways, 2016. Online available at http://www.methanol.org/wp-content/uploads/2016/07/inland-and-marine-waterways-exploratory-work-on-alternative-fuels_kamaljit-moirangthem_final.pdf.
- Kajaste, R.; Hurme, M.; Oinas, P. (2018): Methanol-Managing greenhouse gas emissions in the production chain by optimizing the resource base. In: *AIMS Energy* 6, pp. 1074–1102. DOI: 10.3934/energy.2018.6.1074.
- Karagiannopoulos, L.; Solsvik, T. (2018): Norway will make airlines use more environmentally friendly fuel from 2020. In: *Reuters*, 2018. Online available at <https://www.reuters.com/article/us-norway-biofuels/norway-will-make-airlines-use-more-environmentally-friendly-fuel-from-2020-idUSKCN1ME25U>.
- Kawasaki (2020): Kawasaki Completes Installation of Liquefied Hydrogen Storage Tank for Marine Transport Applications on World's First Liquefied Hydrogen Carrier, Kawasaki. Online available at https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20200309_3090, last accessed on 1 Feb 2021.
- Khandelwal, B.; Karakurt, A.; Sekaran, P. R.; Sethi, V.; Singh, R. (2013): Hydrogen powered aircraft : The future of air transport, 2013.
- Kharina, A. (2018): Kinks in the pipeline: A survey of downstream alternative jet fuels challenges | International Council on Clean Transportation, International Council on Clean Transportation. Online available at <https://theicct.org/blog/staff/kinks-pipeline-survey-downstream-alternative-jet-fuels-challenges>, last updated on 31 Oct 2018, last accessed on 23 Jun 2020.
- Knight (2018): From LNG to Hydrogen? Pitfalls and Possibilities, 2018. Online available at <https://www.motorship.com/news101/fuels-and-oils/from-lng-to-hydrogen-the-pitfalls-and-the-possibilities>.
- Korberg, A. D.; Brynolf, S.; Grahn, M.; Skov, I. R. (2021): Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. In: *Renewable and Sustainable Energy Reviews* 142, p. 110861. DOI: 10.1016/j.rser.2021.110861.
- KR - Korean Register (2020). Forecasting the Alternative Marine Fuel - Ammonia. Korean Register, 2020. Online available at http://www.krs.co.kr/TECHNICAL_FILE/KR_Forecasting%20the%20Alternative%20Marine%20Fuel_Ammonia.pdf, last accessed on 24 Nov 2020.
- Kropiwnicki, J.; Dominiczak, P.; Kneba, Z.; Makowski, S.; Cieśliński, J. T.; Ziółkowski, M. (2017): Analysis of the possibilities of using of DME fuel in motor boat drive systems. In: *Combustion Engines* 56. Online available at http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-2be8834f-2f94-4311-be05-b8a43d094a43/c/kropiwnicki_dominiczak_kneba_makowski_cieslinski_ziolkowski_analysis_ce_4_2017.pdf.
- Kruczynski et al. (2017): Problems with fuelling SI engines with DME, 2017.
- LBST - Ludwig-Bölkow-Systemtechnik GmbH; BL - Bauhaus Luftfahrt e.V. (2016): Schmidt, P.; Weindorf, W.; Roth, A.; Batteiger, V.; Riegel, F. Power-to-Liquids, Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel (Background). Ludwig-Bölkow-Systemtechnik GmbH; Bauhaus Luftfahrt e.V. Umweltbundesamt (ed.). Dessau-Roßlau, 2016.
- LCCC - Low Carbon Contracts Company (2020): How does the CfD Work?, How are generators paid?, Low Carbon Contracts Company. Online available at <https://www.lowcarboncontracts.uk/how-does-the-cfd-work>.

- Lee, D. S.; Fahey, D. W.; Skowron, A.; Allen, M. R.; Burkhardt, U.; Chen, Q.; Doherty, S. J.; Freeman, S.; Forster, P. M.; Fuglestedt, J.; Gettelman, A.; León, R. R. de; Lim, L. L. et al. (2020): The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 117834. DOI: 10.1016/J.ATMOSENV.2020.117834.
- Lin et al. (2010): Waste heat recovery system for fuel cell system, 2010.
- Lindstad, E. (2020): e-methanol. E-Mail, 13 Sep 2020.
- Lipton, M. (2018): Fuel flexibility with GE marine gas turbines, 2018. Online available at <https://gastechinsights.com/article/fuel-flexibility-with-ge-marine-gas-turbines>.
- Liu, Y.; Wilson, C. W.; Blakey, S.; Dolmansley, T. (2011): Elastomer compatibility test of alternative fuels using stress relaxation test and FTIR spectroscopy, 2011. Online available at <http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=E217B4F394A7231DC8A402E8CAD14DCB?doi=10.1.1.658.7436&rep=rep1&type=pdf>.
- LR - Lloyd's Register (2020a): LR and Methanol Institute launch guidance on methanol bunkering, Lloyd's Register. Online available at <https://www.lr.org/en/latest-news/lr-methanol-institute-guidance-on-methanol-bunkering/>, last accessed on 1 Feb 2021.
- LR - Lloyd's Register (2020b): World first for liquid hydrogen transportation, Lloyd's Register. Online available at <https://www.lr.org/en/insights/articles/world-first-for-liquid-hydrogen-transportation/>, last updated on 1 Feb 2021.
- LR - Lloyd's Register; SCC - Shipping in Changing Climates (2016). Low carbon pathways 2050. Lloyd's Register; Shipping in Changing Climates, 2016, last accessed on 25 Apr 2021.
- LR - Lloyd's Register; UMAS (2019). Zero-Emission Vessels: Transition Pathways, We're considering how to turn ambition into reality. Part of the Low Carbon Pathways 2050 series. Lloyd's Register; UMAS, 2019. Online available at <https://www.lr.org/en/insights/global-marine-trends-2030/zero-emission-vessels-transition-pathways/>, last accessed on 24 Nov 2020.
- LR - Lloyd's Register; UMAS (2020). Techno-economic assessment of zero-carbon fuels. Lloyd's Register; UMAS, 2020. Online available at https://storage.pardot.com/12702/248723/Techno_economic_assessment_of_zero_carbon_fuels.pdf, last accessed on 27 Dec 2020.
- Lufthansa Group (2018): Geschäftsbericht 2017, 2018. Online available at <https://investor-relations.lufthansagroup.com/fileadmin/downloads/de/finanzberichte/geschaeftsberichte/LH-GB-2017-d.pdf>.
- LUT - Lappeenranta University of Technology (2017a): Fasihi, M.; Bogdanov, D.; Breyer, C. Long-term hydrocarbon trade options for Maghreb core region and Europe, Renewable Energy based synthetic fuels for a net zero emissions world. Lappeenranta University of Technology. Finland, 2017.
- LUT - Lappeenranta University of Technology (2017b): Fasihi, M.; Breyer, C. Synthetic Methanol and Dimethyl Ether Production based on Hybrid PV-Wind Power Plants, Conference Paper. Lappeenranta University of Technology. Lappeenranta, 2017.
- Makridis (2016): Hydrogen-storage-and-compression, 2016.
- MAN - MAN Energy Solutions (2020). Managing methane slip. MAN Energy Solutions, 2020. Online available at <https://people.man-es.com/docs/librariesprovider51/default-document-library/technical-paper.pdf>, last accessed on 15 May 2021.
- MAN (2014): Using methanol fuel in the MAN BandW ME-LGI Series, 2014.
- MAN (2018): Ship Operation Using LPG and Ammonia As Fuel, 2018. Online available at https://nh3fuelassociation.org/wp-content/uploads/2018/12/0900-Ammonia_vision-Rene-Sejer-Laursen-MAN.pdf, last accessed on 3 Mar 2019.
- Maritiem, B. (2018): Is methanol the clean fuel of the future for the maritime industry?, 2018. Online available at <http://www.bergermaritiem.nl/index.php?item=1314>.
- McKinsey (2017): Evaluation of the NIP Hydrogen and Fuel Cell Technology Phase 1, 2017.
- McKinsey (2019): European Refineries, 2019. Online available at <https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/european-refineries/>, last accessed on 4 Mar 2019.
- Melkert, J. A. (ed.) (2019): Unlocking greater near-term efficiency, while transitioning to the next generation of planes, There is no quick fix. Aviation Decarbonization, Montreal, ICSA. Aviation Decarbonization vol. Online available at <https://www.icsa-aviation.org/wp-content/uploads/2019/02/Melkert-Near-Term-Efficiency-.pdf>, last accessed on 18 Oct 2020.
- Methanol Institut (2017): Physical Properties of Pure Methanol, 2017.

- Methanol Institute (2007): Bechtold, R. L.; Goodman, M. B.; Timbario, T. A. Use of Methanol as a Transportation Fuel. Methanol Institute. Arlington, 2007. Online available at <http://www.methanol.org/wp-content/uploads/2016/06/Methanol-Use-in-Transportation.pdf>, last accessed on 20 Oct 2020.
- Methanol Institute (2016). China: The Leader in Methanol Transportation. Methanol Institute, 2016. Online available at <http://www.methanol.org/wp-content/uploads/2016/06/China-Methanol-Fact-Sheet-1.pdf>, last accessed on 24 Oct 2020.
- Methanol Institute (2020a). Comments on the Inception Impact Assessment of the Fuel EU Maritime initiative. Methanol Institute, 24 Apr 2020. Online available at <blob:https://ec.europa.eu/569a018e-e2dc-4938-8a11-f51e3c405c6b>, last accessed on 20 Oct 2020.
- Methanol Institute (2020b). Methanol: An Emerging Marine Fuel. Methanol Institute, 2020. Online available at <https://www.methanol.org/wp-content/uploads/2020/04/Methanol-Emerging-Marine-Fuel-Presentation.pdf>, last accessed on 9 Apr 2021.
- Methanol Institute (2020c): Methanol Price and Supply/Demand, Methanol Institute. Online available at <https://www.methanol.org/methanol-price-supply-demand/>, last updated on 30 Dec 2020, last accessed on 30 Dec 2020.
- Methanol Institute (ed.) (2015): Dolan, G. Methanol Takes on LNG for Future Marine Fuels, 2015. Online available at https://www.acfa.org.sg/pdf/InFocus18_2015_MI_HP_Viewpoint_on_Methanol_Marine_Fuels_Feb_2015.pdf, last accessed on 23 Oct 2020.
- MKC et al. (2017): Methanol as alternative fuel, 2017.
- Müller, G. V. (2018): Climeworks gewinnt das Vertrauen der Investoren, Neue Züricher Zeitung. Online available at <https://www.nzz.ch/wirtschaft/climeworks-gewinnt-das-vertrauen-der-investoren-ld.1415705>, last accessed on 21 Aug 2019.
- MVO Nederland (2017): Ship 2040 - Pioneers in the maritime sector, 2017.
- MWV - Mineralölwirtschaftsverband e.V.; IWO - Institut für Wärme und Oeltechnik e.V.; MEW - Mittelständische Energiewirtschaft Deutschland e.V.; UNITI - Bundesverband mittelständischer Mineralölunternehmen e.V. (2018): Hobohm, J.; Maur, A. auf der; Dambeck, H.; Kemmler, A.; Koziel, S.; Kreidelmeyer, S.; Piégsa, A.; Wendring, P.; Meyer, B.; Apfelbacher, A.; Dotzauer, M.; Zech, K. Status und Perspektiven flüssiger Energieträger in der Energiewende, Endbericht. Mineralölwirtschaftsverband e.V.; Institut für Wärme und Oeltechnik e.V.; Mittelständische Energiewirtschaft Deutschland e.V.; Bundesverband mittelständischer Mineralölunternehmen e.V. Berlin, 2018.
- NNFCC (2019): Phillips, D. Implications of Imported Used Cooking Oil (UCO) as a Biodiesel Feedstock. NNFCC, 2019. Online available at <https://www.nnfcc.co.uk/files/mydocs/UCO%20Report.pdf>.
- NPM, AG 1 - Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 1 (2020). Werkstattbericht Alternative Kraftstoffe, Klimawirkungen und Wege zum Einsatz Alternativer Kraftstoffe. Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 1, 2020. Online available at https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2020/12/NPM_AG1_Werkstattbericht_AK.pdf.
- OECD - Organisation for Economic Cooperation and Development (2018). The long view: Scenarios for the world economy to 2060. In collaboration with Guillemette, Y. and Turner, D. Organisation for Economic Cooperation and Development. Paris, 2018. Online available at https://www.ledevoir.com/documents/pdf/OCDE_economie_mondiale_2060.pdf, last accessed on 31 Jan 2021.
- Oeko-Institut (2015): Matthes, F. C.; Loreck, C.; Haller, M. Die Umlage des Erneuerbaren-Energien-Gesetzes (EEG). Hintergründe, Trends, Treiber und Perspektiven, Kurzstudie. Oeko-Institut. Berlin, 8 Nov 2015. Online available at <https://www.oeko.de/oekodoc/2448/2015-605-de.pdf>, last accessed on 22 Oct 2020.
- Oeko-Institut (2016): Cames, M.; Harthan, R.; Füssler, J.; Lazarus, M.; Lee, C.; Erickson, P.; Spalding-Fecher, R. How additional is the Clean Development Mechanism?, Analysis of the application of current tools and proposed alternatives. Oeko-Institut, 2016. Online available at https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf, last accessed on 13 Jun 2017.
- Oeko-Institut (2019a): Kasten, P.; Heinemann, C. Kein Selbstläufer: Klimaschutz und Nachhaltigkeit durch PtX, Diskussion der Anforderungen und erste Ansätze für Nachweiskriterien für eine klimafreundliche und nachhaltige Produktion von PtX-Stoffen. Impulspapier im Auftrag des BUND im Rahmen des Kopernikus-Vorhabens „P2X“. In collaboration with Seebach, D. and Sutter, J. Oeko-Institut, 2019.

- Oeko-Institut (2019b): Kasten, P.; Kühnel, S. Positionen zur Nutzung strombasierter Flüssigkraftstoffe (efuels) im Verkehr, Darstellung von Positionen verschiedener gesellschaftlicher Akteure zum Einsatz von efuels im Verkehr. Erstellt als Teil des Kopernikus Fördervorhabens Power2X - Erforschung, Validierung und Implementierung von „Power-to-X“-Konzepten gefördert durch BMBF Förderkennzeichen: 03SFK2H0. Oeko-Institut. Berlin, 2019.
- Offshore Energy (2020): Methanol Institute joins China’s study of methanol as marine fuel. In collaboration with Hakirevic and Naida. Offshore Energy (ed.). Online available at <https://www.offshore-energy.biz/methanol-institute-joins-chinas-study-of-methanol-as-marine-fuel/>, last accessed on 1 Feb 2021.
- Packalén, S.; Nord, N. K. (2017): Combined gas-and steam turbine as prime mover in marine applications. Online available at <http://publications.lib.chalmers.se/records/fulltext/250183/250183.pdf>.
- Paulauskiene, T.; Bucas, M.; Laukinaite, A. (2019): Alternative fuels for marine applications_ Biomethanol-biodiesel-diesel blends. In: *Fuel*, pp. 161–167. DOI: 10.1016/j.fuel.2019.03.082.
- Pechstein, J.; Bullerdiek, N.; Kaltschmitt, M. (2020): A “book and Claim”-Approach to account for sustainable aviation fuels in the EU-ETS–Development of a basic concept. In: *Energy Policy* 136, p. 111014. DOI: 10.1016/j.enpol.2019.111014.
- Penjic, E. (2018): In Depth: Methanol Is Ready for Use as Marine Fuel, 2018. Online available at <https://worldmaritimeneews.com/archives/249601/interview-methanol-is-ready-for-use-as-marine-fuel/>.
- Prognos - Prognos AG (2020): Kreidelmeyer, S.; Dambeck, H.; Krichner, A.; Wünsch, M. Kosten und Transformationspfade für strombasierte Energieträger. Prognos AG, 2020. Online available at C:\Users\m.cames\Documents\Download\transformationspfade-fuer-strombasierte-energetraeger.pdf, last accessed on 16 May 2021.
- Refinitiv (2020). Review of carbon markets in 2019. Refinitiv, 2020. Online available at https://www.refinitiv.com/content/dam/marketing/en_us/documents/reports/carbon-market-year-in-review-2019.pdf, last accessed on 1 Feb 2021.
- Reiter, G.; Lindorfer, J. (2015): Evaluating CO2 sources for power-to-gas applications - A case study for Austria. In: *Journal of CO2 Utilization* 10, pp. 40–49.
- REN21 (2013). Renewables Global Status Report 2012. REN21, 2013.
- Riahi, K.; van Vuuren, D. P.; Kriegler, E.; Edmonds, J.; O’Neill, B. C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; Lutz, W.; Popp, A.; Cuaresma, J. C. et al. (2017): The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. In: *Global Environmental Change* 42, pp. 153–168. DOI: 10.1016/j.gloenvcha.2016.05.009.
- Ricardo Energy & Environment (2019): Ash, N.; Scarbrough, T. Sailing on solar: Could green ammonia decarbonise international shipping?. Ricardo Energy & Environment. Environmental Defense Fund (ed.). London, 2019.
- Ricardo-AEA; Milieu; IHS; AMEC; MARINTEK (2013): Support for the impact assessment of a proposal to address maritime transport greenhouse gas emissions, 2013. Online available at https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/ghg_maritime_report_en.pdf, last accessed on 1 Feb 2021.
- Richstein, J. C. (2017): Project-Based Carbon Contracts: A Way to Finance Innovative Low-Carbon Investments, DIW. Online available at https://www.diw.de/documents/publikationen/73/diw_01.c.575021.de/dp1714.pdf, last accessed on 28 Apr 2020.
- RINA (2017): Approval in principle of innovative projects, 2017. Online available at <https://www.rina.org/en/approval-in-principle-of-innovative-projects>.
- Royal Academy of Engineering (2013): Future ship powering options, 2013.
- Ryanair (2018): Annual Report 2018, 2018. Online available at <https://investor.ryanair.com/wp-content/uploads/2018/07/Ryanair-FY-2018-Annual-Report.pdf>.
- Sayma, A. I. (2017): Gas Turbines for Marine Applications. In: Carlton, J.; Jukes, P. and Sang, C.-Y. (ed.): *Encyclopedia of Maritime and Offshore Engineering*: John Wiley & Sons, Ltd, pp. 1–10.
- Schaefer, M. (2012): Development of a Forecast Model for Global Air Traffic Emissions. Dissertation, DLR - Deutsches Zentrum für Luft- und Raumfahrt. Online available at http://elib.dlr.de/77004/1/DLR_Forschungsbericht_2012-08.pdf, last updated on 2012, last accessed on 15 May 2018.
- Scheelhaase, J.; Grimme, W.; Maertens, S.; Jung, M. (2018): EU ETS versus CORSIA, A critical assessment of two approaches to limit air transport’s CO2 emissions by market-based measures. In: *Journal of Air Transport Management* 67, pp. 55–62.

- Scheelhaase, J.; Maertens, S.; Grimme, W. (2019): Synthetic fuels in aviation – Current barriers and potential political measures. In: *Transportation Research Procedia* 43, pp. 21–30. DOI: 10.1016/j.trpro.2019.12.015.
- Schemme, S. (2020): Techno-ökonomische Bewertung von Verfahren zur Herstellung von Kraftstoffen aus H₂ und CO₂. Dissertation, Fakultät für Maschinenwesen, RWTH Aachen, 2020.
- Schmidt, P. (2019): Hydrogen from electrolysis as a key element in PtX pathways – Scenarios for a massive scale-up. Fuels of the Future. 16th International Conference on Renewable Mobility. Ludwig-Bölkow-Systemtechnik GmbH. Berlin, 22 Jan 2019, last accessed on 30 Apr 2019.
- Schmidt, P.; Weindorf, W.; Roth, A.; Batteiger, V.; Riegel, F. (2016): Power-to-Liquids, Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel., 2016.
- SEI - Stockholm Environment Institute (2015): Kollmuss, A.; Schneider, L.; Zhezherin, V. Has Joint Implementation reduced GHG emissions? Lessons learned for the design of carbon market mechanisms (Working Paper). Stockholm Environment Institute. Stockholm, 2015. Online available at <https://www.sei.org/publications/has-joint-implementation-reduced-ghg-emissions-lessons-learned-for-the-design-of-carbon-market-mechanisms/>.
- SGC (2012): A feasibility study on LPG as marine fuel, 2012.
- Shell (2018): Sky. Meeting the goals of the Paris Agreement., 2018. Online available at <https://mronline.org/wp-content/uploads/2018/11/shell-scenario-sky.pdf>.
- SINTEF (2017): Stenersen, D.; Thonstad, O. GHG and NOx emissions from gas fuelled engines, Mapping, verification, reduction technologies. SINTEF. Trondheim, 2017.
- Smith, A. (1776): The Wealth of Nations, An Inquiry into the Nature and Causes of the Wealth of Nations. London: J. M. Dent.
- SNL - Sandia National Laboratories (2003): Thomas, G.; Keller, J. Hydrogen Storage, Overview. Sandia National Laboratories, 2003. Online available at https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/bulk_hydrogen_stor_pres_sandia.pdf, last accessed on 1 Feb 2021.
- Solarify.eu (2019): Wüsten-Wasserstoff: Neuer Anlauf mit Desertec 3.0, 10 Jahre Dii Desert Energy – Jahrestagung mit Ghorfa in Berlin, Solarify.eu. Online available at <https://www.solarify.eu/2019/11/26/582-wuesten-wasserstoff-neuer-anlauf-mit-desertec-3-0/>, last updated on 26 Nov 2019, last accessed on 6 Dec 2020.
- Sönmez, E.; Kekre, S.; Scheller-Wolf, A.; Secomandi, N. (2013): Strategic analysis of technology and capacity investments in the liquefied natural gas industry. In: *European Journal of Operational Research* 226 (1), pp. 100–114. DOI: 10.1016/j.ejor.2012.10.042.
- Steffen, B. (2019): Financing and innovation in energy transitions, 2019. Online available at https://fsr.eui.eu/wp-content/uploads/2020/01/EUI-2019_SteffenETHZ_clean.pdf, last accessed on 20 Oct 2020.
- Stena Line (2015): WELCOME ONBOARD A GREENER JOURNEY!, - Stena Germanica – the world’s first methanol ferry, Stena Line. Online available at http://www.stenamedia.de/PDFs/Stena_Line_Methanol.pdf, last accessed on 26 Dec 2020.
- StenaBulk (2020). roman Stena Bulk to promote a greener shipping future with additional methanol-ready vessel. StenaBulk, 2020. Online available at https://www.stenabulk.com/sites/default/files/press_releases/proman_stena_bulk_to_promote_a_greener_shipping_future_with_additional_methanol-ready_vessel.pdf, last accessed on 9 Apr 2021.
- SWZ - SWZ Maritime (2020): Bunkering facility not a must to get liquid hydrogen on board a ship, SWZ Maritime. Online available at <https://www.swzmaritime.nl/news/2020/09/09/bunkering-facility-not-a-must-to-get-liquid-hydrogen-on-board-a-ship/?gdpr=accept&gdpr=accept>, last accessed on 1 Feb 2021.
- T&E - Transport & Environment (2020). All aboard!, Too expensive for ships to evade EU carbon markets. Transport & Environment. Brussels, 2020. Online available at [https://www.transportenvironment.org/sites/te/files/publications/ETS_evasion_study_\(VS-CCA\)_FINAL_compressed.pdf](https://www.transportenvironment.org/sites/te/files/publications/ETS_evasion_study_(VS-CCA)_FINAL_compressed.pdf), last accessed on 27 Dec 2020.
- Terwel, R.; Kerkhoven, J.; Saris, F. W. (2019): Carbon Neutral Aviation. In: *Europhysics News* 50 (5-6), pp. 29–32. DOI: 10.1051/epn/2019503.

- The Luxembourg Government (2021): Joint Statement on Sustainable Aviation Fuels, Supported by Denmark, Finland, France, Germany, Luxembourg, the Netherlands, Spain and Sweden. Press release. The Luxembourg Government (ed.). Online available at https://gouvernement.lu/en/actualites/toutes_actualites/communiqués/2021/02-fevrier/08-aviation-fuels.html.
- thinkstep (2019): Schuller, O.; Kupferschmid, S.; Hengstler, J.; Whitehouse, S. Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel. thinkstep. Stuttgart, 2019.
- thinkstep AG (ed.) (2018). GaBI 6.0, 2018.
- Thompson, D. (28 Feb 2013): How Airline Ticket Prices Fell 50 Percent in 30 Years (And Why Nobody Noticed), Thank deregulation, competition, the internet, and fees. Yes, thank fees. In: *The Atlantic*, 28 Feb 2013. Online available at <https://www.theatlantic.com/business/archive/2013/02/how-airline-ticket-prices-fell-50-in-30-years-and-why-nobody-noticed/273506/>, last accessed on 26 Oct 2020.
- Timmerberg, S.; Kaltschmitt, M. (2019): Untersuchung zum PtX-Hochlauf, Wie schnell kann PtX produziert werden? VDI Expertenforum Schifftechnik - Antriebe der Zukunft. Technische Universität Hamburg. Hamburg, 29 Mar 2019.
- TNO et al. (2013): Dimethylether, 2013.
- Trakakis, A. (2018): Methane slip from LNG fueled engines. Online available at <https://safety4sea.com/methane-slip-from-lng-fueled-engines/>, last accessed on 25 Oct 2020.
- TRIS - Technical Research Institute of Sweden (2015): Blomqvist, P.; Evegren, F.; Willstrand, O.; Arvidson, M. preFLASH, Preliminary study of protection against fire in low-flashpoint fuel. Technical Research Institute of Sweden, 2015. Online available at <http://www.diva-portal.org/smash/get/diva2:962918/FULLTEXT01.pdf>, last accessed on 1 Feb 2021.
- TU Berlin (ed.) (2018): Milanzi, S.; Spiller, C.; Grosse, B.; Hermann, L.; Kochems, J.; Müller-Kirchenbauer, J. Technischer Stand und Flexibilität des Power-to-Gas-Verfahrens. Berlin, 2018.
- UBA - Umweltbundesamt (2005): Pache, E. Möglichkeiten der Einführung einer Kerosinsteuer auf innerdeutschen Flügen (Texte, 12/05). Umweltbundesamt, 2005. Online available at <https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/2853.pdf>, last accessed on 2 May 2021.
- UBA - Umweltbundesamt (2016): Schmidt, P.; Weindorf, W.; Roth, A.; Batteiger, V.; Riegel, F. Power-to-Liquids, Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel (background paper). Umweltbundesamt. Dessau-Roßlau, 2016. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierefrei.pdf, last accessed on 2 May 2021.
- UBA - Umweltbundesamt (2018): Maibach, M.; Peter, M.; Killer, M.; Bieler, C.; Zandonella, R.; Notter, B.; Bertschmann, D. Szenario Luftverkehr Deutschland unter Einbezug von Umweltaspekten (Texte, 109/2018). Umweltbundesamt. Dessau-Roßlau, 2018. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-12-14_texte_109-2018-nachhaltige-gueterinfrastruktur.pdf, last accessed on 8 May 2020.
- UBA - Umweltbundesamt (2019a): Katja Purr, Jens Günther, Harry Lehmann und Philip Nuss. Wege in eine ressourcenschonende Treibhausgasneutralität - Rescue Studie. Umweltbundesamt. Dessau-Roßlau, 2019. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/rescue_studie_cc_36-2019_wege_in_eine_ressourcenschonende_treibhausgasneutralitaet.pdf, last accessed on 5 May 2020.
- UBA - Umweltbundesamt (2019b): Lauf, T.; Memmler, M.; Schneider, S. Emissionsbilanz erneuerbarer Energieträger, Bestimmung der vermiedenen Emissionen im Jahr 2018 (Climate Change, 37/2019). Umweltbundesamt. Dessau-Roßlau, 2019. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-07_cc-37-2019_emissionsbilanz-erneuerbarer-energien_2018.pdf, last accessed on 2 May 2021.
- UBA - Umweltbundesamt (2019c): Purr, K.; Günther, J.; Lehmann, H.; Nuss, P. Wege in eine ressourcenschonende Treibhausgasneutralität, RESCUE - Studie (Climate Change, 36/2019). Umweltbundesamt, 2019.
- UBA - Umweltbundesamt (2019d): Wietschel, M.; Haendel, M.; Boßmann, T.; Deac, G.; Michaelis, J.; Doll, C.; Schломann, B.; Köppel, W.; Degünther, C. Integration erneuerbarer Energien durch Sektorkopplung: Analyse zu technischen Sektorkopplungsoptionen (Climate Change, 03/2019). Umweltbundesamt. Dessau-Roßlau, 2019. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-03-12_cc_03-2019_sektorkopplung.pdf, last accessed on 2 May 2021.

- UBA - Umweltbundesamt (2020): Liebich, A.; Fröhlich, T.; Münter, D.; Fehrenbach, H.; Giegrich, J.; Köppen, S.; Dünnebeil, F.; Knörr, W.; Biemann, K.; Simon, S.; Maier, S.; Albrecht, F.; Pregger, T. et al. Systemvergleich speicherbarer Energieträger aus erneuerbaren Energien (Texte, 68/2020). Umweltbundesamt. Dessau-Roßlau, 2020. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/texte_2020_68_systemvergleich_speicherbarer_energetraeger_aus_erneuerbaren_energien.pdf, last accessed on 2 May 2021.
- UBA - Umweltbundesamt (2021): Cames, M.; Böttcher, H.; Fuentes, U.; Wilson, R. Options for international cooperation to close the 2030 climate ambition gap, Policy field synthetic e-fuels (Climate Change, 02/2021). Umweltbundesamt. Dessau-Rosslau, 2021. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021_01_07_cc_02-2021_policy_paper_multilateral_initiatives_synthetic_e-fuels.pdf, last accessed on 2 May 2021.
- ULEMCo (2018a): ULEMCo to Demonstrate First Zero Emission Combustion Engine Truck, 2018. Online available at <http://ulemco.com/?p=2638>.
- ULEMCo (2018b): ULEMCo Works on Hydrogen Fuelled Marine Engines, 2018.
- UO - University of Oxford (2015): Bañares-Alcántara, R.; Dericks, G.; Fiaschetti, M.; Grünewald, P.; Masa Lopez, J.; Tsang, E.; Yang, A.; Ye, L.; Zhao, S. Analysis of Islanded Ammonia-based Energy Storage Systems. University of Oxford. Oxford, 2015.
- USGS - United States Geological Survey (2020): Nitrogen Statistics and Information, United States Geological Survey. Online available at <https://www.usgs.gov/centers/nmic/nitrogen-statistics-and-information>, last updated on 30 Dec 2020, last accessed on 30 Dec 2020.
- Valera-Medina, A.; Xiao, H.; Owen-Jones, M.; David, W.; Bowen, P. J. (2018): Ammonia for power. In: *Progress in Energy and Combustion Science* (69).
- Van Biert et al. (2016): review of fuel cell systems for maritime applications, 2016.
- van Vuuren, D. P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G. C.; Kram, T.; Krey, V.; Lamarque, J.-F.; Masui, T.; Meinshausen, M.; Nakicenovic, N. et al. (2011): The Representative Concentration Pathways: An Overview. In: *Climatic Change* 109 (1-2), pp. 5–31.
- Verbiest, J.; Janvier, T. (2019): Optimisation of a methanol-diesel dual-fuel marine engine. Online available at https://lib.ugent.be/fulltxt/RUG01/002/786/360/RUG01-002786360_2019_0001_AC.pdf, last accessed on 25 Dec 2020.
- Verhelst, S.; Turner, J. W. G.; Sileghem, L.; Vancoillie, J. (2019): Methanol as a fuel for internal combustion engines. In: *Progress in Energy and Combustion Science* 70, pp. 43–88. DOI: 10.1016/j.pecs.2018.10.001.
- Wärtsilä (2020): World's first full scale ammonia engine test - an important step towards carbon free shipping, Wärtsilä. Online available at <https://www.wartsila.com/media/news/30-06-2020-world-s-first-full-scale-ammonia-engine-test---an-important-step-towards-carbon-free-shipping-2737809>, last updated on 1 Feb 2021.
- WAZ (2017): Neues Kraftwerk am Baldeneysee produziert Methanol, 2017. Online available at <https://www.waz.de/staedte/essen/neues-kraftwerk-am-baldeneysee-produziert-methanol-id211143259.html>.
- WHO - World Health Organization (2021): Internationally Peer Reviewed Chemical Safety Information (INCHEM), World Health Organization. Online available at <http://www.inchem.org/#/search>, last accessed on 9 Apr 2021.
- WI - Wuppertal Institut für Klima, Umwelt, Energie; ISI - Fraunhofer Institut für System- und Innovationsforschung; IZES - Institut für ZukunftsEnergieSysteme gGmbH (2018): Viebahn, P.; Zelt, O.; Fishedick, M.; Wietschel, M.; Hirzel, S.; Horst, J. Technologien für die Energiewende, Technologiebericht - Band 2. Teilbericht 2 zum Teilprojekt A im Rahmen des strategischen BMWi-Leitprojekts „Trends und Perspektiven der Energieforschung“ (Wuppertal Reports, 13.2). Wuppertal Institut für Klima, Umwelt, Energie; Fraunhofer Institut für System- und Innovationsforschung; Institut für ZukunftsEnergieSysteme gGmbH. Wuppertal, 2018.
- WIN GD (2020). Next-generation technologies to safeguard LNG-fuelled engine investments. WIN GD, 2020. Online available at <https://www.wingd.com/en/documents/general/papers/next-generation-technologies-to-safeguard-lng-fuelled-engine-investments/>, last accessed on 9 Apr 2021.
- WT - Waste Today (2015): United Airlines invests \$30 million in Fulcrum BioEnergy, Waste Today. Online available at <https://www.wastetodaymagazine.com/article/united-fulcrum-waste-biofuels-aviation/>, last accessed on 1 Feb 2021.

8 Annex

8.1 Future trends and scenarios

Table 43 to Table 48 provide an overview of the main assumptions of the different energy demand and GHG emission projections for international maritime shipping and aviation, with the focus on the underlying growth scenarios.

Table 43: Growth scenarios and other assumptions underlying Fourth IMO GHG Study 2020 projections considered in study

Scenario*	RCP	SSP/alternative growth scenario	Model used for transport work projection
SSP2_RCP2.6_G	RCP2.6	SSP2	Gravity model
SSP2_RCP2.6_L	RCP2.6	SSP2	Logistic model
SSP4_RCP2.6_G	RCP2.6	SSP4	Gravity model
SSP4_RCP2.6_L	RCP2.6	SSP4	Logistic model
OECD_RCP2.6_G	RCP2.6	OECD	Gravity model
OECD_RCP2.6_L	RCP2.6	OECD	Logistic model

Notes: *Name of scenario indicates RCP-SSP combination.

Source: IMO (2020a), authors' own compilation

Table 44: Growth scenarios and other assumptions underlying CE Delft und Lee (2019) projections considered in this study

Scenario	RCP	SSP/ alternative growth scenario	LNG up-take	Emission control area	Efficiency improvement in 2050	Fuel price scenario
1.6°C - Sustainability - high efficiency	RCP2.6	SSP1	low	no extra	high	RCP2.6
1.6°C - Middle of the Road - high efficiency	RCP2.6	SSP2	low	no extra	high	RCP2.6
1.6°C - Inequality - high efficiency	RCP2.6	SSP4	low	no extra	high	RCP2.6
1.6°C - OECD GDP projection - high efficiency	RCP2.6	OECD 2018 projections	low	no extra	high	RCP2.6

Source: CE Delft und Lee (2019), authors' own compilation

Table 45: Growth scenarios underlying DNV GL

Scenario	RCP	SSP
DNV GL (2017a), High trade growth scenario	2.6	3
DNV GL (2017a), Moderate trade growth scenario	'Rather low Growth has been assumed' (Equal or lower growth compared to High Growth (RCP2.6; SSP3) scenario)	
DNV GL (2017c)	'We forecast that trade measured as tonne-miles will experience 2.2% annual growth over the period 2015–2030 and 0.6% per year thereafter, driven mostly by non-energy commodities'	

Source: DNV GL (2017c; 2017a), authors' own compilation

Table 46: EUROCONTROL Challenges to Growth - scenario assumptions

Scenario	Target year	Short description	GDP growth	Free trade	Price of CO ₂ in ETS	Price of oil
Global Growth	2040	Strong global economic growth with technology used to mitigate environmental challenges. This is a high growth scenario.	Stronger	Global, faster	Moderate	Low
Regulation and Growth	2040	Moderate growth regulated to reconcile demand with environmental sustainability issues. This is assessed to be the most likely of the four.	Moderate	Limited, later	Lowest	Lowest
Fragmenting World	2040	A world of increasing tensions and reduced globalisation, as barriers to free trade multiply.	Weaker	None	Highest	High
Happy Localism	2040	Like Regulation and Growth, but with a fragile Europe increasingly and contentedly, looking inwards for trade and travel. In other words, 'small is beautiful'.	Weak	More limited, even later	Lowest	Highest

Source: EUROCONTROL (2018)

Table 47: IEA World Energy Outlook - scenario assumptions

Scenario	Target year	Short description	GDP growth	Population growth	Price of CO ₂ in ETS	Price of oil per barrel	Efficiency improvement p.a. in aviation
Current Policies	2040	Incorporates only those instruments, which have been implemented by 2016	3.4% p.a.	9.2 billion in 2040	40 \$ (2015) in 2040	146 \$ (2015) in 2040	n.a.
New Policies	2040	Central Scenario, incorporates current instruments and energy policies in line with commitments of the Paris Agreement	3.4% p.a.	9.2 billion in 2040	50 \$ (2015) in 2040	124 \$ (2015) in 2040	2.0%
450	2040	Alternative scenario with a 50% chance of limiting global warming to 2°C	3.4% p.a.	9.2 billion in 2040	140 \$ (2015) in 2040	78 \$ (2015) in 2040	2.6%

Source: IEA (2016)

Table 48: BP Energy Outlook - scenario assumptions

Scenario	Target year	Short description	GDP Growth	Population growth	Total energy demand growth p.a.
More Energy	2040	More energy will be needed in future, as around two-thirds of the world's population in 2040 still live in countries in which average energy consumption per head is relatively low	3.2% p.a.	9.2 billion in 2040	n.a.
Evolving Transition	2040	Continuation of policies on defossilization; improvement in living standards will lead to growth in energy demand; carbon emissions will still rise by 0.3% p.a. until 2040	3.2% p.a.	9.2 billion in 2040	1.2% p.a.
Less Globalisation	2040	Escalation of trade disputes, lower GDP growth, more domestically produced energy	2.9% p.a.	9.2 billion in 2040	n.a.
Rapid Transition	2040	Carbon emissions will be reduced by 45% in 2040	3.2% p.a.	9.2 billion in 2040	0.8% p.a.

Source: BP (2019)

8.2 Political action fields

Table 49: European (EU/EFTA) refineries producing jet fuel/kerosene

Country	Location	Name	Operator	Jet fuel	Total capacity (million tonnes p.a.)
AT	Vienna	Schwechat Refinery	OMV	Jet A-1	9.6
BE	Antwerp	Exxon Mobil Antwerpen Raffinerie	ExxonMobil	Kerosene	16.0
BE	Antwerp	Total Antwerpen Raffinerie	Total	Jet fuel	18.0
BG	Burgas	Neftochim Burgas Refinery	Lukoil	Jet fuel	7.0
HR	Rijeka	Rijeka Refinery	INA (MOL)	Kerosene	4.5
HR	Sisak	Sisak, 50 km from Zagreb	INA (MOL)	Jet fuel	2.2
CZ	Kralupy Refinery	Kralupy	Unipetrol / Ceska Rafinerska (Part of PKN Orlen)	Jet A-1	3.3
CZ	Litvinov Refinery	Litvinov	Unipetrol / Ceska Rafinerska (Part of PKN Orlen)	Aviation fuels	5.5
DK	Fredericia	Fredericia Refinery	Shell	Jet fuel, Kerosene	3.4

DK	Kalundborg	Kalundborg Refinery	Statoil	Jet fuel	5.5
FR	Marseille	Berre L Etang Refinery	Lyondell Basell	Jet fuel	4.0
FR	Le Havre	Gonfreville L Orcher Refinery / Normandy Refinery	Total	Jet fuel	12.0
FR	Marseille	Lavera Marseilles Refinery	Ineos	Jet fuel	10.0
FR	130km nw Paris	Petit Couronne Refinery	Petroplus	Jet fuel	8.0
FR	Port Jerome	Port Jerome Gravenchon Refinery	ExxonMobil	Kerosene	11.5
FR	Feyzin		Total	Jet fuel	6.0
DE	Vohburg&Neustadt	Bayernoil	Raffinerieverbund VARO, BP, Rosneft, Eni	Jet fuel	10.3
DE	Lingen	BP Lingen	BP	Jet fuel	4.7
DE	Sachsen-Anhalt	Buna Sow Leuna Refinery	Total	Jet fuel	12.0
DE	Burghausen	Burghausen Raffinerie	OMV	Jet fuel	3.8
DE	Hamburg	Hamburg Holburn Refinery	Tamoil	Kerosene	4.7
DE	Ingolstadt	Petroplus Ingolstadt	Gunvor	Jet fuel	5.5
DE	Gelsenkirchen	Raffinerie Gelsenkirchen	Ruhr Oel GmbH - BP Gelsenkirchen/Rosneft	Jet fuel	2.32
DE	Schwedt	Schwedt refinery	PCK Raffinerie GmbH	Jet fuel	12.0
DE	Cologne area	Shell Rheinland	Shell	Jet fuel	16.6
GR	Aspropyrgos Refinery	Aspropyrgos/Athens	Helenic Petroleum	Jet fuel	7.5
GR	Aegii Theodori, 70kms Athens	Corinth Refinery	Motor Oil Hellas	Jet fuel	9.0
GR	Elefsina	Elefsina Refinery	Helenic Petroleum	Jet fuel	5.0
HU	Szazhalombatta	Danube Duna Refinery	MOL	Jet fuel	8.1
IR	Cork	Whitegate	Irving	Kerosene	3.5
IT	Augusta	Esso Augusta Refinery	Sonatrach (ex ExxonMobil)	Jet fuel	9.5
IT	Geneva	Iplom Busalla Refinery		Jet fuel	2.0
IT	Priolo	ISAB Refinery	Lukoil	Jet fuel	16.0
IT	Sicily	Milazzo Refinery	ENI/KNPC	Kerosene	8.0
IT	Po Valley	Sannazzaro de Burgondi Refinery	ENI	Jet fuel	9.0
IT	Trecate/Po Valley	Sarpom Trecate, Novara Refinery	Exxon/ERG	Jet fuel, kerosene	8.0
IT	Sardinia	Sarroch Refinery	SARAS	Jet fuel	15.0
LT	North-West of Lithuania	Mazeikiu Nafta Refinery	PKN Orlen	Jet A-1	9.0
NL	Rotterdam	Botlek Refinery	ExxonMobil	Kerosene	9.1

NL	Rotterdam	Europoort BP	BP	Jet fuel	20.0
NL	Rotterdam	Shell Pernis Refinery	Royal Dutch Shell	Kerosene	21.0
NL	Rotterdam	VPR (ex Koch)	Vitol Refining Group BV	Jet fuel	4.0
NO	Mongstad	Mongstad Refinery	Statoil	Jet fuel	8.0
NO	Slagentangen	Slagen Refinery	ExxonMobil	Aviation fuels	6.0
PL	Gdansk	Gdansk Refinery	Lotos	Jet fuel	10.5
PL	Plock	Plock Refinery	PKN Orlen	Jet fuel	14.1
PT	Porto	Porto Refinery, Matosinhos	Galp	Jet A-1	5.5
PT	Sines	Sines Refinery	Galp	Jet fuel	10.8
RO	near Ploiesti City	Petrobrazi Ploiesti Refinery	OMV Petrom	Jet A-1	4.5
RO	Constanza	Petromidia Constanza Refinery	Rompetrol	Jet A-1	5.0
ES	Bilbao/Somorrostro	Bilbao Refinery	Petronor	Kerosene	12.0
ES	Cartagena, Murcia, Spain	Cartagena Refinery	repsol	Kerosene	11.0
ES	Castellon	Castellon Refinery	BP	Kerosene	5.5
ES	Gibraltar-San Roque	Gibraltar Refinery	CEPSA	Aviation fuels	12.0
ES	La Coruna	La Coruna Refinery	repsol	Kerosene	5.5
ES	Puertollano	Puertollano Refinery	repsol	Jet fuel	7.5
ES	Tarragona	Tarragona	repsol	Jet fuel	9.4
ES	Tenerife	Tenerife Refinery	CEPSA	Kerosene	4.5
SE	Gothenburg	Preemraff Göteborg Refinery	Preem	Aviation fuels	5.0
SE	Gothenburg	ST1 Göteborg Refinery (ex Shell)	ST	Kerosene, Jet fuel	4.0
CH	Cressier	Cressier Refinery	VARO	Jet fuel	3.4
UK	Southampton	Fawley Southampton Refinery	ExxonMobil	Jet fuel	15.5
UK	Grangemouth, East Coast of Scotland, UK	Grangemouth Refinery	Petroineos	Jet fuel, kerosene	10.5
UK	North Lincolnshire, UK	Humber Refinery	Phillips 66	Jet fuel, kerosene	11.5
UK	North Killingholme, Lincolnshire	Lindsey Oil Refinery	Total	Jet fuel	11.0
UK	Pembroke, Milford Haven, West Wales	Pembroke Refinery	Valero	Jet fuel, kerosene	10.5
UK	South of the Mersey estuary near Ellesmere Port, UK	Stanlow Refinery	Essar	Jet fuel, kerosene	13.5

Sources: Author's own compilation based on various sources, including: ABF (2014), industryabout.com, company websites, McKinsey (2019)

8.3 Roadmaps for achieving zero emissions

Table 50: Assessment of e-fuels

	Hydrogen	Ammonia	Methane	Methanol	Propane	DME	Diesel
Environmental criteria	5.0	4.7	2.0	4.3	4.0	4.3	4.5
Reduction potential	7	7	-7	7	5	7	7
Energy efficiency production	7	5	3	3	3	3	1
Land consumption	7	4	1	1	1	1	1
Toxicity	7	1	7	4	7	7	4
Flammability	1	7	1	4	1	1	7
Explosion risks	1	4	7	7	7	7	7
Readiness	2.4	2.8	6.0	4.6	2.8	2.6	5.4
Readiness - Production	7	7	3	3	3	3	1
Readiness - Ships	1	2	7	5	4	3	7
Flexibility (drop-in)	1	1	7	4	1	1	7
Readiness - Ports, transport infrastructure	1	3	6	5	3	4	7
Readiness - Institutional, legal	2	1	7	6	3	2	5
Costs	4.0	3.8	3.5	4.0	3.3	3.5	5.3
Costs fuel	7	5	2	2	2	2	1
Energy density (loss of cargo space)	1	2	4	3	6	5	7
CAPEX ship	1	4	2	5	3	5	7
Synergies (other sectors/processes)	7	4	6	6	2	2	6

Note: Relative assessment: 7 = positive, 1 = negative.

Source: Authors' own compilation

Table 51: Stakeholder perspectives

	Equal distribution	Emphasis GHG reduction	Ship owner perspective	Environment first	Fast deployment	Hansson et al. (2019)
Environmental criteria						
Reduction potential	7%	16%	5%	17%	4%	9%
Energy efficiency production	7%	16%	5%	17%	4%	10%
Land consumption	7%	5%	3%	7%	4%	4%
Toxicity	7%	5%	8%	10%	4%	5%
Flammability	7%	5%	8%	7%	4%	8%
Explosion risks	7%	5%	8%	7%	4%	8%
Readiness						

Readiness production	7%	5%	5%	3%	11%	13%
Readiness ships	7%	5%	5%	3%	11%	5%
Flexibility (drop-in)	7%	5%	5%	3%	11%	5%
Readiness ports, infrastructure	7%	5%	5%	3%	11%	5%
Readiness institutional, legal	7%	5%	5%	3%	11%	5%
Costs						
Costs fuel	7%	5%	13%	3%	4%	10%
Energy density (loss of cargo space)	7%	5%	13%	3%	4%	3%
CAPEX ship	7%	5%	13%	3%	4%	5%
Synergies (other sectors/processes)	7%	5%	3%	7%	4%	4%

Notes: Weighting of the criteria from different stakeholder perspectives; each column adds to 100%.

Source: Authors' own compilation

Table 52: Overall results

	Hydrogen	Ammonia	Methane	Methanol	Propane	DME	Diesel
Equal distribution	3,9	3,8	3,7	4,3	3,4	3,5	5,0
Emphasis GHG reduction	4,5	4,3	2,5	4,5	3,5	3,8	4,8
Ship owner perspective	3,5	3,8	3,6	4,2	3,7	3,9	5,2
Environment first	5,0	4,3	2,4	4,5	3,7	4,1	4,7
Fast deployment	3,4	3,5	4,5	4,4	3,2	3,2	5,1
Hansson et al. (2019)	4,4	4,4	3,2	4,3	3,4	3,6	4,5
Average	4,1	4,0	3,3	4,4	3,5	3,7	4,9

Notes: Assessment weighted by stakeholder perspectives (columns of Table 50 multiplied columns of Table 51).

Source: Authors' own compilation