European Technology and Innovation Platform

Orientation Paper and Action Plan

ETIP Bioenergy Working Group 3 Distribution & End-use - 2021

Status: 15 March 2021

1. CONTEXT

Where we are today in Europe

Transport is a major contributor to GHG emissions in Europe:

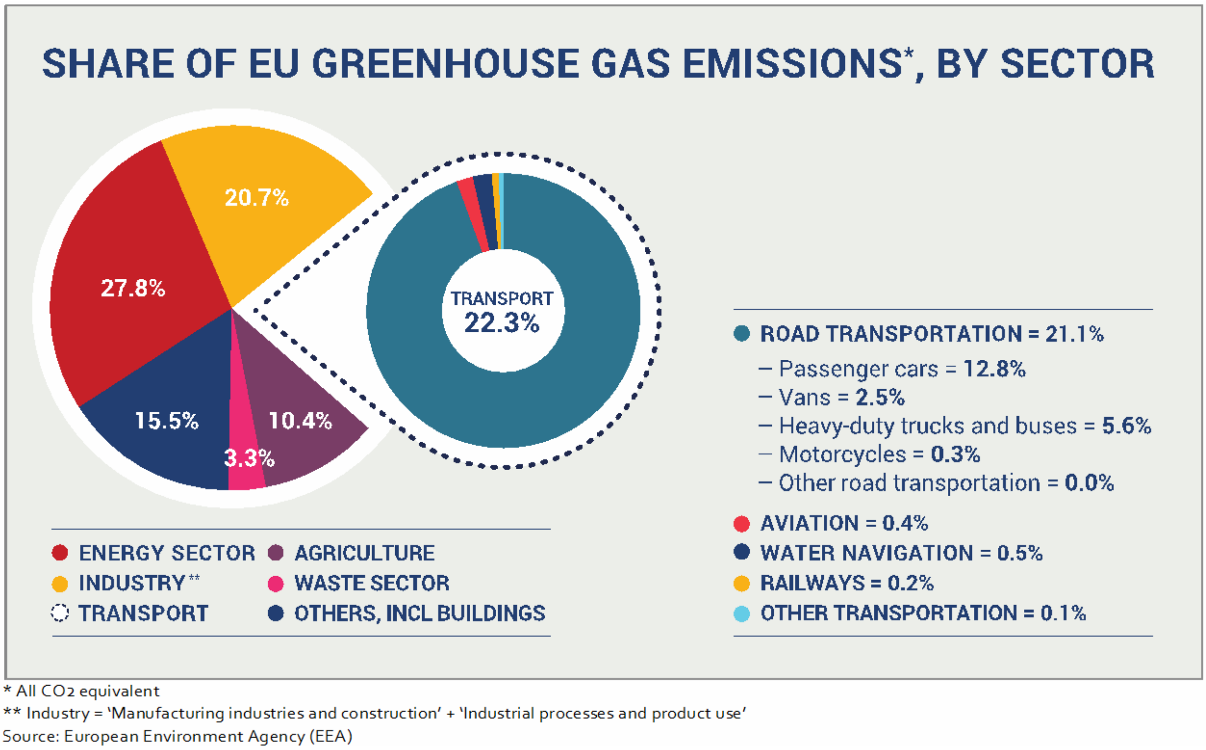

Figure 1: Share of EU greenhouse gas emissions by sector (Source: European Environment Agency).

Emissions in transport are steadily rising worldwide: significant energy efficiency improvements are offset by the sustained growth in demand, the ageing of the mobility fleets and the slow acceptance and integration of lower carbon footprint mobility solutions, when they exist (e.g. electricity or hydrogen in road transport).

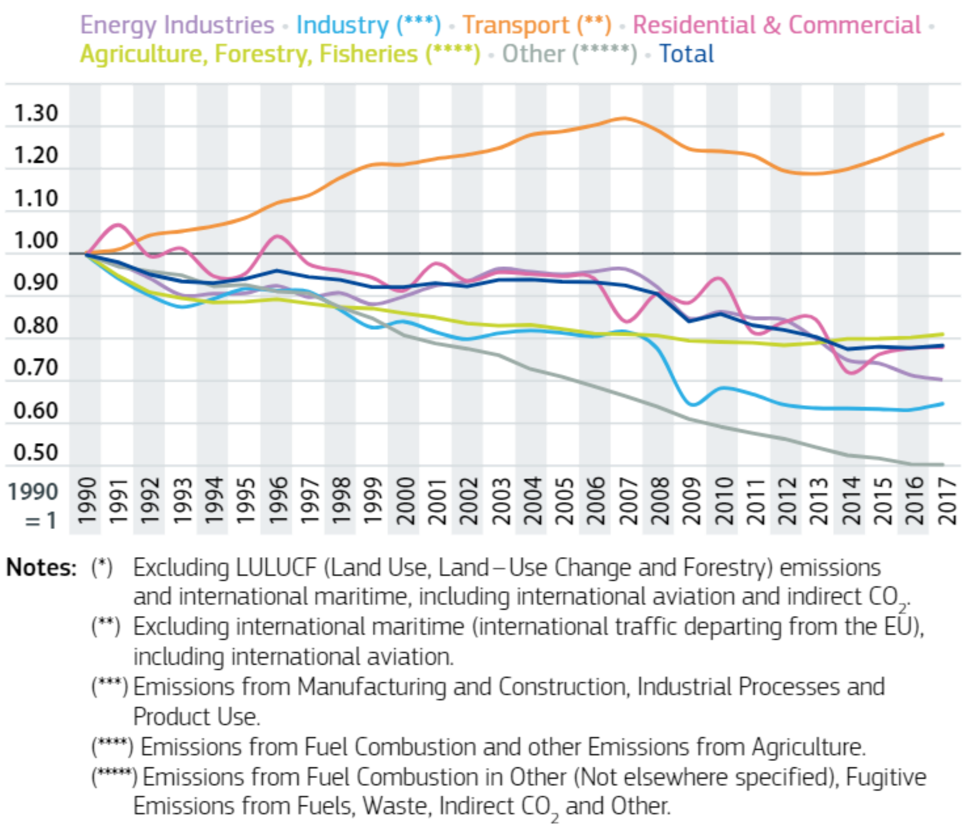

Figure 2 : GHG emissions (EU28) by sector (Source : European Environment Agency (EEA), 2019).

In the recent impact assessment done by the European Commission as part of the Green Deal, modeling shows that liquid biofuels will still play a role in transport in 2050 (Figure 3).

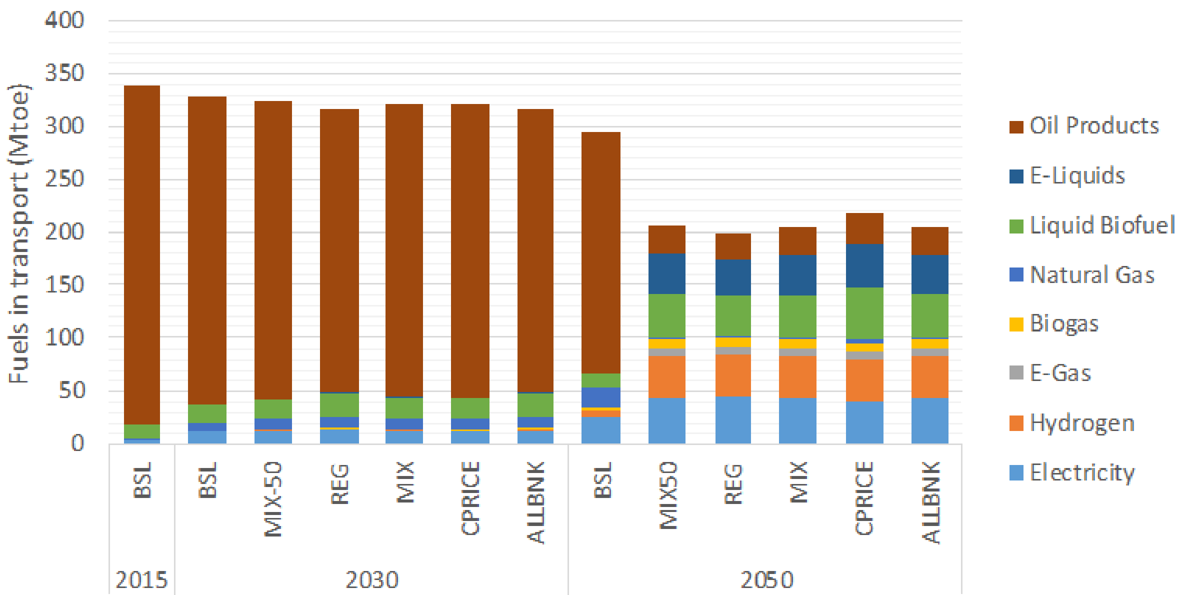

Figure 3 : Fuels in transport, incl. aviation and maritime navigation (Source : Primes model).

2. REGULATIONS

CO2 emissions in road transport in Europe are addressed through two distinct regulations:

1) on fuels, Well-to-Tank (WtT), enforced on the fuels production & distribution industry, covered under RED (Renewable Energy Directive),

2) on new vehicles fleet, Tank-to-Wheel (TtW), enforced by OEMs, mainly LDV and HDV manufacturers. For the aviation industry, ICAO has formulated a standard on GHG emissions applicable to aircraft and turbine manufacturers.

A global carbon footprint reduction obviously comes from a WtW perspective, i.e. from a combination of WtT and TtW measures, benefiting from synergies between fuels and engines progresses.

To be noted: excerpt from the ACEA (road transport OEMs association) recommendation in the 10-point plan for the European Green Deal https://www.acea.be/publications/article/paving-the-way-to-carbon-neutral-transport-10-point-plan-to-help-implement-the-European-Green-Deal, *that proposes* ***a concept of a 'well-to-wheel with split responsibilities' that could be applied post-2030*** *to properly account for the performance of both vehicles and energy carriers.*

2.1 Fuels regulations

Two distinct and complementary regulations: fuel renewable content and fuel quality.

2.1.1 Directive on the promotion of the use of energy from renewable sources (RED II)

Directive 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources (RED II) was published in the Official Journal of the European Union on 21 December 2018. Member States will have to transpose it by 30 June 2021, after which RED I will be repealed. The overall share of renewable energy in the European energy mix should be at least 32% by 2030, an obligation that Member States will meet collectively. In addition, RED II stipulates mandatory biofuels sustainability criteria of at least 50% GHG reduction vs. fossil reference (-60% for units started after 2018 and -65% for units started after 2021).

In the transport sector, fuel suppliers in each Member State will be required to incorporate at least 14% of renewable energy by 2030, following an indicative trajectory set by each national government. If a Member State decides to lower the maximum contribution that food & feed crop-based biofuels can make, it can reduce the transport target in the same proportion. Additionally, a sub-objective of incorporation of advanced biofuels, those coming from residues of biological origin, is established.

The food & feed crop-based biofuels cap is set at each Member State 2020 consumption level, which can be increased by 1% within a maximum of 7%. Members States with food & feed crop-based biofuels incorporation under 1% can set their cap up to 2%. Biofuels produced from feedstock that have been

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produced from feedstock classified as high ILUC-risk will be progressively phased-out from 2023, unless they are certified as low-ILUC risk biofuels. A delegated act will define the high and low-ILUC risk biofuels feedstock and certification.

Advanced biofuels and biomethane for transport, made from Annex IX-A feedstock (e.g. wheat straw or Municipal Solid Waste), are incentivized through a dedicated ramping-up sub-target reaching 3.5% in 2030. Annex IX-A and B biofuels can be double counted towards the transport target, with Annex IX-B biofuels contribution (produced from Used Cooking Oil and animal fats) capped at 1.7% (before double counting). Biofuels used in the aviation and maritime sectors see their contribution counted 1.2 times, except crop-based ones. Renewable electricity in transport is also incentivized with the use of multipliers: four times for renewable electricity in road transport and 1.5 times in the rail sector. Finally, once taken into account the multipliers, the overall target of 14% of renewable should be understood as an administrative target, with a physical share of renewables that is likely to be lower.

To be noted: whenever the term biofuel is used in this orientation paper, it concerns liquid and gaseous biofuels.

To be noted: RED II has to be translated in Member States national laws, which may adjust the above requirements.

2.1.2 Fuel Quality Directive 2009/30/EC

Fuel Quality Directive (FQD) was published in 2009 and applies to road fuels only, aviation fuels abide with the International Civil Aviation Organization (ICAO, a United Nations agency) regulations, based on American Standards for Testing Materials (ASTM) standards, marine fuels abide with the International Maritime Organization (IMO) standards.

The Fuel Quality Directive sets technical specifications based on health and environment grounds for fuels to be used in positive ignition and compression ignition engines, taking into account the technical requirements of these engines. In addition, article 7a of the FQD sets a reduction target of at least 6% GHG emissions per unit of energy by 31 December 2020 compared to 2010.

European technical standards for fuels are drafted by the CEN (European Committee for standardisation), include fuel requirements set in FQD among other technical parameters. EN 228 sets the standard for EU petrol whilst EN 590 is for European diesel. The FQD and the CEN standards can limit the quantity of biocomponents that could be blended in fossil fuels, and thus will have to be updated to be consistent with the Renewable Energy Directive II.

It is of great importance that all relevant data gained in research projects are made available to standardization committees and that the research institutions, as well as companies, take part in the standardization work. The standardization of novel fuels plays a major role to ensure a swift decarbonization of the transport sector. Harmonization ensures a common European basis of transport options and should therefore be pursued.

Petrol

Parameters directly related to oxygenated biocomponents (to be noted: octane and vapor pressure are the key impacted specifications):

• Oxygen content (max. 3.7% m/m), for air-fuel ratio control

• Ethanol (max. 10% v/v): oxygen content (10% v/v ethanol equals 3.7% m/m oxygen); material compatibility, ethanol is corrosive and polar, can attack metals and elastomers; ethanol has a lower energy density, leading to comparatively higher fuel consumption

• Methanol (max. 3% v/v): material compatibility (methanol worse than ethanol), higher vapor pressure and environmental concerns regarding its toxicity in the environment

• Higher alcohols and ethers (12...22% v/v): oxygen content, less material issues than with ethanol

Diesel

Parameters directly related to biocomponents:

• FAME content (max. 7% v/v):

- Some material issues (elastomers)
- High end of distillation temperature
- Possible issues with engine oil dilution (higher boiling point than diesel)

2.2 Vehicles regulations

A lot will be delivered by the road transport industry over the coming decade:

- By 2030, CO2 emissions from the transport sector, non-ETS, will have to be 60% lower than a 2005 baseline.
- In accordance with Regulation 2019 (631) setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles:
  - CO2 emissions from new passenger cars will have to be reduced by 37.5% by 2030 vs 2021 average. Under the Green Deal action plan (COM 2019/940) the review of the target is scheduled for 2021 instead of the 2023 mentioned in the Regulation.
  - CO2 emissions from new light commercial vehicles will have to go down by 31% by 2030 vs 2021 average.
- In accordance with Regulation 2019 (1242), setting CO2 emission performance standards for new heavy-duty vehicles (https://eur-lex.europa.eu/eli/reg/2019/1242/oj), average CO2 emissions of new trucks and buses will have to be reduced by 30% compared to the 2019 baseline.

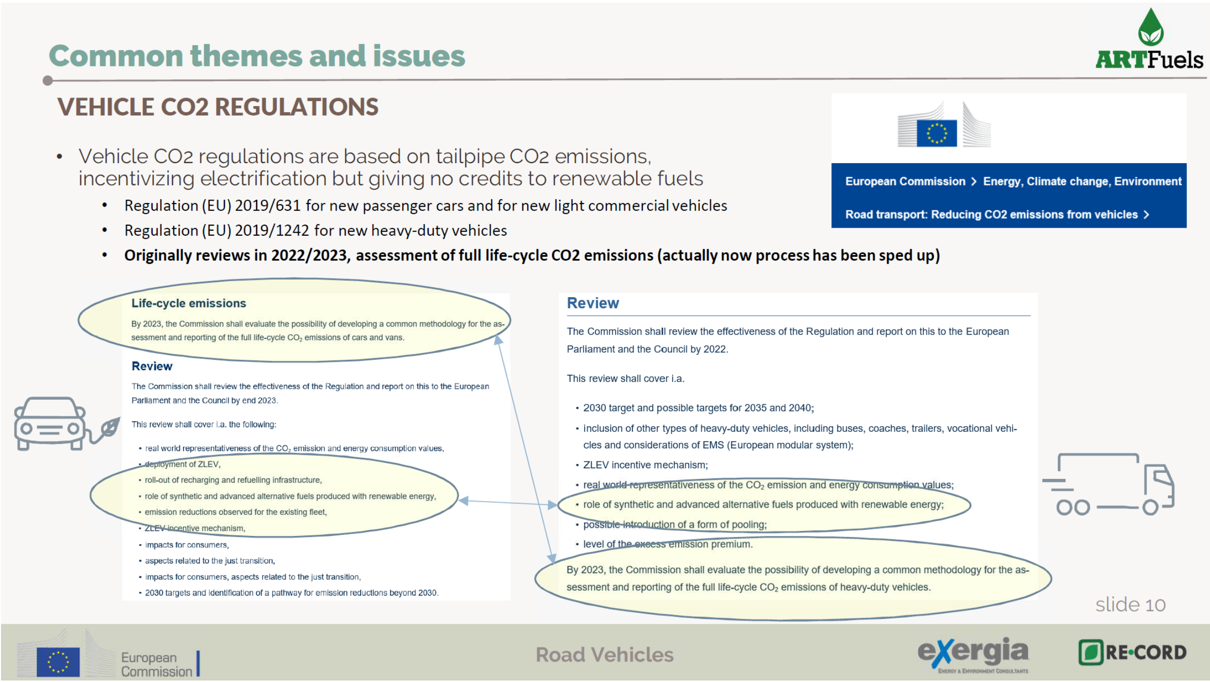


Figure 4: Vehicle CO_2 regulations (Source: ART Fuels Forum, 2020).

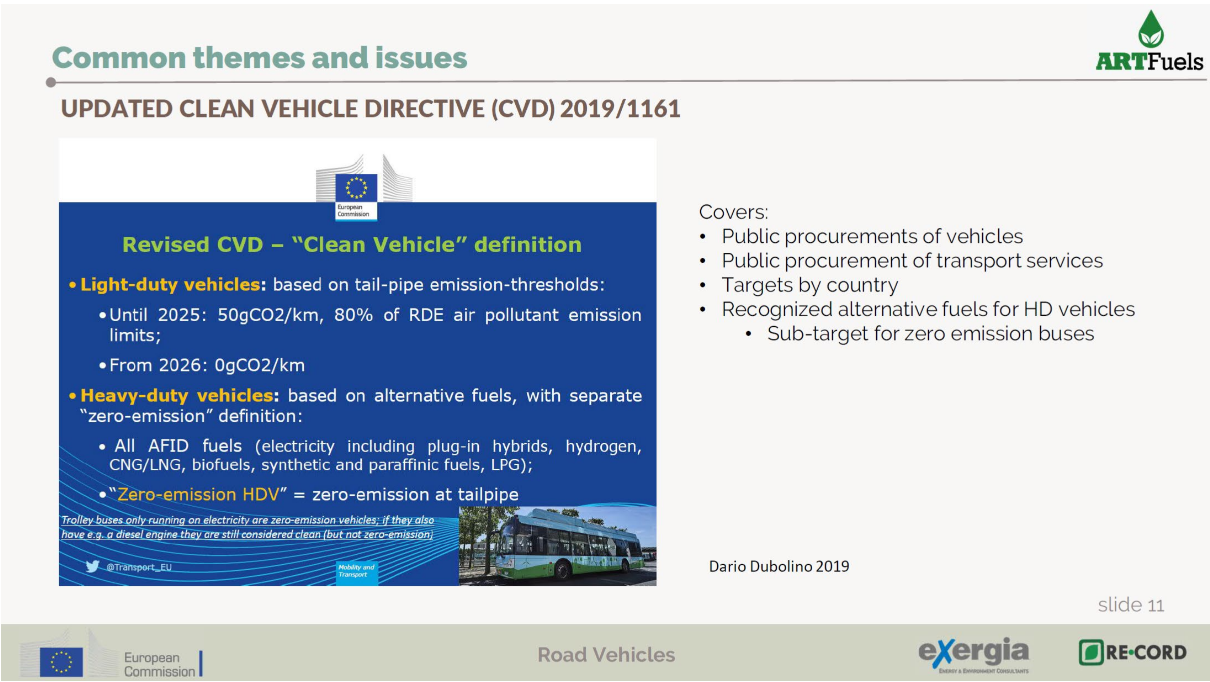


Figure 5: Updated Clean Vehicle Directive (CVD) 2019/1161 (Source: ART Fuels Forum, 2020).

3. CHALLENGES

3.1 Light Duty Vehicles (LDV)

In Europe, LDVs today mostly use petrol and diesel.

ON THE ROAD: THE EU VEHICLE FLEET BY FUEL TYPE

	PETROL	DIESEL	HYBRID ELECTRIC	BATTERY ELECTRIC	PLUG-IN HYBRID	LPG + NATURAL GAS	OTHER + UNKNOWN
CARS	54.0%	41.9%	0.7%	0.2%	0.1%	2.8%	0.3%
TRUCKS	1.0%	98.3%	0.02%	0.01%		0.4%	0.2%

Source: ACEA, Vehicles in use - Europe 2019 | Trucks = medium and heavy-duty commercial vehicles

Figure 6: The EU vehicle fleet by fuel type (Source : ACEA, 2019).

Electricity and hydrogen are foreseen to significantly expand in the next decades to allow the carbon footprint of transport to align with the global objectives of mitigating climate change. However, the pre-eminence of liquid, fossil fuels will not be challenged in the mid-term, implying efforts should be strengthened to reduce the intrinsic carbon footprint of liquid fuels, in coordination with the on-going efforts towards improving the energy efficiency of engines (lower fuel consumption implies lower GHG emissions).

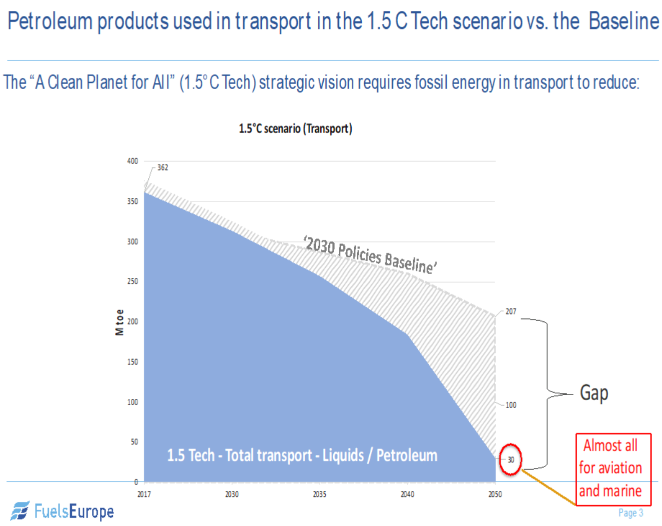


Figure 7: Petroleum products used in transport in the 1.5 C Tech scenario (Source: FuelsEurope).

3.1.1 Petrol LDV

Renewable fuels (biofuels) have been incorporated in petrol in Europe since the '90s, with a significant acceleration since 2010 and the implementation of the Renewable Energy Directive (RED I). Oxygenated molecules, e.g. ethanol and ETBE, are historically the most common and available renewable components.

As stated in the Context chapter, the commercial fuel oxygen content is the limiting factor, called "Blend Wall ", due to technical reasons (compatibility), for the incorporation of oxygenated molecules in existing petrol-powered Internal Combustion Engines (ICE). E10 (max. 10% volume ethanol incorporation in fossil-based petrol) is the base petrol grade in Europe (EN228 standard), E5 (max. 5% volume ethanol) being the protection grade for vehicles whose engine could not accept E10, mostly built before 2000.

RED I is calling for min. 10% renewable energy in transport by 2020, with a max. cap of 7% for first generation biofuels, i.e. produced from food & feed crops. For RED II 2030 target of min. 14% renewable in transport, 7% capped first generation biofuels are to be complemented by "advanced" biofuels produced from waste & residues (see Regulations paragraph above), putting the onus on raw materials origin and sustainability of the value chain.

Challenge # 1: E10 is not yet the main petrol grade in Europe

E10 (petrol with max 3.7% oxygen content) is under-deployed in Europe: in 2019, 13, out of 28, countries marketed this base grade, with penetrations as low as 14% in Germany, despite the fact that the large majority of EU petrol vehicles are compatible with E10, as stated in ACEA E10 compatibility list (https://www.acea.be/uploads/publications/ACEA_E10_compatibility.pdf).

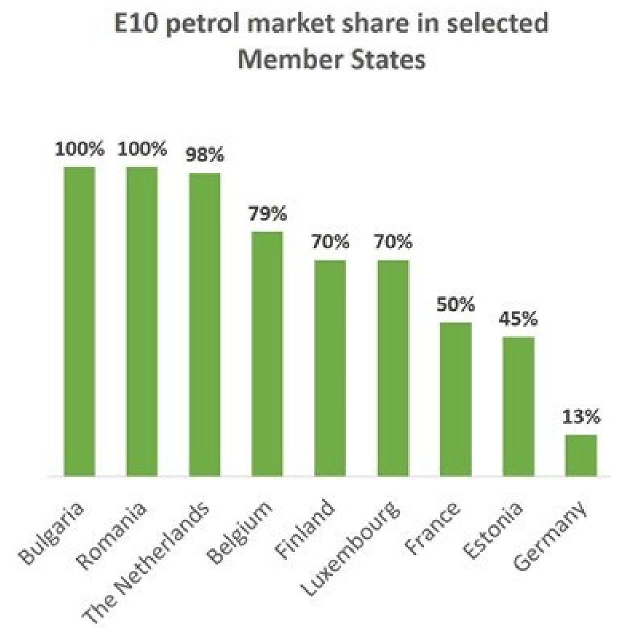


Figure 8: E10 petrol market share in selected Member States (Source: ePure).

Challenge # 2: Maximum ethanol/ oxygenates incorporation in existing ICEs (E10+)

Compatibility of petrol containing oxygenated molecules with the existing petrol-powered ICEs is the key issue to determine the maximum incorporation rate of these bio-molecules, or ultimate blend wall.

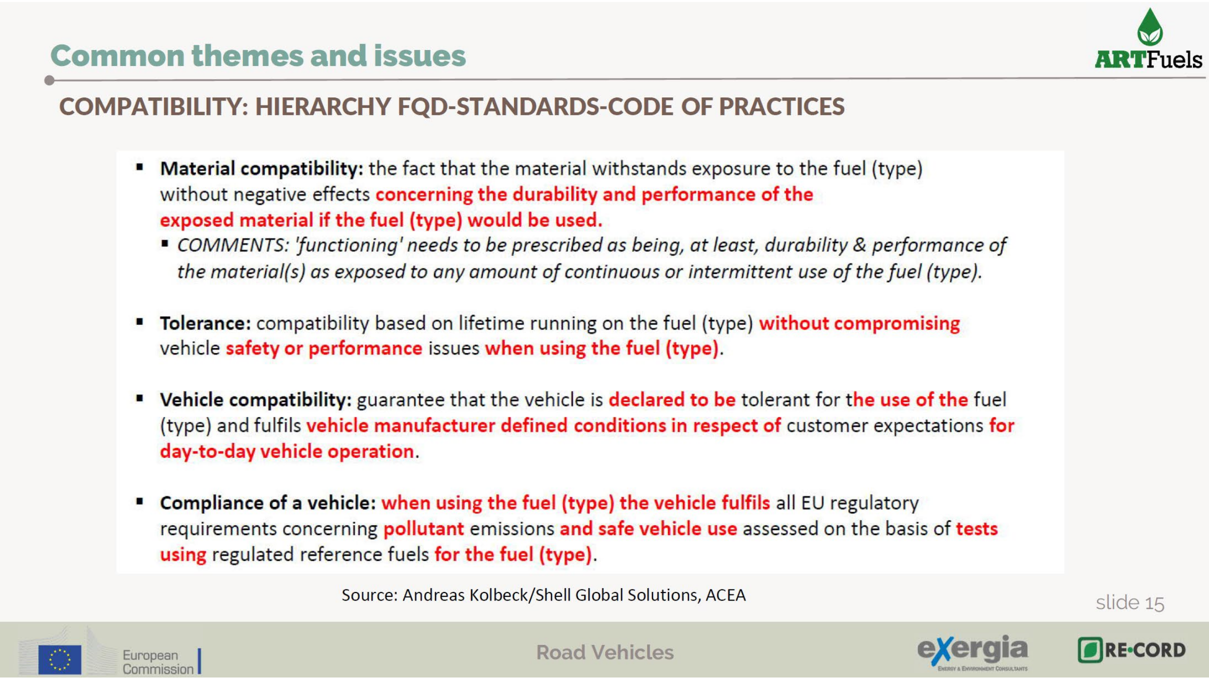


Figure 9: Hierarchy FQD-Standards-Code of Practices (Source: Kolbeck/Shell Global Solutions, ACEA).

Most studies so far estimate max. volume of ethanol at 20-25% for future designed vehicles:

Among most recent studies on E10+: in 2019, the European Standardization Committee (CEN) finalized the project entitled "Engine tests with new types of biofuels and development of biofuel standards", funded by the Horizon 2020 Program. The objective of the project was to study the overall sensitivity of future (Euro 6c technology) vehicles and the fuel logistics' system towards mid-blend oxygenate ("E20/25") petrol; E4tech (UK) Ltd November 2019 study. According to the literature review done in this project, manufacturers suggest that the majority of cars produced in the EU from 2011 onwards are "E20 tolerant", but more research is needed to ensure compatibility with future engines.

Raising octane could be an enabler for higher oxygenated molecules incorporation rates, higher octane is also of interest to boost efficiency (5% improvement can be reached in real driving conditions on an adapted engine by using RON 102 instead of RON 95) (reference Concawe report 8/20 https://www.concawe.eu/wp-content/uploads/Rpt_20-8.pdf), especially in the newer generations of SI turbo charged engines.

Challenge # 3: Deployment of E85 compatible vehicles (Flex Fuel Vehicles, FFV) remains local

Since the Seventies, Brazil is using FFVs, allowing the ethanol content in petrol to reach up to 40%: in this country, where bioethanol is locally produced from sugar cane, a stable regulation supporting the use of high blends of ethanol (up to 100%) has led most customers to buy FFVs. The situation is different in

Europe, where emphasis has been on low blending of ethanol (first, E5, then, E10). In Europe, E85 fuel (ethanol levels up to 85%) has been introduced in some countries, e.g. Sweden and France. The introduction of E85 and FFV encountered mixed success due to uncertainties of fiscal incentives, limited fueling infrastructure, limited acceptance of customers, thus limited FFV offer by car manufacturers.

In France, retrofit of existing engines by specialized companies to use E85 fuel is possible since 2017 and supported an increase of the E85 sales due to very favorable tax incentives. Retrofitting is not supported by OEMs as petrol vehicles have not been developed to perform with high levels of ethanol.

Challenge # 4: Maximization of renewable hydrocarbons incorporation into petrol for existing vehicles and infrastructure

Renewable hydrocarbons have a considerable advantage compared to oxygenated bio-molecules: their similarity to crude oil-based fossil hydrocarbons implies that no adaptation to, either distribution infrastructure, or existing engines, is necessary. As such, their development should be a priority, especially for petrol.

There are several possibilities to manufacture renewable hydrocarbons. Besides synthesis pathways, using renewable materials, such as biomass, directly, or bio-methane, and that can be orientated toward the production of petrol components, two readily and cost-competitive pathways to obtain renewable hydrocarbons must be mentioned:

- Bio-naphtha, a co-product of thermo-chemical bio-pathways, such as lipids hydrogenation (producing renewable diesel, HVO), that transform biomass via a breakdown and/or reconstruction / reconfiguration in hydrocarbons. As a renewable petrol boiling-range component, bio-naphtha can be incorporated in petrol recipes, with the main limitation being its octane level, or upstream in the crude oil refining process scheme, as a bio-component. Bio-naphtha availability depends on the availability of the underlying thermo-chemical process.

- Co-processing: biomass fractions can be co-processed with crude oil-derived fractions in crude oil refineries, the process units where this co-processing takes place delivering various yields of petrol boiling-range components that can be eligible as bio-content. The limitations to co-processing are technical (capability of process units to accept biomass-based, oxygen-containing, feedstocks), economical (relative profitability of processing biomass-based feedstocks), regulatory (eligibility of bio-content, essentially not measured, but indirectly calculated, for instance by mass balance), but are a way for crude oil refiners to reduce the carbon footprint of their activity and products.

Challenge # 5: Incorporation of other oxygenates, methanol, butanol, into petrol

- Methanol: presently limited in EU at 3% vol. maximum in European petrol standard EN228, mostly due to material compatibility and volatility constraints. In China, M15, a petrol with 15% vol. methanol, is standardized, along with M85, M100. In Italy, a national standard for A20 (20% alcohol, 15% methanol, 5% ethanol) exists.
- Butanol: the present limit of oxygenates in petrol being the oxygen content, higher alcohols like iso-butanol, can be blended with petrol, at higher rates, with additional performances in octane and vapor pressure, but are not today, as the industry is historically producing ethanol, from sugar or starch.

Ethers: ETBE, a compound produced from butene and ethanol, MTBE (butene and methanol), TAME (pentene and methanol) are oxygenates, with technical merits vs ethanol (compatibility), that have been and are incorporated in petrol as bio-components.

Challenge # 6: Gas powered vehicles limited by infrastructure constraints

Initially mostly powered by Liquefied Petroleum Gas (LPG), the offer of petrol-powered modified engines (CNG) from car manufacturers is diminishing, mostly due to infrastructure constraints, potentially limiting the use to captive fleets. Liquefied natural gas and bio-methane (incorporation of anaerobic digestion biogas), could improve the carbon footprint of this mobility solution.

The issue of methane slippage is also of interest, methane as a GHG having a Global Warming Potential 25 times higher than CO2.

3.1.2 Diesel LDV

What has been described above for petrol is valid for diesel: in Europe, Fatty Acid Methyl Esters (FAME) have been historically the common biodiesel component, with similar limitations, the blend wall being around 7 to 10% incorporation of FAME in fossil-based diesel. B7 (diesel with 7% vol. maximum FAME incorporation) is the reference grade in the EU, some vehicles are compatible with B10 (ACEA list of B10 compatible vehicles: https://www.acea.be/uploads/publications/ACEA_B10_compatibility.pdf). These grades are distributed and used in both LDVs and HDVs. Captive fleets can use B30 or B100 (the higher FAME content mandating a specific maintenance).

RED I is calling for 10% renewable energy in transport by 2020, with a maximum cap of 7% for first generation biofuels, produced from crops.

Challenge # 1: Development of Renewable Diesel

Renewable Diesel is composed of pure hydrocarbons, produced from renewable resources, such as biomass (also from Municipal Solid Waste or Water Treatment Sludge). As such, Renewable Diesel can completely replace fossil-based diesel (HVO100 is standardized and commercial under a specific EN standard EN15940) and is a readily available solution to 1) meet the RED II 2030 objective, providing feedstocks are not of food and feed crops, 2) eventually fully decarbonize diesel, also bringing additional performances such as similar energy content as fossil fuels, reduced contaminants (sulfur, nitrogen).

- Processes exist at industrial scale: lipids hydrogenation (HVO) is mature, gasification-synthesis has been in place for many decades, using coal and natural gas, co-processing is also possible in crude oil refineries (different catalysis and/or operating conditions compared to petrol maximization).
- Feedstocks are potentially diversified and abundant, either from agriculture or as waste & residue from agriculture, forestry, food value chain (household and commercial).
- Regulatory sustainability, key to acceptance, with challenges for lipids from agriculture (vegetable oils, such as palm and soy oils) and volume limitations for residual lipids (such as Used

Cooking Oil), is today the main hurdle, with the additional cost of production, passed-on to the commercial fuel.

Challenge # 2: FAME blend wall

FAME has stability issues due to its oxygen content, with resulting storage constraints and degradation during combustion and a 7%-10% range is estimated today as the maximum incorporation level in diesel: can experience with higher blends, such as B30 and B100, push the present blend wall upwards?

Challenge # 3: Alcohols incorporation in diesel

Similar to developments in HDV, such as ED95 (95% ethanol) in modified Scania trucks, can alcohols incorporation, e.g. ethanol or butanol, present an interest for (modified) LDV diesel engines?

Challenge # 4: Influence on exhaust emissions

Levels of NO_X, PM and PN raw emissions when using biodiesel show different trends. If a general agreement on the positive effect on PM can be observed, controversial outcomes are related to NO_X, being affected by engine type, fuel injection systems, tested operating conditions and engine control strategies. A further open point is the influence on PN concentration, generally presenting an increase in nanoparticles. Investigations are required to gain a better knowledge on local effects influencing NO_X and particles formation, to help in identifying proper actions for their control.

Challenge # 5: Fuel Stability

The ageing behavior of biofuels can differ significantly from fossil fuels: for instance, FAME is not as stable as conventional diesel, even though nowadays it can be stabilized by additives.

The ageing behavior and fuel stability of every novel fuel has to be examined carefully: unfortunately, this performance during (long time) storage cannot be predicted by measuring stability parameters right after production or right before storage. Apart from oxidation mechanisms, other degradation reactions as well as polymerization reactions can change the properties of a fuel during storage. Especially oxygenated fuels such as alcohols, which already contain high amounts of oxygen, do not tend to oxidize as much as conventional (bio-)fuels. Hence, other ageing mechanisms play major roles. These have to be investigated.

Furthermore, the ageing behavior of multicomponent blends is not understood yet. A blend of several stable fuels might very well show significant property changes during storage.

Therefore, there is an urgent need to fully understand all the fuel ageing mechanisms and to develop suitable test methods for other ageing mechanisms than oxidation stability. Additional methods, which register many ageing mechanisms and can predict the novel fuels ageing behavior over the long time, are needed. Furthermore, counter measures against fuel ageing have to be developed.

Another factor regarding fuel stability is the formation of deposits during the fuels' use: deposit formation must be understood better in order to develop targeted counter measures, such as suitable additives.

Challenge # 6: Fuel-Fuel System Interaction

Fuel-oil dilution as well as the contamination of fuel by engine oil both can cause major issues during engine operation.

The first aspect can have severe impacts on the lubricity of the engine oil. Due to its higher boiling point, FAME, for instance, accumulates differently in engine oil than fossil diesel fuel. Different behavior is expected for every novel fuel whose composition differs from the composition of fossil fuel. Therefore, the lubricity of novel fuels and fuel blends should be thoroughly examined.

The second aspect, contamination of fuel by engine oil, can influence the combustion relevant properties of the fuel like knock resistance. This contamination can cause low speed pre-ignitions because the engine oil contaminations lower the octane rating of fuels. Therefore, it is important to either examine and improve the octane rating of engine oils or to prevent the contaminations by hardware adjustments (sealings). Thereby it is possible to take advantage of the high knock resistances of e.g. oxygenates to use whole engine maps or downsize engines. Hence, the whole topic of fuel-lubricant interaction has significant influence on a fuels' commercial applicability in engines and needs to be investigated carefully.

The material compatibility is a sensitive topic. In ordinary fuel systems, various metals and plastics (including thermoplastics and elastomers) are used. These materials must be resistant to all kind of fuels at diverse conditions. Some materials are exposed to moderate temperatures and pressures (e.g. tanks made of thermoplastics), others are exposed to alternating temperatures and pressures during operation and non-operation times (e.g. sealings made of elastomers). This means that the examinations of material compatibility have to be extensive.

To fully grasp the interaction between the fuel system and fuels, the component compatibility must also be investigated: an example of the necessary examinations is whether the fuel is compatible with diesel injectors. Problems that could occur are for example deposits on the injectors, which can lead to injector failure and thus engine failure.

Challenge # 7: Performance of multi-component fuels

Multicomponent blends in diesel become more important. Here all challenges named above have to be considered, because the interactions between different fuels make it even more complicated to predict the blends' behavior.

Challenge # 8: Sophisticated mathematical models

There is an urgent need for sophisticated mathematical models, which can predict the behavior of various individual fuels and complex fuel blends, like the fuel stability, the material compatibility and the combustion behavior.

An example for these models is the assessment of engine and combustion relevant performance of fuels based on experimental data, such as the model-based evaluation of droplet formation based on physical-chemical data like vapor pressure and surface tension.

3.2 Heavy Duty Vehicles (HDV)

As shown in the first graph of the LDV chapter, HDVs mostly use diesel today (more than 98% market share). Regulations facing both sectors are of the same nature, the main difference between the LDV and HDV sectors lies in the ownership: for LDVs, millions of private owners with limited technology knowledge, relying on an ubiquitous, no-nonsense, refueling infrastructure, with one or two grades maximum available at the pump, whereas the HDV sector can be described as highly cost-competitive, concentrated in decision-making and fleets / refueling, and highly dependent on equipment / engine on-the-road reliability.

Challenges: those described for diesel in the LDV sector apply as well to the HDV sector, with a clear impact on Total Cost of Operation (TCO), critical to competitiveness, and a request for fuel stability to avoid excessive wear and tear and consequent unreliability.

The concentration in the sector will obviously open the possibility of modified motorizations, using other alternative fuels, i.e. beyond biofuels, such as (bio)methane, alcohols like methanol or ethanol (ED95), DME or electricity, if the forthcoming equipment regulation proves too severe for traditional ICEs, and / or related cost and fuel infrastructure are proven doable.

3.3 Between petrol and diesel: the peculiar position of kerosene

As said earlier, road transport relies mainly on petrol and diesel, mostly produced from crude oil: these petroleum fractions are not adjacent in the crude oil distillation curve or molecular repartition, as kerosene is produced in-between and is used as the sole aviation fuel component or as a diesel component (light fraction). As also said earlier, different energy carriers, such as electricity or hydrogen, are considered and developed as low- or zero-carbon alternatives for road transport and may well overtake, or even replace, in the long term, petrol and diesel. If this drastic reduction in demand for bio-petrol and bio-diesel happens in the long term, this could eventually concentrate the demand for biofuels in the aviation sector, where alternative energy carriers, which necessitate alternative aircraft and engine designs, may take much more time to replace the existing kerosene-fueled turbine.

It may thus be advisable to give consideration to flexibility toward aviation fuel usage for biofuels or bio-components primarily designed for petrol or diesel replacement: while this consideration mainly concerns the transformation process, the understanding of the aviation fuel, aircraft and engine requirements is necessary.

4. AVIATION

Air transport is a global, highly competitive, activity: the only global regulation, enacted by the International Civil Aviation Organization (ICAO), a UN agency, addresses the reduction of the aircrafts carbon footprint.

Montréal, 6 March 2017 – The 36-State ICAO Council has adopted a new aircraft CO_2 emissions standard which will reduce the impact of aviation greenhouse gas emissions on the global climate.
Contained in a new Volume III to Annex 16 of the Chicago Convention (Environmental Protection), the aircraft CO_2 emissions measure represents the world's first global design certification standard governing CO_2 emissions for any industry sector.
The Standard will apply to new aircraft type designs from 2020, and to aircraft type designs already in-production as of 2023. Those in-production aircraft, which by 2028 do not meet the standard, will no longer be able to be produced unless their designs are sufficiently modified.[1]

No such global regulation exists for aviation fuels, even though ICAO has committed, in its 2050 Vision for Sustainable Aviation Fuels (SAF), adopted during its March 2018 Council, to a " quantified proportion of fuels to be substituted with SAF by 2050 ". The Air Transport Action Group, a coalition of OEMs and air transport operators, is thus proposing a 50% reduction of GHG emissions by 2050, compared to 2005 emissions, which, in a context of a sustained growth for air transport, fueled by Asian demand, will require a significant reduction in the carbon content of fuels:

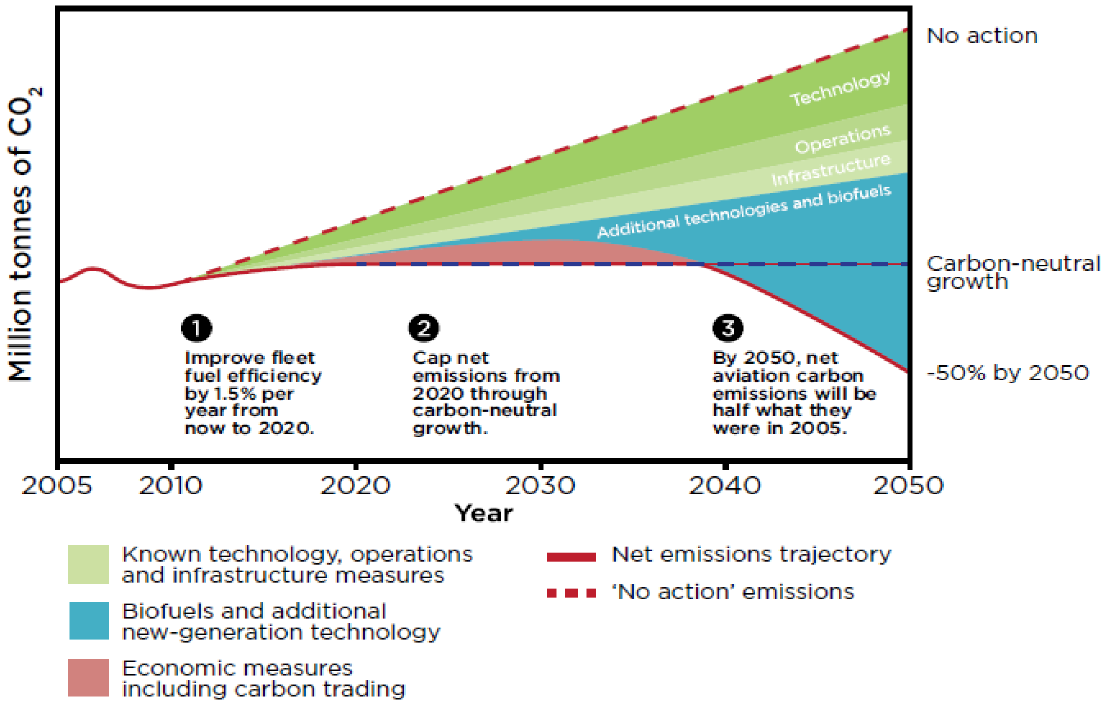


Figure 10: Emissions from aviation in the absence of any action, and emissions-reduction goals set by the industry (Source: Air Transport Action Group).

[1] Philbin & Raillant-Clark, 2017 :https://www.icao.int/Newsroom/Pages/ICAO-Council-adopts-new-CO2-emissions-standard-for-aircraft.aspx

For the time being, a handful of States, like Norway and Sweden, has passed regulations to incorporate Sustainable Aviation Fuel (SAF) in commercial aviation fuel at national level, more countries (e.g. France, The Netherlands, Spain), consider this possibility in the near future, like 2025. These limited mandates (less than 5%) still raise questions about the risk of cost competitiveness for impacted airlines (like national flagships), airports, fuel suppliers ("tankering"): advocacy to extend regulations at regional level, EU perimeter, is on-going.

Challenge #1: Sustainable Aviation Fuel (SAF) technology portfolio offer

Co-development of aviation fuel between the oil industry and the aviation OEMs (aircraft and turbine manufacturers) in the last seventy years has led to a very specific product, available with a constant quality on a world-wide basis, featuring pure hydrocarbons in a narrow boiling range and severe specifications, particularly for cold flow resistance, flammability, stability and equipment compatibility (e.g. minimum aromatic content). Thus, any alternative aviation fuel has to be composed of comparable hydrocarbons only, ruling out alternative fuels such as electricity, natural gas and hydrogen on a large scale for several decades, and the whole production pathway has to be certified at international level for use in any country and on any aircraft/engine combination: the American Standard for Testing Material (ASTM) is in charge of the certification process (ASTM D4054).

4.1 Research on the 100% usage of SAF in aircraft.

It is a long and costly procedure to have new SAF feedstock- technology certified. Currently, nine feedstock-technology SAF combinations ASTM are certified. The minimum aromatic content today implies that most certified aviation fuels can accept a maximum of 50% biocomponent. To respect this minimum aromatic content, this limit could prove a hurdle on the way to decarbonize air transport, even though the next generation of aircrafts are developed to remove this constraint, allowing the use of 100% paraffinic fuels: it should then be investigated what the effects could be for 100% SAF to be used on the aircraft engine.

Some OEMs are already taking the lead on these types of studies, such as Rolls Royce and Safran, but further support and collaboration is needed to ensure the possibility to increase the blend threshold of SAF.

4.2 Blending of SAF

SAF distribution will be a smaller issue due to the nature of these fuels, as just explained: blending of SAF with fossil fuel will take place upstream of the supply chain, with limited impact on end-use.

The list of ASTM-approved pathways and candidates presently undergoing ASTM approval process can be found in Annex 1 in details, below in a summary.

Pathways and processes	Feedstock options	Producers using the pathway	Date of ASTM approval	Current blending limit
Fischer-Tropsch (FT) Synthetic Paraffinic Kerosene (SPK)	Biomass (e.g. forestry residues, grasses, municipal solid waste (MSW))		2009	Up to 50%
Hydroprocessed esters and fatty acids (HEFA-SPK)	Algae, jatropha, camelina	World Energy, Neste, SkyNRG	2011	Up to 50%
Hydroprocessed fermented sugars to synthetic isoparaffins	Microbial conversion of sugars to hydrocarbon	Amyris-Total	2014	Up to 10%
FT-SPK with aromatics	Renewable biomass such as MSW, agricultural wastes and forestry residues, wood and energy crops	Fulcrum, Velocys	2015	Up to 50%
Alcohol-to-jet (ATJ) SPK (isbobutanol)	Agricultural waste products (e.g. stover, grasses, forestry slash, crop straws)	Gevo, Red Rock	2016	Up to 50%
ATJ-SPK (ethanol)	Industrial waste gases, agricultural waste products (e.g. stover, grasses, forestry slash, crop straws)	LanzaTech	2018	Up to 50%
Catalytic hydrothermolysis synthetic jet fuel	Triglyceride-based feedstocks (plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil)	ARA, Euglena	2020	Up to 50%
High hydrogen content synthetic paraffinic kerosene	Biologically-derived hydrocarbons such as algae	IHI World	2020	Up to 10%

Table 1 : ASTM-approved pathways and candidates presently undergoing ASTM approval process (Source : ASTM International).

For the near-term, lipids hydrogenation (HEFA, similar to HVO renewable diesel discussed above) is the only certified pathway with commercial scale: its main challenge lies in resources, limited volume of "advanced" feedstocks (RED II Annex IX-style), sustainability as a whole, beyond GHG emission reduction, for not volume-limited vegetable oils. R&D will have to address these issues to allow HEFA to develop.

To allow a proper level playing field for end-users, focus on maturing a diverse range of viable SAF technology pathways, including co-processing, making sure other SAF technologies reach commercial scale, would guarantee a sustainable scale-up of the industry.

Certification of SAF technology pathways, not yet approved (such as ASTM International, Def Stan) for commercial aviation, is also a priority to allow the level playing field to occur as soon as possible (see Annex).

Challenge #2: Non-CO2 effects

The impact of SAF usage on Aviation Radiative Forcing Components compared to conventional jet fuel, e.g., the impact of the low amount of particulate matter and the absence of Sulphur on Radiative Forcing.

The Radiative Forcing (RF) components that make up the Aviation Radiative Forcing are currently only studied for the combustion of fossil kerosene at high attitudes, many of these components being studied too little. Lee et. al (2020)[2] provided a clear overview of the scientific understanding of the majority of these RF components for fossil kerosene, and the conclusion is clear: all these elements are in clear need for further investigations except for the CO2 effect of the combustion of fossil kerosene on high altitudes. As unblended SAF has a different composition than fossil kerosene, it can be expected that the Radiative Forcing effects differ. Therefore, to assess the impact of SAF on these effects, we first need to have a baseline to compare it to. Hence, the need to put a major effort in quantifying the Radiative Forcing effects of the combustion of fossil kerosene, specifically looking at the non-CO2 effects.

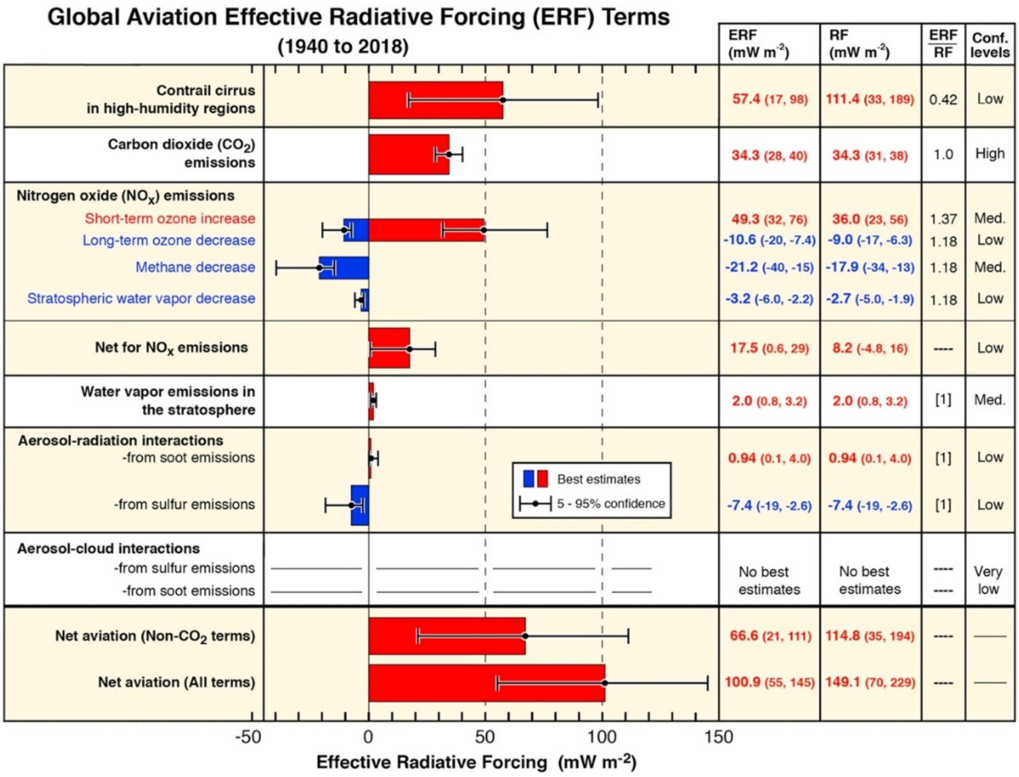


Table 2 : Global Aviation Effective Radiative Forcing (ERF) Terme (1940 to 2018) (Source Lee et al., 2020).

More details can be found in Annex 2.

[2] Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., & Gettelman, A. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834.

2.2 The impact of hydrogen as an alternative renewable fuel on the non-CO2 Radiative Forcing effects of aviation

Hydrogen as a fuel has a completely different composition than fossil kerosene. Similar to SAF, in order to compare its effect on Radiative Forcing components a proper base line is needed. As burning hydrogen results in the formation of water vapor, it is therefore expected that the water vapor emissions in the stratosphere will increase. It is thus of importance to characterize the aviation related RF effects of water vapor emissions in the stratosphere, as current agreement and evidence is scored as 'medium' by Lee et al. (2020).

Current knowledge states that water vapor emissions in the stratosphere account for 3% of non-CO2 RF effects of burning fossil kerosene. Approximately 1.1 kg H2O / kg fuel is emitted, however the energy content of hydrogen is 141 MJ/kg vs 44 MJ/kg of kerosene. Therefore, less hydrogen is needed for an equivalent amount of energy from kerosene. Thus, lower emissions expected, even if the H2O effects themselves are expected to be higher. Still, this remains an important topic for further investigation. We should be aware of the effect off an all-hydrogen aircraft fleet before a priority is given to such a possibility.

Challenge #3: Structuring SAF impact

SAF Design to model SAF composition with highest GHG effects (both CO2 and non-CO2 effects; contrails, radiative forcing etc.).

Since the combustion of liquid fuels consist of burning of n-, i- and cyclo-paraffinic hydrocarbons and aromatics in the C8-C18 range, research of the CO_2 and non-CO_2 effects of burning these elements on high altitude will create a deeper understanding of desirable and non-desirable synthetic jet fuel components. Based on the knowledge created within topic 1, and aided by the insights created in topic 2, it is valuable to model an ideal liquid fuel composition to achieve the lowest possible GHG effects. Furthermore, based on this 'ideal liquid fuel' research can shed light on the most sustainable production pathway for the production of this design fuel with a maximum amount of GHG emissions mitigated during production and utilization of the fuel.

Newer aircraft are constantly being optimized to increase fuel efficiency and decrease emissions. The results of a study modelling the optimal SAF composition with minimized GHG emissions can be used to inform original engine manufacturers (OEMs). That way, OEMs can test whether the designed fuel would be fit for usage in existing equipment and fuel infrastructure, or whether potentially minor adjustments to equipment are necessary for safe operations. Based on this knowledge, engine manufacturers can steer engine development in the direction of these cleaner burning fuels.

Whereas modern jet engine combustors are designed to significantly reduce emissions compared to older engines, fuel properties have been found to impact these emissions. For instance, research has linked the combustion of aromatic compounds directly to the formation of particulate matter[3]. However, exclusion of aromatic compounds in SAFs is currently not allowed by ASTM since engine seals require aromatic content for proper seal swelling to avoid leakage. To reduce the dependency on aromatic

[3] Airport Cooperative Research Program, State of the Industry Report on Air Quality Emissions from Sustainable Alternative Jet Fuels (2018)

content, the ASTM community is currently researching the potential for cyclo-paraffinic content to ensure this seal swelling without the need for aromatic components. The design of an ideal low GHG emitting SAF composition can be utilized to inform aircraft manufacturers on compatible alternatives and optimize engine development for sustainability purposes.

While simultaneously the production route towards the low GHG emitting SAF is evolving and engine developments continue to decrease fuel pollution effects, both parties are working towards achieving a more sustainable airspace. While over time older type aircrafts are being retired, sustainable newer aircraft take over. Since we foresee liquid fuels are essential to operate long-haul flights in the next 40-50 years, and the lifespan of an aircraft fleet is around 25 years, developments in this field and a good collaboration with aircraft manufacturers has the potential to profoundly increase the sustainability impact of air transport.

Challenge #4: Lower hydrogen input

Research the potential to lower the hydrogen dependency of most SAF conversion technologies.

All SAF pathways require hydrogen input. Especially with Power-to-Liquid fuels (fuels made from CO_2 and hydrogen) entering the field, the demand from the SAF sector for hydrogen increases. This is a challenge, as preferable we want the hydrogen to be produced using renewable electricity, so the renewable energy capacity in the EU should increase as well.

As producing green electricity, to produce green hydrogen, to produce SAF, is not efficient, this process only makes sense if a surplus of renewable electricity is available. Otherwise, the scarce renewable electricity could better be used for applications where the efficiency loss is not this big (electrical cars, heating and cooling of houses etc.).

Therefore, either the EU Member States need to produce a surplus of renewable electricity to use this resource to create green hydrogen and SAF, or a second option could be explored. The second option is to consider further investigations into technologies which have the potential to lower hydrogen dependency of most of the SAF conversion technologies. There are already technologies available which can transform waste fats and other low value organic oils into hydrocarbon without the use of hydrogen. This would be a major opportunity to reduce the demand for (green) hydrogen from the SAF sector and to decrease the carbon intensity of the different SAF pathways as hydrogen is no longer needed as input for producing SAF. Further investigation in Europe is needed to explore this opportunity.

5. MARINE

The maritime transport sector shares many similarities with air transport, international, competitive, committed to the same carbon footprint reduction by 2050, context of growth, as can be seen in the IMO following graph.

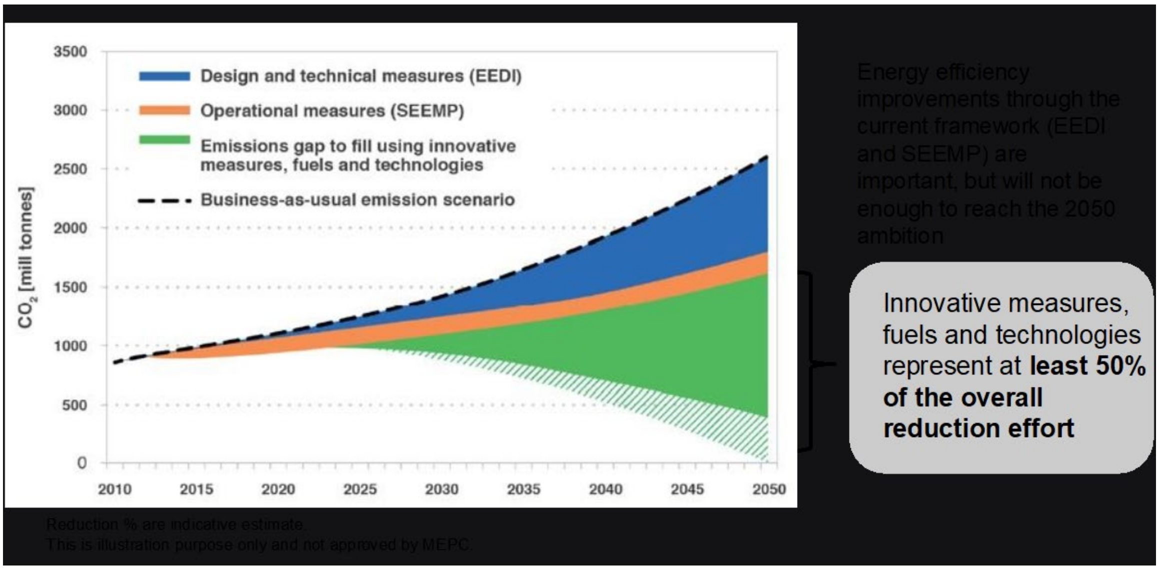


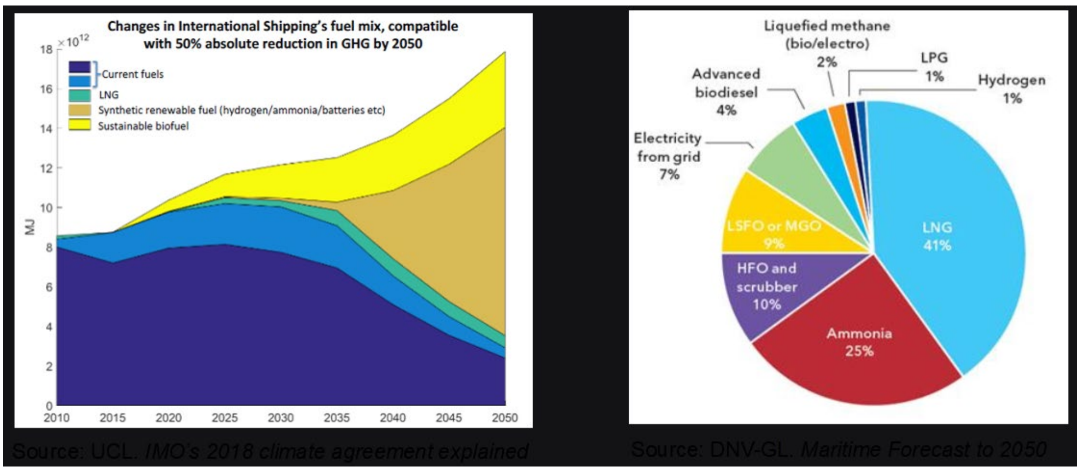
Figure 11: Reduction of GHG emissions from ships - ways to achieve the levels of ambition (Source: Hoenders, 2020).

A notable exception for fuels: many alternative fuels, beyond heavy fuel-oil and marine diesel, where incorporation of biofuels is possible, e.g. biomethane, methanol, ammonia, synthetic diesel from biomass/waste, electricity, or even nuclear energy, are available and have been, or are in the process of being, demonstrated on diverse commercial scales.

So far, alternative fuels, such as biofuels or natural gas, are only beginning to be used in the marine industry.

Challenge: Keep biofuels part of the sustainable shipping solutions

The challenge for biofuels in the maritime sector is similar to what has been described in paragraph 2 for HDVs, including the fuel stability issue. Studies are indeed showing biofuels, heavy fuel and marine diesel fuel drop-in components, can play a significant role in the future, two outstanding benefits of biofuels lying in the compatibility with existing engines and the limited investment required in infrastructure, the latter being, for the shipping industry, a significant element of the supply chain, at least for international, long-distance, trade, which concentrates most of the fuel demand, thus most of the GHG emissions.



6. KEY R&I SUBJECTS

Three horizons are considered: short-term (now), mid-term (2030), long-term (2050)

1. Short-term

- E10 as main European petrol grade in all Member States in Europe: technically, no R&D is necessary, but a strong information re-establishing the merits of E10 should be put together by all stakeholders, fossil fuel & biofuel industries, car manufacturers.
- E85 and FFV: technically, no R&D is necessary, but establishing a consensus on the value and target market share of E85 development requires a debate between the above cited stakeholders.
- Development of Renewable Diesel: although the ultimate solution to replace fossil-based diesel, R&D is today mainly focused on the sustainability of the feedstock-production process value chain. Still, there may be a need for additional R&D to ensure a deep understanding of this new fuel. To be noted, under the responsibility of ETIP Bioenergy WG1 & WG2: in addition, there is R&D need to develop the supply chain for these new fuels (how to mobilise the resources towards the industrial sites).
- Increasing the FAME blend wall to maximize incorporation in diesel (stability issue) for specific applications, e.g. captive fleets.
- Give consideration in biofuel development to end-usage as sustainable aviation fuel or component.

2. Mid-term

- E10+ (E20…25 or highly oxygenated fuels) as the next high octane reference grade for petrol: R&D to

  1) identify the optimum octane, and other petrol specifications if pertinent, to maximize the benefits of an increased incorporation of oxygenated molecules,

  2) ensure a deep understanding of this new fuel, in domains such as oxidation stability (ageing during storage), interaction with lubricant (lubricity, low-speed pre-ignition phenomena), material compatibility,

  3) facilitate and accelerate certification and standardization.
- Maximization of renewable hydrocarbons incorporation in petrol: R&D on bio-naphtha yield and quality optimization as co-production in biomass-based thermo-chemical processes, maximization of co-processing in crude oil refineries with specific R&D to understand the key issues leading to petrol boiling-range bio-components maximization, in yield and quality. To be noted under the responsibility of ETIP WG1 & WG2: additional R&D is needed on how to scale up the new technologies (e.g. pyrolysis), which are not at

industrial scale yet and face issues in terms of corrosion, for example, that needs to be solved.

- Incorporation of other oxygenates in petrol, beyond ethanol and ETBE: R&D to identify the required qualities, the optimum blends, the possible petrol specification changes, if necessary, and to facilitate and accelerate certification and standardization.

  Development of Renewable Diesel: although the ultimate solution to replace fossil-based diesel, R&D is mainly focused on the sustainability of the feedstock-production process value chain. Still, there may be a need for additional R&D to ensure a deep understanding of this new fuel. To be noted, under the responsibility of ETIP WG1 & WG2: in addition, there is R&D need to develop the supply chain for these new fuels and for the scale-up of some promising technologies. Co-processing for gasoline is also another promising technology. Maximization of alcohols incorporation in diesel: R&D on qualities required for these bio-components to allow incorporation in diesel.

- Impact of biodiesel on engine performance: exhaust emissions, fuel stability, material and component compatibility, interaction with engine oil, consequences of blending several different fuels.

  With the above actions, the RED II 2030 objective of 14% renewable content in road transport could be met, providing the feedstocks and production processes respect the sustainability and origin criteria set in the regulation, the feedstocks are available and a proper standardization level is attained for all alternative fuels considered.

- Sustainable Aviation Fuel: R&D is focused on the identification, development and scale up of new pathways, beyond the mature lipids hydrogenation producing HEFA, and this R&D implies a deep understanding of SAF interaction with existing equipment, turbines and aircraft systems (e.g. APU), mandatory for a successful certification (engine testing), and identification of non-CO_2 benefits.

- Give consideration in biofuel development to end-usage as sustainable aviation fuel or component.

3. Long-term

- Maximization of renewable hydrocarbons incorporation in petrol: identification of new bio-molecules for direct incorporation in petrol or for blending recipes of petrol.

- Sustainable Aviation Fuel: R&D is focused on the identification and development of new pathways, beyond the mature lipids hydrogenation producing HEFA, and this R&D implies a deep understanding of SAF interaction with existing equipment, turbines and aircraft systems (e.g. APU), mandatory for a successful certification (engine testing), and identification of non-CO_2 benefits.

- Renewable liquid hydrogen for aviation: as this fuel will require a new engine technology, there is a massive R&D at stake, to be led by turbine manufacturers, such as Safran and Rolls-Royce in Europe. This subject also applies for hydrogen use in road and marine transport.

- Give consideration in biofuel development to end-usage as sustainable aviation fuel or component.

ANNEX 1: Status of Sustainable Aviation Fuels ASTM Certification

1. Approved Fuels

The following drop-in alternative jet fuels went through the ASTM D4054 process and are qualified for commercial use (presented in chronological order of approval, as listed in the Annexes of ASTM D7566). These approved fuels represent multiple conversion processes associated with various feedstock types.

Annex A1: Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

- Year of Certification: 2009.
- Blending: Required to be blended with petroleum-based jet fuel, up to a 50% maximum level.
- Feedstock(s): Synthesis gas (or syngas, a mixture of CO and H_2). Syngas is typically produced from the gasification of biomass such as municipal solid waste (MSW), agricultural and forest wastes, and wood and energy crops, as well as non-renewable feedstocks such as coal and natural gas. The feedstock is gasified at high temperatures (1200 to 1600 degrees Celsius), which deconstructs the feedstock into carbon monoxide, hydrogen, and CO_2 primarily, as well as some ash. The gas mixture is separated and cleaned to produce pure syngas, and it is then converted to long carbon chain waxes through the FT Synthesis Process. Syngas, or its components, can also come from other industrial processes.
- Process/Product Description: The Fischer-Tropsch (FT) Synthesis Process is a catalyzed chemical reaction in which synthesis gas is converted into liquid hydrocarbons of various forms via the use of a reactor with cobalt or iron catalyst. The wax is then cracked and isomerized to produce drop-in liquid fuels essentially identical to the paraffins in petroleum-based jet fuel, but the FT process does not typically produce the cyclo-paraffins and aromatic compounds typically found in petroleum-based jet fuel.

Annex A2: Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)

- Year of Certification: 2011
- Blending: Required to be blended with petroleum-based jet fuel, up to a 50% maximum level.
- Feedstock(s): Specifically, fatty acids and fatty acid esters, or more generally various lipids that come from plant and animal fats, oils, and greases (FOGs).
- Process/Product Description: Natural oils are converted from lipids to hydrocarbons by treating the oil with hydrogen to remove oxygen and other less desirable molecules. The hydrocarbons are cracked and isomerized, creating a synthetic jet fuel blending component comprised of paraffins.

Annex A3: Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)

- Year of Certification: 2014
- Blending: Required to be blended with petroleum-based jet fuel, up to a 10% maximum level
- Feedstock(s): Sugars
- Process/Product Description: The process uses modified yeasts to ferment sugars into a hydrocarbon molecule. This produces a C15 hydrocarbon molecule called farnesene, which after hydroprocessing to farnesane, can be used as a blendstock in jet fuel.

Annex A4: Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)

- Year of Certification: 2015
- Blending: Required to be blended with petroleum-based jet fuel, up to a 50% maximum level.
- Feedstock(s): Same as Annex A1.
- Process/Product Description: Uses the FT Synthesis Process plus the alkylation of light aromatics (primarily benzene) to create a hydrocarbon blend that includes aromatic compounds that are required to ensure elastomer seal swell in aircraft components to prevent fuel leaks. FT-SPK/A introduces the migration toward fuels that offer a full spectrum of molecules found in petroleum-based jet fuel, rather than just paraffins.

Annex A5: Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)

- Year of Certification: 2016
- Blending: Required to be blended with petroleum-based jet fuel, up to a 50% maximum level.
- Feedstock(s): This annex is intended to eventually cover the use of any 2 to 5 carbon alcohols, but at present, it only allows the individual use of ethanol and isobutanol. The alcohols can come from any source, but are usually derived from:
  - Fermentation of starches/sugars, which themselves can come from starch/sugar producing feedstocks (e.g. field corn, sweet sorghum, cane, sugar beets, tubers) or derived from cellulosic biomass (e.g. via hydrolysis from lignocellulose).
  - The biochemical conversion of other forms of hydrogen and carbon (e.g. via organisms that convert CO, H_2 and CO_2 to alcohol).
- Process/Product Description: Dehydration of isobutanol or ethanol followed by oligomerization, hydrogenation and fractionation to yield a hydrocarbon jet fuel blending component.

Annex A6: Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)

- Year of Certification: 2020

- Blending: Required to be blended with petroleum-based jet fuel, up to a 50% maximum level.
- Feedstock(s): Specifically, fatty acids and fatty acid esters, or more generally various lipids that come from plant and animal fats, oils and greases (FOGs).
- Process/Product Description: Hydroprocessed synthesized kerosene containing normal and iso-paraffins, cycloparaffins, and aromatics produced from hydrothermal conversion of fatty acid esters and free fatty acids along with any combination of hydrotreating, hydrocracking, or hydroisomerization, and other conventional refinery processes, but including fractionation as a final process step.

Annex A7: Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)

- Year of Certification: 2020
- Blending: Required to be blended with petroleum-based jet fuel, up to a 10% maximum level.
- Feedstock(s): Specifically, bio-derived hydrocarbons, fatty acid esters, and free fatty acids. Recognized sources of bio-derived hydrocarbons at present only include the tri-terpenes produced by the *Botryococcus braunii* species of algae.
- Process/Product Description: Bio-derived hydrocarbons and lipids are converted to hydrocarbons by treating the feedstock with hydrogen to remove oxygen and other less desirable molecules. The hydrocarbons are cracked and isomerized, creating a synthetic jet fuel blending component comprised of paraffins.

The ASTM Committee D02 on Petroleum Products, Liquid Fuels, and Lubricants, as well as their D02.J0 Sub-committee on Aviation Fuels, have also approved the co-processing of renewable content with crude oil-derived middle distillates in petroleum refineries. This includes:

- Lipids (plant oils and animal fats)
- Fischer Tropsch Biocrude (unrefined hydrocarbon content coming from an FT reactor)

The co-processing provisions have been added to Annex A1 of ASTM D1655, Standard Specification for Aviation Turbine Fuels. The Annex includes co-processing of up to 5% by volume of these components as feedstocks in petroleum refinery processes.

2. Current Fuels in the D4054 Qualification Process

The table below shows the pathways actively pursuing certification at various stages in the process.

ASTM Progress	Pathway	Feedstock	Task Force Lead
ASTM Balloting	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	Hydrocarbon-rich algae oil	IHI
Phase 2 Testing	Hydro-deoxygenation Synthetic Kerosene (HDO-SK)	Sugars and cellulosics	Virent (inactive)
	Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	Sugars and cellulosics	Virent
Phase 1 OEM Review	High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK)	Renewable FOG	Boeing
Phase 1 Research Report	Integrated Hydropyrolysis and Hydroconversion (IH^2)	Multiple	Shell
Phase 1 Testing	Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Sugars and lignocellulosics	Swedish Biofuels, Byogy

Table 3 : Pathways pursuing certification at various stages.

ANNEX 2: Non-CO2 effects supplemental information

Terms	Evidence	Agree-ment	Conf. level	Basis for uncertainty estimates	Understanding change since L09
Contrail cirrus formation in high-humidity regions	Limited	Medium	Low*	Robust evidence for the phenomenon. Large remaining uncertainties in magnitude in part due to incomplete representation of key processes	The inclusion of contrail cirrus processes in global climate models.
Carbon dioxide (CO_2) emissions	Robust	Medium	High**	Trends in aviation CO_2 emissions and differences between simplified C-cycle models	Better assessment of uncertainties from multiple models
Short-term ozone increase	Medium	Medium	Medium*	Observed trends of tropospheric ozone and laboratory studies of chemical kinetics, reliance on a large number of model results for aviation emissions	Elevated owing to many more studies
Long-term ozone decrease	Limited	Medium	Low*	Reliance on chemical modelling studies	Not provided previously
Methane decrease	Medium	Medium	Medium*	Observed trends of tropospheric methane and laboratory studies of chemical kinetics, reliance on a large number of model results for aviation emissions	Elevated owing to many more studies
Stratospheric water vapour decrease	Limited	Medium	Low*	Reliance on chemical modelling studies	Not provided previously
Net NO_x	Medium	Limited	Low*	Associated uncertainties with combining above effects	Elevated owing to more studies but lowered in total owing to additional terms and methodological constraints
Water vapor emissions in the stratosphere	Medium	Medium	Medium	Limited studies of perturbation of water vapor budget of UT/LS	Elevated owing to more studies
Aerosol-radiation interactions					
From soot emissions	Limited	Medium	Low	Limited studies and uncertain emission index	More studies
From sulfur emissions	Limited	Medium	Low	Limited studies and uncertain emission index	More studies
Aerosol-cloud interactions					
From sulfur emissions	Limited	Low	Very low	None available; few studies, probably a negative ERF	Not provided previously
From soot emissions	Limited	Low	Very low	None available; few studies, varying in sign and magnitude of ERF constrained by poor understanding of processes	Not provided previously

Table 4 : Confidence levels of ERF estimates (Source: Lee et al., 2020).

*This term has the additional uncertainty of the derivation of an effective radiative forcing from a radiative forcing.

**This term differs from 'Very High' level in IPCC (2013) because additional uncertainties are introduced by the assessment of marginal aviation CO2 emissions and their resultant concentrations in the atmosphere from simplified carbon cycle models.

Source: Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., & Gettelman, A. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834.

Medium High agreement Limited evidence	**High** High agreement Medium evidence	**Very High** High agreement Robust evidence
Low Medium agreement Limited evidence	**Medium** Medium agreement Medium evidence	**High** Medium agreement Robust evidence
Very Low Low agreement Limited evidence	**Low** Low agreement Medium evidence	**Medium** Low agreement Robust evidence

Table 5 : Basis for confidence levels (Source: Lee et al., 2020).

The basis for the confidence level is given as a combination of evidence (limited, medium, robust) and agreement (low, medium and high) based on guidance given by Mastrandrea et al. (2011).

Source: Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., & Gettelman, A. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834.

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