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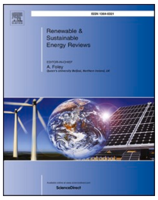

Assessing the future prospects of emerging technologies for shipping and aviation biofuels: A critical review

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ABSTRACT

There is an urgent need to switch from fossil to bio-based fuels in the transport sector, particularly in shipping and aviation. The growth of the world's population has resulted in a significant impact on passenger transport, with a noticeable increase in greenhouse gas emissions, depletion of fossil resources and associated risks in all three pillars of sustainability. In this context, new policies, standards and targets have been developed to reduce this environmental damage, which is mainly caused by the use of fossil fuels. Therefore, the alternative of using biofuels seems to be the most appropriate solution, to the extent that important targets have been set and specific directives have been developed for the integration of biofuels in the maritime and aviation sectors. However, to demonstrate that switching to biofuels is indeed beneficial, it is necessary to evaluate new biofuel scenarios from a life-cycle perspective, with particular emphasis on analyses that provide information beyond the present, such as prospective life-cycle assessments. To this end, the focus of this review is on the current trends in the production of biofuels for the marine and aviation sectors, taking into account the main targets set, the existing regulations and directives on the subject, and an analysis of the type of technologies used for their production. It also addresses biofuel Life Cycle Assessment (LCA) scenarios and future LCA approaches, and how these analyses should be carried out to be effective. Finally, key policies, standards and certifications are analyzed. The trends and bottlenecks discussed in this review concerning the actual and future development of the biofuels sector could be used by policy makers and stakeholders to identify efforts that favor the integration of biofuels into the value chain. Furthermore, it could be concluded that the evaluation of the guidelines foreseen in the development of competitive scenarios based on emerging technologies, as well as the adoption of policies and restrictions on the use of fuels, are key conditions to establish the roadmap for the widespread implementation of biofuels.

1. Introduction

The growth of population is directly affecting over the transport sector. The intensity and the "road transport" is causing important issues over the environment, given the emissions, and to communities' health, as a more pollutant ambient is being faced. Regarding air pollutants, just focusing on transport sector, it is responsible of the 45% of the emissions of nitrogen oxides. 2% of sulfur oxides emissions, 13% of particular matter, 8.7% of non-methane volatile organic compounds and 1.2% of NH_3 emissions, according to the European Environment Agency. Besides, in 2021 a total of 0.84 Gt and 0.71 Gt of CO_2 has been emitted by shipping and aviation sectors, respectively, according to the International Energy Agency. These emissions are mostly the result of the use of fossil-based fuels, that entails, not only the release of harmful compounds in the use-phase, but also in the production one. Given this, there is a need on providing more efficient and less harmful primary resources to respond to the demands of population with respect to passenger transport daily routines and travels, and the use of bio-based fuels could imply important benefits, as those are less harmful and could also be more efficient.

In this regard, the use of bio-based fuels, which entails less environmental damage throughout its life cycle, should be promote. Besides, the combination of eco-efficient trajectories together with the use of biofuels could add value in the pursuit for more sustainable transport

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[1]. In this context, the main targets for transport sector are the ones reported by the European Union (EU) Strategy, European Green Deal, EU Emissions Trading System, International strategies (International Marine Organization's (IMO)) and ReFuelEU Initiative, and included below.

1. Reduce carbon intensity by at least 40% using low-carbon fuels by 2030, and 70% by 2050, using zero-carbon fuels (IMO strategy).
2. Establish control mechanisms for CO_2 emissions in terms of monitoring, reporting and verification (Regulation (EU) 2015/757 of the European Parliament and of the Council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport).
3. Encourage market-based carbon measures, such as a CO_2 tax (ReFuelEU Initiative, 'Fit for 55' package").
4. In absolute terms and with a time horizon, 50% reduction of total annual GHG emissions by 2050 (European Green Deal, EU Strategy, EU Emissions Trading System) [2,3].

These targets are the main driving force for the development of new emerging technologies for biofuel production. Reducing the carbon footprint in the transport sector towards to achieve zero-carbon emissions requires the adoption of sustainable technologies and the use of renewable resources [4,5]. The technology must evolve from low Technology Readiness Level (TRL) values to high values in order to prove the technological feasibility of the process on a large scale, which will provide insight into future potential, stability, risk and market penetration.

The use of prospective methodologies is considered a suitable tool to develop the assessment of the carbon impact from a broad perspective [6,7]. Considering the need to provide a forward-looking perspective, assessments should take into account changes in the environment in which the technology will be applied at least 50 years from now, trying to envision the most accurate future scenario that the emerging technology will face [8,9]. The use of prospective assessments require the use of expert knowledge, projected estimations and databases [10–12]. To this end, it is necessary to know the existing situation considered as a reference scenario, to propose possible improvements but also the main bottlenecks that hinder the transition to biofuel production.

In this regard, the main goal of this critical review is to evaluate the technology and the methodologies being developed in the field of biofuel production, as well as the identification of standards and certifications schemes on the use of biofuels in transport activities. On the other hand, the potential and market penetration of biofuels, the use of prospective life cycle assessment (LCA), social life cycle assessment (S-LCA) and techno-economic assessment (TEA) as appropriate environmental, social and techno-economic impact assessment are also evaluated.

2. Regulations on biofuels in the transport sector

The EU has adopted the Renewable Energy Directive (REDII 2021–2030) as the core for achieving the decarbonization of transport sector, including the limitation on the use of energy crops for the subsequent biofuel production, the encouragement of the development of advanced biofuels and the defense on the maintenance of bio-based natural resources below the earth limits, to avoid its depletion and its environmental effects [13–16]. The commitment to the valorization of agricultural, livestock and forestry residues, the use of algae, non-food raw materials, as well as other non-useable waste streams, such as waste cooking oil, are the main approaches to focus on biofuel production alternatives.

This Directive also introduces the main criteria that the biofuels may comply in order to ensure that its production and use is encompassed within the boundaries of sustainability development that, in general terms, refers to the fact that those biofuels does not entail an environmental load comparable or higher than that of fossil-based fuels. In this way, governments, stakeholders, policy makers and development organizations are betting on a proactive and anticipatory action, with the aim of avoiding the environmental damage caused by the massive and uncontrolled use of fossil resources for the production of fuels.

In this context, other organizations have developed a series of guidelines, documentation and certification schemes focused on the biofuel sector, with the objective of supporting their development from a perspective that promotes sustainable production and use. One of the most recognized is the guidance biofuel certification document created by the International Sustainability & Carbon Certification (ISCC), mainly focused on wood-based biofuels [17]. It is considered a verification of compliance with social, environmental and traceability criteria for biofuels in accordance with the targets defined by the European regulations for transport fuels. This document compiles sustainability requirements [18,19], GHG emissions estimation [20] and traceability of biofuels value chain [21].

As it could be seen on Fig. 1, there are two transportation sectors (aviation and maritime) that, both at present and in the estimated projections, have the higher potential impact on the levels of emissions and environmental damage derived from the use of fossil fuels, because of this, a large number of regulations have been developed for these sectors. The American Society for Testing and Materials (ASTM) D7566 has approved the use of Sustainable Aviation Fuels (SAF) in jet engines for passenger and freight transport, given their good performance and reduced environmental loads compared to traditional fossil fuels [22], but with some restrictions. The use of biofuels in the fuel blends is subjected to the ASTM standard, in order to ensure the technical and safety conditions in flights. Using biofuels for aircraft, decarbonization of the aviation sector could be achieved, but still certain barriers could be detected when implementing bio-based fuels in the aviation sector. Some of them includes higher cost in comparison to fossil fuels, lack of guidelines for certification process and of policy framework and governmental funding for implementation [23–25]. Replacing 90% of conventional aviation fuels with biofuels is expected to reduce emissions by 53% by 2050 [26,27].

The Air Transport Action Group has published the Waypoint 2050 report, with the purpose of achieving net-zero emissions by 2050 in the aviation sector, following the guidelines set to achieve the goals of the European Green Deal and the SDGs [28,29].

The Fit For 55-package of the European Green Deal is a recent European Commission action plan (July 2021). The proposal aims to create a European mandate for the supply and implementation of SAF at most EU airports, encouraging the use of biofuels for air transportation. The main reason for the development of this initiative is to achieve the EU climate targets for the reduction of emissions and dependence on fossil resources. The main goal is that the percentage of SAF in the air transport departing from EU airports would increase gradually, reaching the target of 63% by 2050.

According to ICAO (International Civil Aviation Organization), 57 airports distribute SAF worldwide, representing more than 440 000 commercial flights. Around 24 policies have been adopted or are being developed by international organizations and purchase agreements have been signed for some 34.9 billion liters of SAF [30]. Moreover, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a scheme that favors the integration of biofuels in this transport sector. The scheme promotes the reduction of carbon dioxide emissions through the improvement of aviation technologies and operational conditions, as well as the development of national and/or regional regulatory initiatives [31].

On the other hand, in order to encourage the use of advanced shipping bio-fuels in a large-scale market value chain, and to regulate its prices, the European Commission has introduced the "Inducement Price for the Promotion of Renewable fuels" [32]. The goal of this proposal is to make the use of advanced biofuels for a market supply chain possible for shipping sector through price regulation. The assessments conducted to link the relationship between price and biofuel effectiveness have

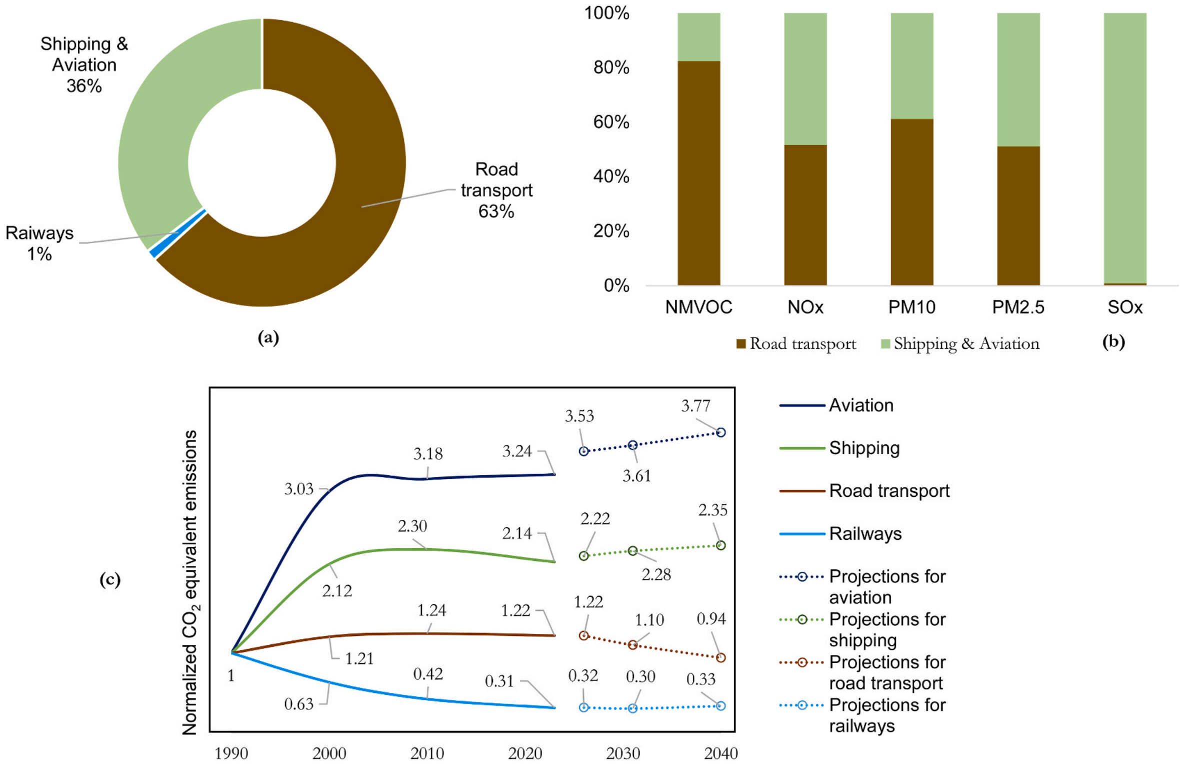

Fig. 1. Contribution on transport sectors on (a) GHG emissions, (b) air pollutants and (c) progression on CO_2 eq. emissions and projections per sector. Database: European Environmental Agency, Eurostat.

been developed using 100% biofuels for a transport distance of at least 21 600 nautical miles. With an economic approach, the Poseidon Principles have also been developed, with the objective of carrying out a methodology to integrate the environmental risk within the financial and investment decision for the shipping sector [33].

For example, the European Investment Bank has succeeded in developing a Green Shipping Guarantee (GSG) Program, with the aim of accelerating investments in more sustainable and green technologies for shipping companies [34,35]. One of the goals in technology improvement is to achieve energy efficiency in shipping activities. In this context, the SEEMP (Sheep Energy Efficiency Management Plan), a mechanism developed by the International Maritime Organization, introduces a set of guidelines for the development of ship energy efficiency, encompassing calculation methods for measuring energy efficiency (Annex 7) [36], carbon intensity and correction factors (Annexes 14 and 17) [37,38], carbon-based indicators (Annex 15) [39], and carbon intensity classification of ships (Annex 16) [40], among others.

All of the above policies, standards, targets, etc. are a reflection of the necessity for the sector to meet the requirements and objectives established for biofuels. An urgent acceleration of the commercialization of biofuels with a high level of quality is a must to be achieved. In this regard, the implementation of appropriate policy definitions and assessments could be considered a key role in the biofuel production sector. In fact, there are currently policies about this, briefly described below.

- *10-Year Framework of Programs on Sustainable Consumption and Production (SCP) Patterns*: a global initiative to increase international cooperation to enhance SCP.
- *OECD: Sustainable Materials Management and Green Claims*: a policy to foster green and sustainable growth at both economic and demographic levels.
- *UNIDO/UNEP Program on Resource-Efficient Cleaner Production*: based on the recognition of methodologies and procedures that bring benefits to adequately address global challenges on stabilizing and improving sustainable environmental, social and economic practices, among others [41].

3. What are the actual perspectives on the use and commercialization of shipping and jet biofuels?

The development of more sustainable fuels for shipping and jet transports the main efforts and challenges are divided in Ref. [42].

1. Technical management (i.e. improvement of the technologies to be more efficient).
2. Operational conditions (i.e. combustion temperature).
3. Enhance the use of more environmentally-friendly fuels (i.e. advocate for avoiding the fossil-based fuels).
4. Alternative power sources (i.e. using renewable sources).
5. Establishment of carbon capture and storage techniques on ship and aviation boards.

In this context, all the strategic development on the shipping and aviation sector should be in line with the objectives of reducing **carbon emission** in both short, medium and long term (Fig. 2) [43,44]. But huge efforts are needed to achieve a zero-carbon emission of both transport sector because, given the estimations of the International Energy Agency, aviation sector requires about 220 Mton/year of biofuel oil equivalents to fully decarbonized, while for the case of shipping sector, is a little bit higher, amounting to 240 Mton/year of oil equivalents [45].

According to Solakivi et al. (2022), the marine fuels could be divided in four main categories: non-sustainable conventional fuels, LNG/LPG and non-renewable hydrogen, sustainable but underdevelopment biofuels and renewable/advanced biofuels and e-fuels [45]. In this regard, the main characteristics of the alternative marine alternative fuels are depicted on Table 1. On the other hand, it should be taking into account that the marine transportation sector could go for further alternative

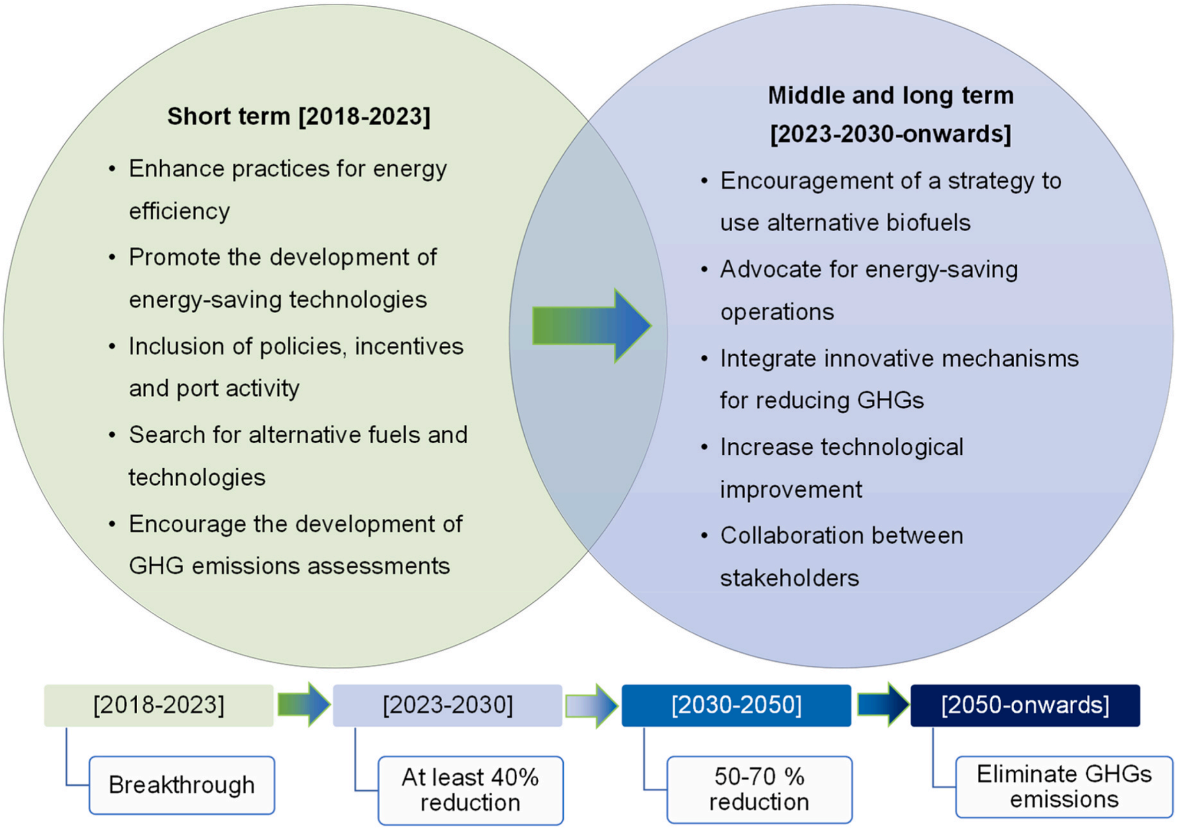

Fig. 2. Goals for reducing the GHGs from shipping and aviation industries.

fuels to replace the fossil-based ones in comparison to aviation sector, as the engines and infrastructures of ships are more adequate to use lower-quality fuels [46]. But, indeed, for both sectors, the main challenges to be addressed are the reduction on the production costs, the need of a higher technological mature and the increase on the availability of infrastructure to the alternative fuels use and distribution [47, 48].

Given the assessment of the most researched and developed alternatives for maritime fuels, should be mentioned which are the ideal characteristics that should have in order to be effective for the engines and infrastructures. The report developed by Gray et al. (2021) have identified the following: high energy density (to avoid the high storage volumes), low emissions levels, reduced production and use costs (to be attractive to replace the conventional ones), scalability (to be used for both short and long transport distances) and compatibility with actual infrastructure [52].

In this context, the report developed by Xing et al. (2021) have analyze different issues related with the adequacy of the alternative marine fuels, classifying them in priority levels and strengths for its application [59]. The use of methanol, hydrogen and ammonia as maritime fuels are the most adequate form the point of view of environmental impacts, however the differences on engines and on the capacity of energy production should be taking into account. While methanol could be used to all types of transport, ammonia is not yet available to be used for deep sea routes, while compressed H_2 is only effective for domestic shipping. In order to avoid these disadvantages, it has been reported that a possible solution is the use of propulsion technological systems, which should be adapted in function on the transport distance.

Regarding the aviation sector, the requirements for the development of alternative fuels are stricter in comparison to that for maritime transport, as higher quality is required, with unique fuel properties required to be compiled. In this regard, for example, biodiesel could not be used as jet fuel, given its reduced energy density and high freezing point [60]. To this end, the main alternative for decarbonizing the aviation sector is with the use of SAF (Sustainable Aviation Fuels), defined as alternative fuels with similar properties to that of conventional ones but with reduced environmental footprint, thus being more sustainable. The advantage of the use of SAF relies on the fact that are classified as “drop-in” fuels, meaning that they could be used in the planes without needs of modifying the engines or infrastructures [61]. In this regard, the main companies manufacturing SAF are depicted on Table 2, including the type of feedstock, the production process methodology used by each of them, the production capacity and the applications. While on Table 3 some examples of airlines using SAF are depicted.

As for shipping fuels, Gray et al. (2021) have also identified the idealities for jet-alternative-fuels, being the following the most outstanding: high energy density, high specific energy (to enhance the efficiency), high flash point (to be safe), low emissions levels, low viscosities and freezing points (to ensure the fuel quality at reduced temperatures), high thermal stability and good lubrication properties [52].

3.1. Some advances on the use of bio-fuels

Wärtsilä, a marine engine manufacturer, constructed a bio-methanol based engine for a ferry of the company Stena Germanica, the first of the world. This engine is based on a cylindric engine in which the bio-methanol is injected and ignited using an unsignificant amount of fossil-based fuel [52]. On the other hand, regarding directly the bio-methanol, one of the biggest production facilities is located in Canada, Enerkem plat, being able of producing a total of 38 ML/year using as feedstock, municipal solid waste. Another company is BioMCN, with a lower capacity, 15 t/year, and using an alternative raw material, biogas. To this end, it could be observed that the degree of development of bio-methanol production could be encountered between a TRL6 to 8.

Table 1
Main alternative fuels developed for replace fossil-based maritime fuels.

Fuel alternative	Emissions compared to conventional	Advantages	Disadvantages	Other issues	Future challenges	Reference
Ammonia	Reduced level emissions of CO_2, SO_x and PM Cleaner energy C-neutral fuel	Clean energy carrier Better store conditions than bio-H_2 (higher T) Could be used in internal combustion engines and fuel cells	Higher level of NO_x emissions 5-times more storage volume than conventional diesel Low heating value	Shipping infrastructure and bunkering is not adequate for using ammonia as fuel Difficult storage Incomplete submission leads to NO_x emissions	Develop efficient ignition engines given its low auto-ignition	[44,45,49–51]
H_2	Reduced level emissions of CO_2, SO_x and PM	Available in abundance, higher efficiencies in fuel cells than fossil-based fuels	Found in compound form, its energy potential is lost when it is refined, difficult storage, fuel cells are expensive, high flammability entailing potential risks	Fuel cells require low maintenance	Reduce the cost of fuel cell devices to enhance the use of as H_2 biofuel	[45,50]
Methanol	High level of NO_x, medium level of CO_2	Availability, not as expensive as other biofuels, engine simplicity, able to adapt existing engines	Low energy content, low density and high viscosity than conventional fuels,	11 chips on services uses methanol as fuel, various feedstocks could be used for its production, including waste resources Most used form of marine fuel, with 160 ktons consumed annually	Engine and fuel supply infrastructures adaptation	[44,45,51,52]
Bio-LNG[a]	Lower emission of $CO_{2,}$ lower sulfur content and limited SO_2 emissions	Modification of engine and fuel supply structure	Lower cost than other biomass-based fuels, low energy density, higher storage volume	The engines could be modified to reduce the emissions of NO_x, most likely options to comply IMO[f] regulations	Need to reduce the limitation of the availability of bunkering facilities	[45,48,50,51]
HVO[b]	Reduced emissions of NO_x and CO_2	Slight modification of propulsion systems and engines, high energy density	Its production could entail deforestation (feedstock) and is a expensive alternative fuel	High quality fuel	Expected growth in the next years	[45,53,54]
FAME[c]	Higher carbon footprint than other alternative fuels	Slight modification of propulsion systems and engines	Blend with conventional fuel to be effective, low energy content, low density and high viscosity than conventional fuels, high cost	It could lead to filter clogging and reduced fuel flow at medium temperatures	Reduce its production complexity of removing the glycerol content	[45,55,56]
e-fuels	Reduced emissions and could be considered as “carbon capture systems” as are produced by combining CO_2/N_2 and hydrogen	Compatible with actual engines, fungible with conventional fuel, adequate energy density	Low energy conversion efficiencies, high production costs in comparison with conventional and biomass-based fuels	Safety fuels, aware on the feedstock availability for its production	Increase the technology readiness level for its further development	[51,57]
Bio-ethanol	Local emissions of CO_2 and NO_x could be increased, depending on the engine used	Biodegradable, lower production prices than other alternative fuels	It can be corrosive for the engine materials	Bio-ethanol fuel cells are a viable option for its implementation	Need to adapt for its use on lower engines: increase cetane number and lubricating power	[51]
HDPO[d]	Able to reduce the CO_2 emissions in more than 50%	Large availability of biomass feedstock for its production, high energy density	High production costs	Technology is not mature yet	Engines and new technologies are under construction	[53,58]
DME[e]	Clean combustion with reduced emissions	Heating value similar to diesel, compatible with diesel engines	Lower density than conventional fuels, low viscosity and lubricity	Similar properties as propane, so infrastructures to its distribution and use are yet available.	Analyze the possibility of blending to increase its viscosity and lubricity	[46]

[a] LNG: liquified natural gas.
[b] HVO: hydrotreated vegetable oil.
[c] FAME: fatty acid methyl ester.
[d] HDPO: Hydrotreated Pyrolysis Oil.
[e] DME: Dimethyl ether.
[f] IMO: International Maritime Organization.

The main problem to its further TRL is the bio-based feedstocks used for its production, its management and process stages required to the final bio-methanol production, at least for now, have a limit, that is a maximum capacity of 1300–2600 t/day.

Some technological companies have also developed interesting process schemes to the production of alternative marine and jet sustainable fuels: Honeywell Co., an American company, uses vegetable oils and fats to obtain green diesel and Haldor TopsØe has constructed a hydrotreating-based technology to produce green diesel using raw grease raw materials. On the other hand, other companies such as SkyNGR, Project Solaris or Petrobras have adopted co-processing technologies in which the marine and jet bio-fuels are blended with petroleum-based traditional fuels. The rationale behind this is the attempt to achieve a more sustainable fuel give the reduced sulfur content that a mixing with a bio-based fuel could provide, thus also reducing the carbon-related emissions [55].

4. What is the current stage of biofuel production and commercialization?

According to the International Energy Agency (IEA), in 2020 the demand of biofuels amounts to 146.72 billion liters of biofuels and this

Table 2
Some examples of companies producing SAF.

Company	Feedstock	Technology	Production annual capacity (million gallons)	Some application
Neste	100% renewable waste and residues (i.e cooking oil, fats and greases)	NEXBTL™ technology, based on HEFA-technology (hydrodeoxygenation, isomerization and distillation)	515	Commercial airlines KLM, Lufhansa, Delta and American Airlines are using Neste SAF. Is available in 12 airports in the US and in 3 in Europe
Gevo Inc.	Inedible corn feedstock	Alcohol-to-jet process using bio-ethanol and bio-isobutanol, produced using corn.	55, increasing to 100 in a five-year term	Agreement with Delta Air Lines for supplying 75 million gallons of SAF yearly for the next seven years
World Energy	Inedible oils and waste	HEFA-technology	230 per year	Operating with United Airlines
SkyNRG	Agricultural residues	HEFA-technology	33	40 airlines worldwide are using SkyNGR SAF, and this company has invested in a startup “Synkero” for producing e-fuel using green hydrogen and renewable energy
Phillips 66	Waste oils	HEFA-technology	290	It supplies SAF for British Airways
Lanzajet	Lignocellulosic (mainly waste wood and biomass)	Ethanol-to-jet technology	100	Partnership of the “Marquis Industrial Complex” the first carbon-neutral industrial area from with SAF is supplied for Chicago O’Hare and Midway international airports
Fulcrum Bioenergy	Landfill waste	Gasification/Fischer-Tropsch	7	The first US airline that has invested in a SAF company uses Fulcrum SAF. It has also agreements to operate with UK airlines in the future
Red Rock Biofuels	Wood-based residues (i.e. slash piles from forest clean-up usually burned in winter)	Gasification/Fischer-Tropsch	6	Is a company included in the Cellulosic Fuel Purchase and Sale Agreement given its capacity of producing renewable diesel and SAF
Shell	Cooking oil, municipal waste and woody biomass	Fischer-Tropsch	2 by 2025	Spanish Ryanair airlines have signed an agreement with Shell as SAF supplier. Also Luthansa, with a value amounting to 1.8 Mtons in the period 2024–2030

value increased to 155.43 billion liters in 2021 [62]. Bio-based fuels will be gradually introduced in aviation for outbound flights, considering first a 2% substitution of fossil-based fuel in 2025, and increasing the percentage by 5% (2030), 20% (2035), 32% (2040), 38% (2045) and 63% (2050) [63]. In this sense, at European level, the total number of facilities producing biofuels from different feedstocks is 339: 80.2% of them are already on a commercial scale, 16.2% on a pilot/demonstration scale and 3.5% are under R&D. Fig. 3 shows the total number of facilities per country and type of feedstock (agricultural {orange label}, forestry {dark green}, grasses and short-rotation coppice {light green}, waste residues {brown} and marine feedstocks {blue}).

Fig. 4 provides a more holistic view on the current development of biofuel supply chains. Most of the supply chain is ruled by fossil-based fuels (93% share), the use of diesel and gasoline is dominant with percentage 60% and 24%, respectively. Concerning the biofuels, biodiesel is the one that stands out, followed by HVO (Hydrotreated Vegetable Oil) and bioethanol, with 20% and 13% share, respectively.

Another important aspect regarding the biofuel value chain is about where are those facilities located for its production, in which the use of marginal areas is increasingly. The production of bioenergy, particular bio-based fuels, in marginal areas provides both opportunities and challenges in terms of sustainability [64]. Those areas are typically characterized to be low agricultural productive, thus offering a viable alternative for the growing of energy crops, thus avoiding the competition and potential impacts over food security, one of the targets of the Sustainable Development Goals” [65,66]. Biobased fuels obtained by the harvesting of marginal areas could contribute to the diversification of the energy resources and to the reduction on the depletion of fossil fuels and on the impacts over the environment, as those are lower massified [67]. However, in order to ensure sustainability, careful analysis of the use of marginal areas should be developed. Firstly, the selection of the type of crop used for biofuels production, those selected should have higher energy yields, low chemical and fertilization requirements and minimal negative environmental impacts [68,69]. Besides, the land management is also essential to ensure its long-term viability for biofuels production, for which crop rotation, agroforestry or soil conservation techniques could be effective [65]. Secondly, also economic and social factors should be assessed, local communities of those marginal areas should be involved in the decision-making progress in order to ensure a fair distribution of the benefits from the production of biofuels. On the other hand, the use of this marginal areas should also create employment opportunities and should promote rural development and economic growth [70,71]. As a general conclusion, it could be stated that the production of biofuels using marginal areas has the potential to promote more sustainable actions and to ensure food security in a higher level, but to achieve this, the address of environmental, social and economic factors is essential in order to provide a positive impact of biofuels projects in these regions.

5. Which are the types of biofuels being assessed?

95% of biodiesel (first-generation biofuel) is produced from edible oil-crops as feedstock. Food competition, large crop areas and water consumption are the main barriers [72]. The use of food crops to produce biofuels such as bioethanol leads to higher GHG emissions compared to bioethanol obtained from lignocellulosic feedstocks [73]. Biofuels obtained from non-food feedstocks are known as second-generation biofuels, which encompass the use of energy crops, waste streams from crops and agricultural activities, wood-derived waste resources and discarded cooking oil [73,74]. Second-generation biofuels are considered cleaner fuels than first-generation biofuels because of their lower environmental impact and higher energy efficiency, as well as cheaper feedstock supply [75]. However, higher investment is required due to the need of emerging technologies [76,77]. Finally, third-generation biofuels from the use of algae are considered the most promising for the future. Their production process is at an early stage of development; advantages include cheaper production processes than other biofuels, high feedstock availability and remarkable productivity, as algae -based feedstocks can produce 15–3000 times more oil for biodiesel production compared to first and second generation biofuels [78–80].

Despite the differences in first, second and third generation biofuels, evidence of lower environmental impacts compared to those of fossil origin has been reported (94 g CO_2 eq/MJ for petrol and diesel,

Table 3
Some examples of airlines using SAF.

Company	Prospects	Companies providing SAF	Approximate/ available quantities	Other info
Air France	By 2030 incorporating at least 10% of SAF, to achieve 63% in 2050	Neste and DG Fuels	1.6 Mtons of SAF from 2023 to 2036	First flight using SAF launched in 2011
Air Canada	Researching on hydrogen, electric and hybrid aircraft technologies	Neste	–	Four commercial flights using SAF has been operated last year
British Airways	By 2030 incorporating at least 10% of SAF	Phillips 66 & Lanzajet	Multi-year agreement	Co-partner of Speedbird project, aiming to increase SAF production in UK using alcohol-to-jet technolgies
Finnair	Half the net emissions by the end of 2025 and C-neutrality by 2045	Gevo	7 million gallons/year for 5-years starting from 2027	Agreement with other companies, such as Neste, as SAF suppliers
Luthansa	Half the C-emissions by 2030	OMV, Shell.	800 thousand tons from 2023 to 2030 with OMV and 1.8 Mtons with Shell between 2024 and 2030	Pioneer on testing SAF emissions in regular flights
Malaysia Airlines	By 2030 incorporating at least 10% of SAF, to achieve C-neutrality in 2050	Neste	–	First passenger flight using Neste's SAF blended with jet fuel in 2022
TAP Air Portugal	By 2030 incorporating at least 10% of SAF, to achieve 63% in 2050	Neste	–	The 1st flight using 39% of SAF launched in 2022
Swiss	Half the C-emissions by 2030	Neste	–	Support on Synhelion company, that aims to provide SAF using solar energy sources
United Airlines	Reduce the GHG emission at 100% by 2050	Neste	52.5 million gallons over the next 3-years	First US airline investing on SAF
Qatar Airways	Replace 10% of conventional jet-fuel with SAF by 2030	Gevo	25 million US gallons in the next 6-years	First airline in the Middle East that has achieved the highest level of the IATA accreditation
Iberia Airlines	By 2030 incorporating at least 10% of SAF	Gevo	6 million gallons	First flight with SAF in 2011 and using biofuel produced from residuals in 2021.
Ryanair Airlines	By 2030 incorporating at least 12.5% of SAF	Shell	120 million gallons between 2025 and 2030	Agreement to construct supply SAF infrastructures in more than 200 airports
Norwegian Airlines	45% less CO_2 emissions by 2030	Neste	–	The aircrafts of Norwegian are capable on tank up to 50% SAF
Vueling Airlines	By 2030 incorporating at least 10% of SAF	Cepsa, Repsol S.A.	800 thousand tones of SAF by 2030 with Cepsa,	This airline has reduced its emissions in 60-ton CO_2 eq in three months with the use of SAF
Virgin Atlantic	Replace 10% of conventional jet-fuel with SAF by 2030	Gevo	70 million US gallons over the next 7 years	Expected to be the 1st net zero transatlantic flight in 2030 from the UK

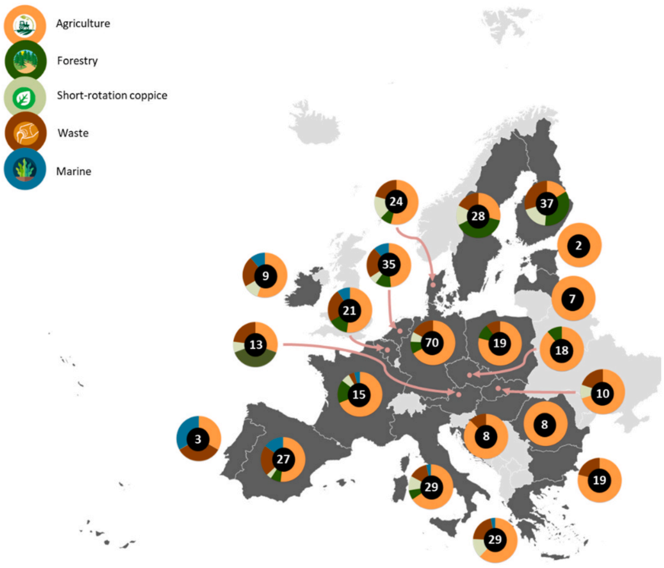

Fig. 3. European facilities producing biofuels categorized by country and type of feedstock. Adapted from Data-Modelling platform of resource economics (European Commission).

according to REDII) [76,81,82]. To this end, research and innovation in sustainable technologies must be the main focus of attention in future development.

6. Technological pathways to produce biofuels

The technologies used classified as thermochemical processes are **hydrothermal liquefaction, gasification, fast pyrolysis** [83]. **Gasification** is based on partial oxidation generating solid and gaseous fuels, while **pyrolysis** requires absence of oxygen (no oxidation) and produces solid, liquid and gaseous fuels. **Fast pyrolysis** provides higher yields for liquid biofuels, and is characterized by shorter residence time and fast heating rates [84]. **Hydrothermal liquefaction** shows significant potential in biofuel production, given the ease and efficiency of the process (low reaction time, applicability to different feedstocks, high yields), producing a biocrude with low oxygen content and higher stability to be

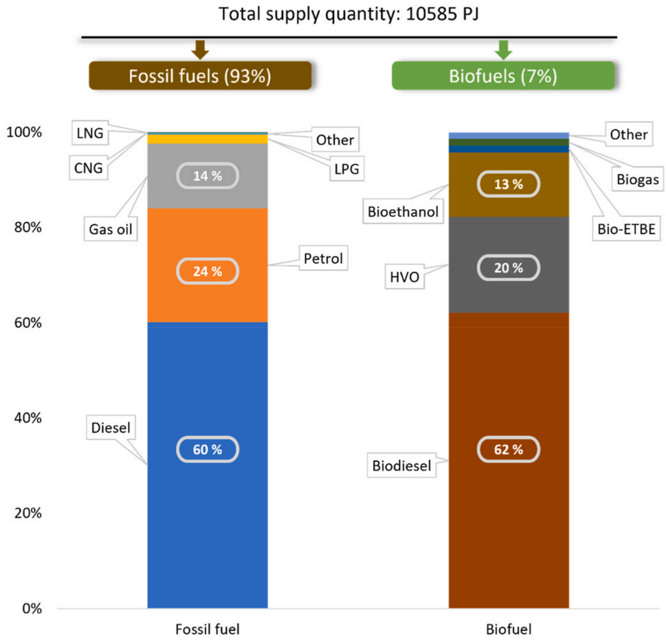

Fig. 4. Total quantities of fuel supply in the 27 EU-member states in 2020. Data obtained from: ETC CM Report 2022/02 Greenhouse gas intensities of transport fuels in the EU in 2020. Acronyms: LNG (Liquefied Natural Gas), CNG (Compressed Natural Gas), LPG (Liquid Petroleum Gas), HVO (Hydrotreated Vegetable Oil) and ETBE (Ethyl tert-butyl-ether).

used as fuel [85–87]. One of the main bottlenecks in the implementation of biofuel production using a hydrothermal process, based on a **gasification** and Fischer–Tropsch synthesis, are the investment and operational costs [88], in addition to the energy requirements [89].

Hydrotreatment is applied on a commercial scale for biojet production, which can be classified as HEFA (hydrotreated esters or fatty acids) or **HVO**. According to the ASTM D7566 standard, the process scheme known as HEFA-SPK (synthetic paraffinic kerosene) produces more than 5 billion liters of HEFA biofuel worldwide [90]. This process has two hydro-processing stages in which a combination of deoxygenation and decarboxylation reactions of lipid-based feedstocks takes place [91–93]. The main bottleneck for commercialization of the HEPA-SPK biojet fuel is the selling price, which could amount to 825–2000 $/ton, in comparison to that of fossil-based jet fuel: 329 $/ton [94]. However, the advantage of using HEFA-SPK biojet fuels mainly relies on the reduction of the carbon intensity in GHG emissions: 13.9 g CO_2 eq./MJ when using waste cooking oil as feedstock, 17.2 g CO_2 eq./MJ for corn oil and 22.5 g CO_2 eq./MJ using tallow [90].

According to Gao et al. (2022) the **biochemical alternative** for biofuel production includes five main stages: anaerobic digestion of lignocellulosic biomass, cleaning of the biogas produced in the digestion stage (for the removal of water, sulfur and nitrogen compounds), followed by the production of syngas with a reforming unit, with subsequent emission of flue gases, which pass through the Fisher-Trop reactor to obtain a mixed product that is separated into biodiesel, light gases recycled to the reforming stages and water [95,96].

The production of third-generation biofuels from microalgae requires a pretreatment step followed by a hydrolysis step, which can be chemical (under acidic conditions) or biological (using enzymes), rendering sugar recovery yields of up to 90% (Hemalatha et al., 2019; De-Farias-Silva et al., 2018).

Although bio-based technologies for biofuel production demonstrate potential feasibility in terms of production yield, it is foreseeable that in a future scenario the integration of biofuel production into conventional fuel facilities will be the most viable alternative. This has been the approach followed by Ketabchi et al. (2019), a hybrid refinery using willow and algae residues as feedstock for ABE (Acetone-Butanol-Ethanol) **fermentation**. The butanol undergoes a pyrolysis stage, in which bio-oil is obtained, and then a gasification process of the gaseous stream is carried out for the production of syngas. After purification of the syngas to remove sulfur and nitrogen compounds (mainly H_2S and NH_3), the biofuel is obtained from the Fischer–Tropsch reaction [97]. The **alcohol-to-jet technology** is also framed as a fermentation procedure, using lignocellulosic biomass, crops and sugar-based feedstocks to produce bioethanol, and also other alcohols, but in a smaller proportion. The liquid stream is then dehydrated, oligomerized and hydrogenated to obtain the final biofuel, which is usually applied in the fuel blend [98].

Table 4 summarizes the main European industrial facilities that produce biofuel using different production schemes. It also provides information on the TRL, the main feedstocks used and the production capacity of the facilities. This provides an overview of the technological maturity of biofuel production in Europe, as well as the degree of development and commercialization of biofuels.

7. Assessment of the sustainability of biofuel technologies and value chains

The integration and evaluation of sustainability aspects (economic viability, social equity and environmental protection) must be taken into account in the biofuel production strategy. In this regard, the use of Life Cycle Assessment (LCA) methodology is considered as a long-standing methodology to assess the environmental loads of processes and/or products within their life cycle. It is based on ISO 14040:2006 standard and it has been used as a methodology to assess the environmental impact loads in biofuel production, as shown on Table 5, that provides examples of the most recent sustainability reports on biofuels. In order to get those, SCOPUS database has been used, considering as searching keywords “LCA”, “sustainability” and “biofuels”, and also reducing the time frame to the most recent years, from 2010 to the present. The selection of the articles has been made according to the information given (type of biofuel, inventory analysis, environmental profiles, among others), the type of technology (mostly considering emerging technologies for the production of biofuels) and the LCA calculation method used for the assessment, achieving the total articles presented on Table 5 afterwards a critical analysis of them based on the abstract, methods and main conclusions. On the other hand, only the articles on English language have been selected.”

The main drawback encountered when assessing the articles reported on Table 5 is based on the fact that most of them are barely based on the evaluation of the environmental loads considering different feedstocks for the production of biofuels using different technologies, but there is a lack on the development of techno-economic assessments to evaluate the degree of profitability of the technology and process scheme being assessed. When talking about the prosperity and future framework of biofuels, ensuring that are beneficial under an economic perspective is a key factor for its integration on the value chain. On the other hand, neither a comparison with conventional fuels is being developed in most of the cases, with the exception of [110], in which report it has been concluded that the production of liquid biofuels using pine sawdust by gasification technology is not as productive to be competitive with the commercial prices. On the other hand, other authors have noticed that one way of increasing the competitiveness of biofuels on the value chain is by the use of renewable energy, as it is one of the main costs and also constraints when talking about sustainability [111,112].

Environmental and economic assessments in the development of technology provide additional criteria in the decision-making process. Firstly, because of the need to control and reduce emissions released into the environment, taking into account the policies and restrictions imposed, and secondly, regarding the economic pillar, the technology must be able to achieve reasonable performance and productivity

Table 4
European biofuel production facilities including the TRL, technology used, type of feedstock and production capacity.

Facility	Location	TRL	Technology	Feedstock	Output (amount)
Center of Biorefining Technologies	Denmark	4–5	Hydrothermal liquefaction	Agricultural residues: sewage sludge, manure, industrial wastes, lignocellulosics	Bio-oil (30 t/y)
Advanced Biofuel Solutions Ltd	United Kingdom	8	Gasification	Organic residues and waste streams	SNG (1500 t/y) Hydrogen (500 t/y)
ALTACA ENERGY	Turkey	6–7	Fast pyrolysis	Various biomass sources	Bio-oil (20 000 m^3/y)
AquaGreen ApS	Denmark	9	Fast pyrolysis	Organic residues, sludge	Syngas and biochar (N/A)
ArcelorMittal	Belgium	8	Fermentation	Waste gases	Bioethanol (62 000 t/y)
ARD	France	4–5	Fermentation	Lignocellulosic	Bioethanol (100 m^3/y)
Audi AG	Germany	8	Methanation	Waste gases	SNG (300 m^3/h)
AustroCel Hallein	Austria	8	Fermentation	Lignocellulosics: spent sulfite liquor (SSL)	Bioethanol (30 000 t/y)
BEST	Austria	6–7	Gasification with FT-synthesis	Biogenic resides and lignocellulosic waste	FT liquids (58 m^3/y)
BioGasol	Denmark	6–7	Fermentation	Straw, grasses, garden waste	Bioethanol (4000 t/y)
Biojet AS	Norway	6–7	Gasification	Forest residues	SAF (N/A)
BioMCN	Netherlands	8	Gasification	Lignocellulosic: wood chips	Bio-methanol (413 000 t/y)
Bio SNG Guessing	Austria	6–7	Gasification	Lignocellulosics	SNG (576 t/y)
BioTfuel – consortium	France	4–5	Gasification	Forest waste, straw, dedicated crops	FT liquids (60 t/y)
Biozin	Norway	8	Fast pyrolysis	Forest and sawmill residues	Pyrolysis oil (100 000 t/y)
Borregaard AS	Norway	6–7	Fermentation	Sugarcane bagasse, straw, wood, energy crops	Bioethanol (110 t/y)
		9	Fermentation	Spent sulfite liquor (SSL)	Bioethanol (15 800 t/y)
BP	Spain	9	Hydrotreatment	Oil crops, oils and fats	SAF (N/A)
BTG-BtL	Netherlands	4–5	Fast pyrolysis	N/A	Pyrolysis oil (1000 t/y)
		8	Fast pyrolysis	Wood pellet processing waste	Pyrolysis oil (3200 kg/h)
Butamax	United Kingdom	8	Fermentation	Sugar and starch crops: corn	Bio-butanol (240 500 t/y)
Butamax Advanced Biofuels LLC	United Kingdom	6–7	Fermentation	Agricultural residues	Bio-butanol (15 t/y)
Cepsa	Spain	6–7	Hydrotreatment	Organic residues and waste streams	HVO (50 000 t/y)
Chempolis Ltd.	Finland	6–7	Fermentation	Non-wood and non-food lignocellulosics	Bioethanol (5000 t/y)
CHOREN Fuel Friberg GmbH & Co. KG	Germany	6–7	Gasification	Dry wood chips and residual forestry wood	FT liquids (13500 t/y)
		8	Gasification	Dry wood chips and recycled wood	FT liquids (200000 t/y)
Clariant	Germany	6–7	Fermentation	Wheat straw, corn stover, miscanthus, sugarcane bagasse	Bioethanol (1000 t/y)
Conoco Philipps	Ireland	6–7	Hydrotreatment	Vegetable oils	HVO (40000 t/y)
Cutec	Germany	4–5	Gasification	Straw, wood, silage, organic residues	FT liquids (0.2 t/y)
Domsjoe Fabriker	Sweden	9	Fermentation	Spent sulfite liquor (SSL)	Bioethanol (19000 t/y)
DTU Chemical Engineering	Denmark	4–5	Gasification	Organic residues and waste streams	Clean syngas (N/A)
Ekobenz	Poland	8	Hydrotreatment[a]	Sugar and starch crops	Gasoline-type fuels (22500 t/y)
Energochemica	Slovakia	8	Fermentation	Dedicated crops and agri-food residues	Bioethanol (55000 t/y)
Enerkem SA	Spain	8	Gasification	Organic residues and waste streams	Bio-methanol (265000 t/y)
ENI	Italy	8	Hydrotreatment	Oil crops, oils and fats	HVO (750000 t/y)
	Italy	9	Hydrotreatment	Oil crops, oils and fats	SAF (10000 t/y)
	Italy	9	Hydrotreatment	Oil crops, oils and fats	HVO (500000 t/y)
	Italy	8	Hydrotreatment	Soybean oil, used cooking oil, animal fats and waste vegetable oil	HVO (360000 t/y)
Enviral	Slovakia	9	Fermentation	Lignocellulosics	Bioethanol (50000 t/y)
E.ON Gasification Development AB	Sweden	9	Gasification	Wood biomass	SNG (200 MW)
Eta Bio	Bulgaria	8	Fermentation	Wheat straw	Bioethanol (50000 t/y)
Fintoil	Finland	8	Hydrotreatment	Crude tall oil	HVO (100000 m^3/y)
FlexJET Consortium	United Kingdom	6–7	Hydrotreatment	Oil crops, oils and fats	SAF (1200 t/y)
FLITE	Netherlands	8	Alcohol-to-jet	Sugar and starch crops	SAF (30000 t/y)
Fraunhofer Umsicht	Germany	4–5	Fast pyrolysis	Sewage sludge	Bio-oil (450 m^3/y)
GIDARA Energy B.V.	Netherlands	9	Gasification	Organic residues and waste streams	Bio-methanol (87500 t/y)
Global Bioenergies	Germany	6–7	Fermentation	Cane sugar, beet sugar and starch	Bio-isobutene (100 t/y)
Goteborg Energi AB	Sweden	8	Gasification	Forest residues	SNG (50000 t/y)
Green Fuel Nordic	Finland	9	Fast pyrolysis	Forest residues: sawdust, crown trunks	Pyrolysis oil (24000 t/y)
HCS Group and Gevo	Germany	6–7	Alcohol-to-jet	Biomass	SAF (60000 t/y)
IBN-One	France	8	Fermentation	Cane sugar, beet sugar and starch	Bio-isobutene (50000 t/y)
INA	Croatia	8	Fermentation	Miscanthus, wheat straw	Bioethanol (55000 t/y)
Joint Venture of Air Liquide	Netherlands	8	Gasification	Organic residues and waste streams	SAF (60000 t/y)
Karlsruhe Institute of Technology	Germany	6–7	Gasification	Straw	DME (608 t/y) Gasoline-type fuels (360 t/y)
LanzaTech UK	United Kingdom	8	Alcohol-to-jet	Organic residues and waste streams	SAF (100000 m^3/h)
Neste	Netherlands	9	Hydrotreatment	Oil crops, oils and fats	SAF (500000 t/y)
	Finland	8	Hydrotreatment	Palm il, rapeseed oil and animal fat	HVO (190000 t/y)
	Singapore	9	Hydrotreatment	Oil crops, oils and fats	HVO (1300000 t/y)
	Finland	6–7	Hydrotreatment	Tall oil pitch	HVO (40000 t/y)
PNK ORLEN	Poland	9	Hydrotreatment	Used cooking oil (UCO)	HVO (300000 t/y)
Preem	Sweden	9	Hydrotreatment	Oil crops, oils and fats	HVO (367000 m^3/y)
	Sweden	8	Hydrotreatment	Tall oil	HVO (800000 t/y)

(*continued on next page*)

Table 4 (*continued*)

Facility	Location	TRL	Technology	Feedstock	Output (amount)
RenFuel	Sweden	8	Depolymerization	Forest residues	Bio-oil (200000 m^3/y)
Repsol	Spain	9	Hydrotreatment	Organic residues and waste streams	HVO (250000 t/y)
SCA	Spain	6–7	Hydrotreatment	Crude tall oil	HVO (200000 m^3/y)
Shell	Netherlands	9	Hydrotreatment	Used cooking oil (UCO)	SAF (410000 t/y), HVO (410000 t/y)
Silva Green Fuel	Norway	6–7	Hydrothermal liquefaction	Forest residues	Bio-oil (1400 t/y)
SkyNRG	Netherlands	9	Hydrotreatment	Oil crops, oils and fats	SAF (100000 t/y), Bio-LPG (15000 t/y)
Solena Fuels	United Kingdom	8	Gasification	Organic municipal solid wastes	SAF (120000 t/y)
SunPine	Sweden	9	Hydrotreatment	Forest residues, tall oil from pulp and paper	HVO (39000 t/y)
Uniper	Sweden	6–7	Fischer Tropsch	Biomass	SAF (100000 t/y)

[a] Note1. Meaning of TRL numbers: 4–5 (Pilot scale demonstration), 6–7 (Demonstration), 8 (First-of-a-kind commercial), 9 (Commercial). Note2. Acronyms: SNG (Synthetic Natural Gas), FT (Fischer Tropsch), SAF (Sustainable Aviation Fuels), HVO (Hydrotreated Vegetable Oil), DME (Dimethyl Ether), LPG (Liquefied Petroleum Gas).

Table 5
Small sample of the most recent articles on LCA reports on biofuels.

Reference	Biofuel	Feedstock	Technology	LCA	Approach	Database	Methodology	Tool	TEA	Main result
[99]	Bioethanol	Lignocellulosic	Fermentation	Y	Cradle-to-wheel	Ecoinvent v3.5	ReCiPe 1.1 Hierarchist	SimaPro v9.0	N	–
[100]	Bioethanol	Oil crop	Fermentation	Y	Well-to-wheel	Food LCA	Impact 2002+	SimaPro v8.2	N	–
[101]	Biodiesel + bioethanol	*Eruca sativa* plant	Esterification/ Fermentation	Y	Well-to-wheel	–	Impact 2002+	SimaPro v8.3	N	–
[102]	Bioethanol	Banana agricultural waste	Fermentation	Y	Well-to-wheel	Ecoinvent v3	ReCiPe midpoint	SimaPro v8.0	N	–
[103]	Liquid biofuel	Corn stover	Fast pyrolysis and hydro processing	Y	Well-to-wheel	US LCI Database	TRACI 2.0		N	–
[104]	Bioethanol	Fiber sorghum	Fermentation	Y	Cradle-to-wheel	Ecoinvent v2.2	IPCC	SimaPro v8.2	N	–
[105]	Bioethanol	*Eucalyptus globulus*	Fermentation	Y	Cradle-to-wheel	Ecoinvent v2.0	ReCiPe 2008	SimaPro v7.8	N	–
[106]	Bioethanol	*Arundo donax* L. (non-food crop)	Fermentation	Y	Cradle-to-wheel	Ecoinvent v2.2	ReCiPe midpoint H	SimaPro v8.2	N	–
[107]	MEK	Lignocellulosic biomass	Fermentation	Y	Cradle-to-grave	Ecoinvent v3.7	ILCD2011	–	N	–
[108]	Bioethanol	Sugarcane	Gasification	Y	Cradle-to-gate	Ecoinvent v.3	ReCiPe midpoint V1.13H	OpenLCA v1.10	N	–
[109]	Bio-crude oil	Microalgae	Hydrothermal liquefaction	Y	Cradle-to-grave	–	TRACI	GaBi	N	–
[110]	Liquid bio-fuels	Pine sawdust	Gasification with Fischer-Tropsch	Y	Cradle-to-grave	GREET database	–	GaBi	Y	Could not compete with commercial prices
[111]	Bioethanol	Sugarcane molasses and agave juice	Fermentation	Y	Cradle-to-gate	Ecoinvent	ReCiPe 2016 midpoint (H)	Simapro v8.0	Y	Economically viable when renewable energy is used
[112]	Biodiesel and bioethanol	Palm oil and sugarcane	Transesterification	Y	Well-to-tank	–	IMPACT 2002+	Simapro v8.0	Y	Economic feasibility when integrated both feedstocks
[113]	Solid biofuels	*Sida hermaphrodita* biomass	Combustion	Y	Cradle-to-gate	Ecoinvent v3.5	ILCD2011	GaBi	N	–
[114]	Biodiesel	Microalgae	Transesterification	Y	Cradle-to-gate	Ecoinvent v3.3, Agri-footprint v3	ReCiPe 2016 Endpoint H	Simapro v.9.0	N	–
[115]	Bio-butanol	Macroalgae	Fermentation	Y	Cradle-to-grave	Ecoinvent v3.3	ReCiPe	Simapro v8.0	N	–

indicators to be considered as a cost-effective process.

In accordance with the social pillar, the use of Social-LCA (S-LCA) is encouraged, and in order to assess economic viability, the methodology of techno-economic evaluations (TEA) is proposed as the best approach [116,117]. These three studies are necessary to evaluate the feasibility of developing a sustainable process, bearing in mind that the use of inventories that only take into account the current situation ("static" data inventories) means that the future prospects of the scenario are not reflected [118]. This can be a shortcoming when it comes to assess the market potential of an emerging technology, both from an environmental point of view (legal obligations regarding environmental protection and increasingly strict emission limits and require the adoption of more sustainable production models that promote circularity and integrated resource use), from an economic (variability of product market prices, raw material and electricity costs, etc.) and social point of view (greater environmental awareness of the population will mean greater demands for more sustainable industrial practices, and the increase in the world's population implies higher consumption of resources).

Therefore, the life cycle analysis methodology from one perspective should roughly consider the adaptability of the process in a future scenario, taking into account the evolution of technology, legal constraints and market capacity. The occurrence of unexpected events, such as the COVID-19 pandemic, may definitely delay the trend in a context of low technological development and economic crisis, hindering the penetration of emerging technology in the market [11,119]. Such unexpected events should be considered by evaluating scenarios under a range of probabilities, both favorable and unfavorable prospective situations.

8. Assessing future scenarios with LCA methodology

The most common method for evaluating the life cycle of a product or process is the "ex-ante" one, in which the production scenario is evaluated at an early stage of development [120,121]. It is a suitable methodology to determine the potential impact of the technology or product during the development and operation stage. Based on the results obtained, the production model could be adapted to establish alternative scenarios that promote a new production model with higher productivity and a more favorable sustainability profile, from the environmental, economic and social perspective. However, one of the main weaknesses of using this framework is the lack of foresight in assessing the potential and adequacy of the process/product being developed in a future scenario [11,122,123].

It is at this point that computational methodologies are required that provide an estimated view of the future scenario in which the emerging technology under development is intended to be framed. The first of these methodologies is the "anticipatory LCA", a non-predictive analysis model that, in an estimated way, tries to establish potential future scenarios; a more favorable one (in which the emerging technology achieves stability and adaptability to the development of technology, environmental legislation and social demand) and a more adverse one (in which the emerging technology develops in a technological, economic and social framework that is not fully favorable) [124,125]. Therefore, the anticipatory LCA methodology tries to establish benchmark scenarios in which uncertainties that can affect both positively and negatively the process under consideration are evaluated through a stochastic analysis [126,127].

Another approach is the "prospective LCA", the main difference with the anticipatory LCA is that, even the emerging technology is assessed at a small/pilot scale, the LCA is evaluated at a large-scale in a future scenario. To perform this assessment, it is necessary to use available exogenous bibliographic database in order to determine/simulate the environmental, societal and technoeconomic changes in the forthcoming future [128]. For the development of this LCA methodology, an attributional approach should be considered, taking into account that, to assess the uncertain future, quantitative values from life cycle inventories should be combined with qualitative scores available in databases to orient a future LCA approach [119]. Those qualitative values from databases are to be evaluated as explicit assumptions for future forecasts [129]. When using bibliographic or statistical databases, the data quality should be as reliable and accurate as possible to avoid discrepancies, the use of statistics or artificial intelligence could help on reducing the risk of errors. Moreover, up-to-date metadata might not be representative of technology development and/or economic, environmental and societal trends and demands, so defining the data time frame and selecting reliable datasets is one of the most essential steps in developing a prospective LCA [130,131].

Another method for assessing future trends is the "dynamic weighting system", which could be based on expert panel judgment, monetization or distance-to-target (DTT) approaches. The DTT approach is considered to have the highest quantifiability, predictability and feasibility, as it is based on emission targets and resource use management, while expert judgment is conditioned by moral criteria, education and personal knowledge, and monetization is mainly based on economic criteria, which are quantitative but unrepresentative at the level of predictability and future feasibility [132]. To this end, DTT approach aims to represent the variability of environmental impacts and pre-selected targets over time.

In this context of assessing the prospects for biofuel production, Table 6 presents various scientific reports that combine emerging biofuel technologies and prospective LCA studies, including the technology, the system boundaries, the time scope for analyzing the adequacy of biofuel production in the future, as well as the assumptions and limitations identified in developing the prospective assessments.

9. How should a prospective-LCA be performed? Brief recommendations

When developing a prospective-LCA it is important to keep in mind the limitations in knowledge and accuracy of future scenarios based on assumptions and available data. In addition, the usual scenario is the need to scale new emerging technologies from a low to a higher TRL, which also implies a certain risk of overestimation/underestimation in the scale-up phase. These are the main issues of prospective LCA: uncertainty, data availability and also comparability (how prospective LCA could be used as a tool to assess a comparison between well-established and developing technologies). To overcome these main issues, a more tangible future scenario could be envisioned by taking into account expert recommendations and knowledge, literature data, artificial intelligence (use of neural networks to estimate data and performance), discussion with technology developers, use of empirical design rules, and statistical analysis based on the most meaningful and reliable parameters [123,139]. In this regard, some recommendations are depicted on Table 7, aiming to provide a pathway on where to improve when performing a prospective LCA [128,140].

10. Challenges and prospects on the future of shipping and aviation biofuels. A global framework discussion

Commercial development of emerging biofuel technologies in large-scale production facilities has not been as fast as needed due to financial, regulatory, scale-up, technological inefficiency and regulatory barriers [141,142]. Another aspect to consider is the feedstock used for biofuel production. Its contribution to the total production cost can reach 80%, as is the case of hydrotreated esters and fatty acids (HEFA) technology [89,143]. In this regard, the use of waste feedstock, such as waste cooking oil, can help reduce the cost of production. In addition to the type of biomass used, another aspect that contributes significantly to the economic viability of biofuels is the capital costs (CAPEX) since, while for conventional processes it can reach 15% of the total, in the case of biofuel production routes this value can reach 30% [144]. The high operating and capital costs of biofuel production are the result of the use of an emerging technology that is at a very early stage of development, where energy efficiency has not been achieved and therefore, significantly increases the process economics.

Future research should be based on the improvement of available technology, on the appropriate selection of residual streams and on the optimization, both in terms of energy requirements and production yields, of the biofuel production process. These key actions will facilitate the penetration of biofuels in the market, as production costs will be lower and, therefore, so will their minimum selling prices.

Given the need to reduce GHG emissions, the depletion of fossil resources and the development of more circular processes, the implementation of more stringent policy tools and legal requirements on environmental, economic and sustainable perspectives could help biofuels become part of the solution. Although biofuels policies were being developed, the implementation of biofuels policies should be effective and based on the following precepts [22,145,146].

Table 6
Scientific reports based on biofuels production under a prospective LCA perspective.

Reference	Main aim	Type of LCA	Type of main technology	Temporal scope	Assumptions	Uncertainties & limitations
[133]	To assess the effectiveness of wood biofuels under an environmental and social perspective	"cradle-to-wheel"	Thermochemical conversion	Germany: 2050	Economic and environmental future values based on statistics. For the economic assessment, 2.5% interest and 20 years of depreciation has been assumed	Values for the fossil gasoline and bio-based fuel prices.
[134]	To evaluate the viability on the use of wood-based residues for the production of shipping biofuel using different conversion technologies	"well-to-propeller"	Gasification, methanation, hydrothermal liquefaction and fast pyrolysis	Norway: 2030,2040, 2050	Projection of the electricity mix in Norway and average energy consumption for maritime bunkers based on statistics.	Values for process productivity, impact categories characterization values and process emissions
[135]	Upscale from lab to pilot scale for producing biobutanol	"cradle-to-gate"	Biotechnological process with algae	N/A	Theoretical and expert stakeholders estimations of process capacity based on the state-of-the-art of the biotechnology	Assumptions for technology capacities and productivities, lack of process optimization of the biobutanol production from algae and upscaling done by linear approach of process design, that could entail important errors and limitations
[136]	Environmental assessment of biofuel production using short rotation crops	"well-to-wheel"	Combination of torrefaction and pyrolysis, followed by hydrodeoxygenation stage	100-year time horizon	To evaluate the forward future scenarios, the characterization methodology of IPCC 2013 GWP 100a has been used, based on the characterization factors of the method	Errors on the estimation of the future scenario, based on the methodology of calculation, and lack of concretion of how the system expansion is assessed
[137]	Butanol production within an integrated forest biorefinery	"biomass-to-liquid"	Fermentation	Canada: 2050	Increased availability of feedstock for the biorefinery, reduction by 10% of the investment cost from the improved technology, energy efficiency and expected reduction targets for GHG emissions	Lack of certainty about carbon market and emission credit purchases, and expected increase on the use of solid biomass to produce biofuels in the future
[138]	LCA of potential future poplar feedstocks for bioethanol production	"cradle-to-grave"	Fermentation	2030	Different percentages of bioethanol in the blend of the biofuel, 100 km of travel of the case studies	Future scenario based on bibliographic references, expert estimations, data sets and international standards

1. Timing of policies support. Profit expectations from a biofuel production facility could be achieved over a longer timeframe compared to traditional investments. In this sense, policies should be aware and support for at least the time necessary for the process to be profitable.
2. Incentivize new generation technologies. Currently, first-generation biofuels are conquering the biofuels market to a greater extent than second- and third-generation biofuels. The more developed technology and the current lower prices are behind these circumstances. However, efforts should be made to encourage research and innovation in alternative biofuels to avoid competition with the food market.
3. Give extra benefit for circular and sustainable process technologies. Looking for achieving the targets of EU Green Deal, Sustainable Development Goals, etc. there should be policies aiming to encourage the development and research on more efficient, sustainable and circular technologies. The use of biofuels has demonstrated that could reduce the environmental loads significantly, both in the production and use stages, making the transport sector more sustainable and environmentally friendly.
4. Support for biofuel demand. The viability of biofuel production depends to a large extent on market demand for biofuels. The formulation of contracts, financial support for facilities using biofuels or deflation in the purchase cost of biofuels, through reductions in interest rates, for example, could be appropriate practices to incentivize their demand.
5. Development of biofuel certifications and standards, together with efficient guidelines. Specific certification schemes and eco-labels for biofuels, taking into account the pillars of environmental, economic and social sustainability, can improve the visibility of their benefits. In fact, consumer confidence should improve with the certification and validation of biofuels, encouraging their use. On the other hand, certification and labeling should not be an obstacle to the penetration of biofuels in the market, but a support tool.

11. Conclusions

The development of emerging technologies to produce sustainable biofuels is a suitable alternative to reduce dependence on fossil fuels. However, in order to assess their potential in the future, it is necessary to develop a prospective sustainability assessment. This methodology offers the possibility of advancing the current situation of the value chain to a foreseen future scenario, for which a variety of circumstances and consequences must be evaluated. This approach must take into account expected restrictions on emission levels, as well as variations in the market chain, economic fluctuations, consumer demand for products and services, and other possible events that could have a significant effect on the development of the technology. On the other hand, it is also important to highlight the role of policies in the development of emerging biofuel technologies, which must be adapted to favor their expansion and to improve market penetration.

CRediT authorship contribution statement

Ana Arias: Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Chrysanthi-Elisabeth Nika:** Methodology, Investigation, Supervision. **Vasileia Vasilaki:** Visualization, Supervision. **Gumersindo Feijoo:** Supervision, Writing – review & editing. **Maria Teresa Moreira:** Supervision, Writing – review & editing. **Evina Katsou:** Conceptualization, Validation, Supervision, Writing – review & editing.

Table 7
Main recommendations for performing an accurate prospective LCA.

Issue	Recommended action
Definition of goal and scope	Definition of the type of scenario: predictive, explorative and/or normative Identification of the time horizon Accurate evaluation of the actual TRL and identification of the potentialities for expected TRL in the time horizon considered Awareness on policies and standards Proposition of alternative and comparative scenarios Follow a stepwise approach
Inventory data	Definition of a cross-consistency data check, based on variations on the main parameters, considering optimal and worst scenarios Use of Monte Carlo method to obtain a probability distribution of the data scores Evaluation of different available data sources: literature, experts' judgement, policy makers, technology developers, etc. Improve the consistency of the inventory data by applying mandatory considerations Streamline and unification of the technology's underdevelopment Identification of the key factors and the ones with higher influence on the specific sector under assessment Avoid the temporal mismatch among background and foreground scenarios
Results interpretation	Perform sensitivity assessments based on the main input parameters of the inventory data Evaluate the scenarios under the best and worst perspectives Check the consistency of the results according to the assumptions made Analyze the scores from policy, society and retail perspectives

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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