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Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake

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A R T I C L E I N F O

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A B S T R A C T

Advanced biofuels are among the available options to decarbonise transport in the short to medium term especially for aviation, marine and heavy-duty vehicles that lack immediate alternatives. Their production and market uptake, however, is still very low due to several challenges arising across their value chain. So far policy has established targets and monitoring frameworks for low carbon fuels and improved engine performance but has not yet been sufficient to facilitate their effective market uptake. Their market roll-out must be immediate if the 2030 targets are to be met. Analysis in this paper reiterates that the future deployment of these fuels, in market shares that can lead to the desired decarbonisation levels, still depends largely on the integration of tailored policy interventions that can overcome challenges and improve upstream and downstream performance. The work presented aims to i) inform on policy relevant challenges that restrict the flexible, reliable and cost-efficient market uptake of sustainable advanced biofuels for transport, and ii) highlight policy interventions that, have strong potential to overcome the challenges and are relevant to current policy, Green Deal and the Sustainable Development Goals (SDGs).

1. Introduction

Policy in Europe strives for energy security [1] and gradual decarbonisation in highly polluting sectors like transport through innovation [2] and improved value chains [3,4]. However, despite rapid increase of electric vehicles in the European market [5], light and heavy-duty road vehicles still account for nearly three-quarters of transport CO2 emissions, while emissions from aviation and marine continue to rise [6] (IEA, 2020). The unprecedent COVID 19 crisis has reduced emissions however this is not expected to last long and have major long-term impacts.

Advanced biofuels are essential for the transition to zero carbon [7–11] as planned by the European Green Deal [12] and the UN Sustainable Development Goals [13,14]. Their use can decrease emissions [15] and dependency on imported fossil fuels [16,17] while biomass supply can also create employment in rural areas [18]. Their production costs [19–21] however are higher than their fossil counterparts [22] and they still require significant innovation [23–26], technological development [27] and scale up [28–30]. Even though the Renewable Energy Directive II [31] set clear targets both the industry and the scientific community agree that additional interventions are needed with focus on the challenges [32–35] these fuels face along the value chain [36,37]. This will increase investor confidence and avoid risking the 2050 climate targets [38].

This paper aims to i) inform on challenges that restrict the flexible, reliable and cost-efficient market uptake of advanced biofuels for transport, and ii) highlight policy interventions that are relevant to current policy, Green Deal and the Sustainable Development Goals (SDGs) and have strong potential to overcome the challenges. The work applies value chain analysis [39–41] (biomass supply, conversion

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pathways, end use) and competitive priority theory [42] and is structured in four sections. The first rationalises the role of advanced biofuels in the current markets and outlines EU policy. The second analyses policy relevant challenges that prohibit market uptake of advanced biofuels, discusses associated policies and performance towards flexibility, reliability, and cost. The third presents policy interventions that can overcome challenges and are relevant to current policy and the Sustainable Development Goals. Finally, the fourth provides concluding remarks for future policy.

The analysis in this paper focuses on advanced biofuels from lignocellulosic feedstock that will safeguard issues with land use changes. Individual analysis is included for the aviation, marine and heavy-duty road sectors. Rail is not included; it a very small user of fuel, as electrification is already quite significant in EU.

1.1. *The role of advanced biofuels in current EU markets and policy regime*

The average energy share of renewables (including liquid biofuels, hydrogen, biomethane, 'green' electricity, etc.) used in transport increased from 1.5% in 2004 to 8.3% in 2018 [43]. From this, total biofuel consumption was 17.0 Mtoe in 2018 compared to 15.4 Mtoe in 2017 [44]. In terms of energy content, biodiesel's share was 82.0%, bioethanol was 17.1% and biomethane fuel was 0.9%, respectively.

Blending of conventional (food and feed based) biofuels is estimated at 4.1%, well below the 7% cap set by the ILUC Directive [45], and RED II [46] while blending of advanced (non-food/feed based) biofuels is estimated at 1.2%. The majority of this, as recorded by a Eurobserver survey [47] in July 2020 (3.5 out of 4.8 Mtoe for EU28 in 2019) is produced as Fatty Acid Methyl Ester (FAME) for biodiesel from waste fats and oils with only a small percentage from agricultural and forestry by-products such as Used Cooking Oil (UCO), tall oil and cellulosic feedstock oils (Fig. 1).

Advanced biofuels are the only immediately available solution that can enable transport to meet the 2030 objectives of GHG emission reduction, as electricity, and even more hydrogen, will only be nascent at this horizon (the recent Smart & Sustainable Mobility strategy [49] objective for 30 million EVs on the road in the EU represents only 12% of the car-pool).

This paper followed a linear policy analysis [50–52] approach comprising three stages Fig. 2 (**Error! Reference source not found.**):

i) Agenda: analysis of current state in markets and policy,
ii) Decision: identification of challenges and policy relevant gaps in individual value chain stages,
iii) Implementation: development of future policy concepts tailored to market and industry requirements.

1.1.1. *Market for advanced biofuels*

Advanced biofuels are defined as liquid or gaseous biofuels made from materials listed in Part A of the Annex IX [53] of the Renewable Energy Directive II (REDII). An outlook of advanced biofuel options is presented in Table 1.

1.1.2. *Aviation*

Decarbonising the aviation sector has since long [81] received significant interest by airlines, airplane manufacturers, and policy makers [82]. Only short distance aviation may be electrified in the medium term; therefore, liquid fuels will dominate the industry much beyond 2030 for long distance flights [83,84]. Biofuel use in the sector is mainly based on Hydro-processed Esters and Fatty Acids (HEFA) biojet (produced by vegetable oils, waste lipids and animal fats) [85,86]. Up to date there have been more than 200,000 flights [87] using various blends with aviation biofuels [88]. Current share in jet kerosene is however very low (<0.1%) [89,90]. Due to high safety standards, and compatibility with aircraft fleet and refuelling infrastructure, only drop-in Sustainable Aviation Fuels (SAF) [91] with excellent performance in jet engines [92,93] are approved with ASTM D7566 [94,95].

- up to 50% blends: Fischer Tropsch (FT-SPK) fuels, Hydrotreated Esters and Fatty Acids (HEFA), Synthetic paraffinic kerosene with aromatics via Fisher Tropsch (FT-SKP/A), and Alcohol-to-jet (ATJ), from isobutanol (certified in 2016) and ethanol (certified in 2018).
- Up to 10% blends: Renewable Synthesized Iso-Paraffinic (SIP) fuels

In 2011 the European Biofuels Flightpath in Aviation [96,97], proposed a target on 2 million tons of biokerosene by 2020; however, due

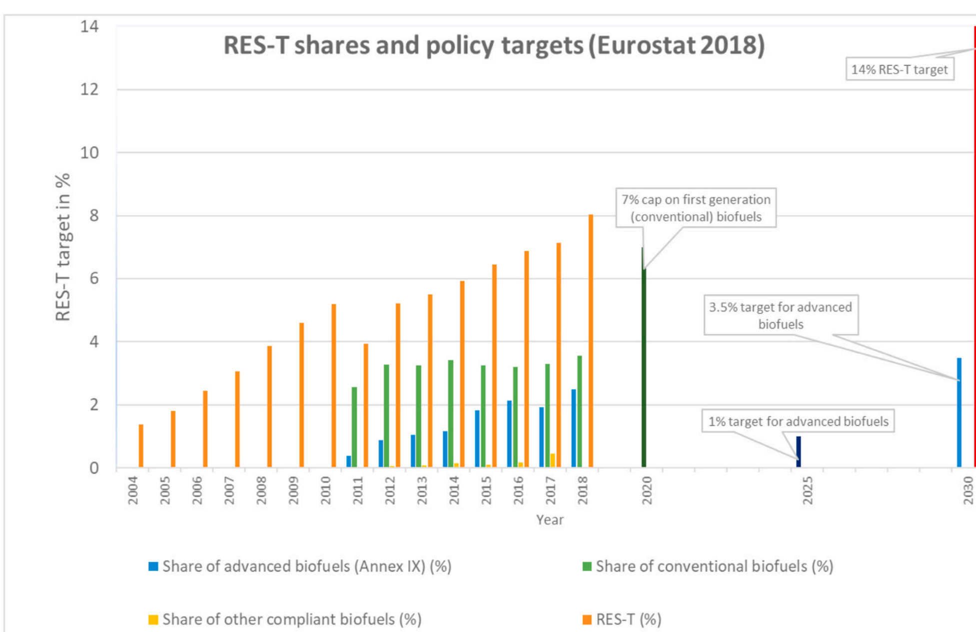

Fig. 1. Share of Renewables in transport (RES-T) and role of conventional and advanced biofuels - including double counting [48] (Source: SHARES Renewables 2017, Eurostat).

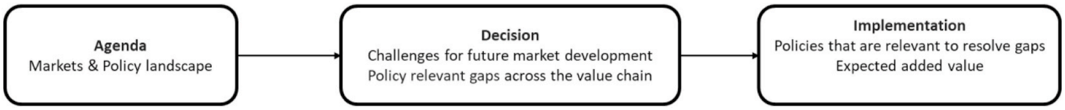

Fig. 2. Value chain approach (adapted from Panoutsou et al., 2020).

Table 1
Outlook of advanced biofuel options (adapted from SGAB. 2017 [54]).

Raw material	Conversion pathway	Biofuel type	Status TRL [1]	Fuel	Market [55]
Waste oils and fats, Used Cooking Oil (UCO), Veg oils, liquid waste streams and effluents [56]	Esterification or transesterification	Traditional biodiesel- Fatty Acid Methyl Ester (FAME)	Commercial	Blends with fossil diesel, B7 (drop-in), B10 [57, 58], B30 [59] or neat FAME	
	Hydrotreatment	Hydrotreated Vegetable Oil (HVO)/ renewable diesel		Drop-in blends with road diesel [60–63] (i.e. H30) or neat HVO [64], Sustainable Aviation Fuels [65]	
MSW [66], sewage sludge, animal manures, agricultural residues, energy crops	Biogas or landfill production & removal of CO2	Biomethane		bioCNG; bio-LNG [67] in heavy-duty road, LBG in marine and CBG in light-duty road transport, captive fleets or injected in the gas grid	
Lignocellulosic, MSW, *solid* industrial waste streams/ residues [68]	Enzymatic hydrolysis & fermentation	Ethanol Other alcohols (methanol [70–72], butanol)	TRL 8-9 TRL 6-7	Gasoline blends such as E5, E10 [69] (drop-in), E20 (minor engine modifications), E85 flexi-fuel engines), ethanol with ignition improvers for diesel engines (ED95), or ethanol/butanol upgraded to biokerosene (ATJ)	
	Gasification + fermentation	Ethanol	TRL 6-7		
Lignocellulosic, MSW, *liquid* industrial waste streams & effluents [73] or intermediate energy carriers [74]	Gasification + catalytic synthesis	Synthetic [75] fuel	TRL 6-7	Drop-in blends with diesel, gasoline, Sustainable Aviation Fuels, bunker fuel or as pure biofuel e.g. bio-SNG, DME [76,77], methanol,	
Pyrolysis oils or biocrudes from lignocellulosic, MSW, waste streams	Pyrolysis [78] or liquefaction (i.e. HTL) + Hydrotreatment	Hydrotreated bio-oil/ biocrude	TRL 4-5	Neat or drop-in diesel, bunker fuel, gasoline, Sustainable Aviation Fuels	
	Co-processing in existing petroleum refineries [79]	Co-processed bio-oil/ biocrude	TRL 7-8	Neat or drop-in diesel, bunker fuel, gasoline, Sustainable Aviation Fuels	
CO_2 from RES systems	Reaction with RES H_2	Synthetic [6]	TRL 6-7	Depends on fuel type, i.e. bio-SNG, methanol or DME, ATJ [80]	

the lack of biokerosene producing facilities this target was never met. The present market limitation to ensure a continuous supply of biokerosene hinders airlines from procuring biokerosene for their operations [98].

1.1.3. Marine

Less than 1% of the current marine fuel supply uses biofuels, mostly in inland or short-sea shipping [99] due to high costs, low fuel availability, retrofitting and bunkering practices, and institutional approval. Merchant shipping, which plays a major role in transporting goods via international routes, still relies on fossil fuels.

The European Commission has recently designed the Inducement Prize for the Promotion of Renewable fuels in retrofitted container ships [100] which has the objective of a relatively large existing ship travel the distance around the world on 100% advanced biofuel and has not been demonstrated yet [101]. So far, initiatives have had less ambitious goals in terms of scale, distance, and quality of biofuel, mainly indicating possible options for the future [102].

1.1.4. Road

1.1.4.1. Heavy duty vehicles (trucks & buses). Currently 97% of trucks are powered with diesel [103]. According to IEA [104] '*Emissions from trucks and buses have risen by around 2.6% annually since 2000. While policy coverage for heavy-duty vehicles (HDVs) still lags behind that for cars and vans, momentum has been growing. Benchmarking for the EU HDV CO_2 standards beginning in July 2019, an estimated 70% of HDVs sold worldwide in 2019 were in markets that had fuel economy and CO_2 emissions standards in place, compared with less than 50% in 2016.*' The first-ever EU-wide CO_2 emission standards for HDVs, adopted in 2019 [105], sets targets for reducing average emissions from new HDVs for 2025 and 2030. The Regulation (EU) 2019/1242 setting CO_2 emission standards for HDVs entered into force on August 14, 2019 [106].

1.1.4.2. Light duty vehicles (cars & vans). There are 312.7 million vehicles in the EU roads, powered by diesel (42%) and gasoline (54%) [107]. Light duty vehicles were responsible for 52% of transport emissions in 2018 (cars 44% and light-duty trucks 8%) [108]. The rest including Electric Vehicles (EVs) and gaseous fuels account for approximately 4% [109] (Hybrid Electric Vehicles 0.7%; BEV 0.3%; NG + LPG 2.8%).

Passenger cars and vans in EU have an average lifetime of 10.8 years so vehicles with internal combustion engines (ICEV) purchased in 2020 will represent the average fleet in 2030. Despite high policy support and incentives for electric vehicles (EV), their market uptake is not enough to meet the 2030 decarbonisation targets and large volumes of renewable drop-in fuels will be required to reduce the environmental impact of the European light-duty vehicle fleet [110,111].

1.2. Current policy

The European Green Deal [112], sets a dynamic tone for climate neutrality by 2050 and transition pathways that use resources efficiently, restore biodiversity and cut pollution. Decarbonisation of heavily polluting sectors like transport however is still at early stages (AFF, 2020 [113]). GHG emissions in the European transport sector have declined by only 3.8% since 2008, compared to at least 18% reduction in other major sectors [114].

Policies for biofuels and advance biofuels have been in place since 2003 with the biofuels directive [115] and 2009, respectively. The Renewable Energy Directive (RED) mandated that, by 2020, 10% of energy used in the transport sector should come from renewable energy sources (RES) [116]. In 2015, it was amended by the EU Indirect Land Use Change (ILUC) directive [117], which introduced a 7% cap on the contribution that conventional food and feed-based biofuels could make to the RES-transport target and a further non-binding 0.5% target for advanced biofuels in 2020 [2] (Fig. 3).

The revised Renewable Energy Directive (REDII) [118] (2018) introduced a 14% RES-transportation energy target and a 3.5% (already double counted) advanced biofuels sub-target by 2030 [2]. Biofuels from used cooking oil and animal fats can double-count towards the 14% RES-transport target, but are capped at 1.7% on a physical basis, 3.4% when including double-counting. REDII [119,120] also presents a more targeted approach to ensure safeguarding of sustainability and reduced Indirect Land Use Change (ILUC) impacts. After December 2023, biofuels, bioliquids and biomass fuels produced from food or feed crops -for which a significant expansion of the production area into land with high carbon stock is observed [121] - will be reduced to zero by 2030. Finally, the Delegated Regulation (EU) 2019/807 [122] encourages production of biomass raw materials that: '*are produced under circumstances that avoid ILUC effects, by virtue of having been cultivated on unused, abandoned or severely degraded land or emanating from crops which benefited from improved agricultural practices* [123].

Additional important targets to reduce EU transport emissions by 2030 [124] include:

- **Speeding up the deployment of low-emission alternative energy for transport,** such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels.
- **Moving towards zero-emission vehicles.** Europe needs to accelerate the transition towards low- and zero-emission vehicles, and
- EU Member States must require **fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy** [125].

To achieve these targets within a decade (2020–2030) a step change with immediate, targeted policy interventions is required to increase low carbon fuel availability [126].

1.2.1. Policy framework for aviation

From 2012, flights from, to and within the European Economic Area (EEA) – the EU Member States, plus Iceland, Liechtenstein, Norway and United Kingdom– are included in the EU emissions trading system (EU ETS). Airlines receive tradeable allowances covering a certain level of CO_2 emissions from their flights per year. The system has so far reduced the carbon footprint of aviation by more than 17 million tonnes annually, with compliance covering over 99.5% of emissions.

In 2016, the International Civil Aviation Organisation (ICAO) reached an agreement on a global market-based scheme to reduce aviation-derived carbon emissions through off-setting [127–129] (IRENA, 2017). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to stabilize CO_2 emissions at 2020 levels. Currently, Netherlands, Norway, the U.S. and Sweden have established policies to encourage bio-jet fuel production. The Swedish Government announced in September 2020 its intention to introduce a greenhouse gas reduction mandate for aviation fuel. The reduction level is expected to be 0.8% in 2021 and gradually increase to 27% by 2030, with most of the savings expected to come from the use of SAF.

Policy mechanisms for Sustainable Aviation Fuel use include market measures like off-take, commercial agreements between airports or airlines to purchase SAF at a given price; usually very close to the prevailing price of jet kerosene before the COVID-19 crisis [130], and legal interventions such as i) low-carbon fuel standards (LCFSs), ii) blending mandates and iii) capital support to commercialise SAF production facilities.

In July 2020, the European Commission [131] published the Roadmap for the legislative initiative aimed at amending the EU ETS regarding aviation. This will serve to implement the Carbon Offsetting

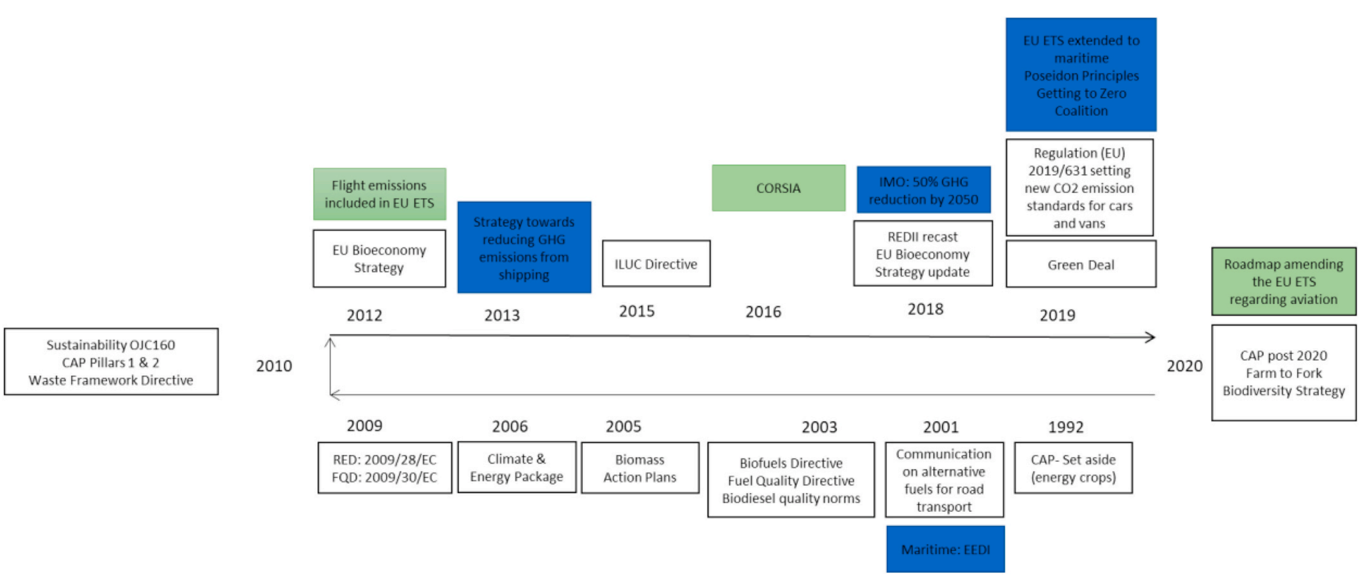

Fig. 3. Biofuels & Advanced biofuels policy evolution (1992–2020).

and Reduction Scheme for International Aviation (CORSIA [132]) in a way that is consistent with the EU's 2030 climate objectives. During the period 2021–2035, and based on expected participation, the scheme is estimated to offset around 80% of the emissions above 2020 levels. This proposal will be part of the broader European Green Deal.

1.2.2. Policy framework for marine

Port authorities' regulations together with sustainability commitments of marine operators and sulphur cap requiring significant SOx reductions are critical issues for the marine sector [133] and the most compelling reasons for utilising advanced biofuels. Policies in the sector are regulated by the International Maritime Organisation (IMO). A key regulation for controlling SO_x, NO_x and GHG emissions from shipping since 1973 is the Maritime Agreement Regarding Oil Pollution (MARPOL). Initially the focus was on SO_x, limiting sulphur content in bunker fuel to 4.5%, then 3.5% and gradually dropping over time to 0.5%, in 2020. There are different ways to reduce SO_x emissions including: i) engine retrofitting and use of liquefied natural gas (LNG), ii) low sulphur fuels, iii) methanol used with dedicated engines iv) installation of scrubbers to remove SO_x and v) biofuels which usually have very low sulphur levels.

In spring 2018, IMO adopted a strategy to reduce total GHG emissions from shipping by 50% in 2050, and to reduce the average carbon intensity by 40% in 2030 and 70% in 2050, compared to 2008. These regulations mean that an estimated 70% of the fuels currently used by the sector needs to be modified or changed.

In December 2019, the EC committed to extend EU ETS to cover marine within the European Green Deal [134]. In parallel, the private sector has proactively introduced two initiatives:

- Poseidon Principles [135]: signed in 2019 by a group of banks jointly representing around USD 150 billion in shipping financing and commits the signatories to integrate climate risk considerations into financial decision-making in the maritime industry.
- Getting to Zero Coalition [136]: it is dedicated to commercialising deep-sea zero-emission vessels (ZEVs) by 2030 along with the associated infrastructure.

The European Sustainable Shipping Forum (ESSF) [137] also aims to support the European Green Deal to achieve a reduction in the greenhouse gas emissions by 2050. The ESSF has been at the origin of the concept of the Green Shipping Guarantee (GSG) Programme [138] managed by the European investment Bank which aims to accelerate investments in greener technologies by European shipping companies.

1.2.3. Policy framework for road

Fuels used for road transport in EU are regulated by the Fuel Quality Directive (2009/30/EC) [139] which also regulates the sustainability of biofuels [140]. In addition, council Directive (EU) 2015/652 [141] defines the method to calculate, and the details to report, the greenhouse gas intensity of regulated fuels. Member States apply these rules as of April 21, 2017.

1.2.3.1. Heavy duty vehicles [142] (trucks & buses). The first-ever EU-wide CO_2 emission standards for heavy-duty vehicles, adopted in 2019, set targets for reducing the average emissions from new lorries for 2025 and 2030. The Regulation (EU) 2019/1242 setting CO_2 emission standards for heavy-duty vehicles entered into force on August 14, 2019. The Regulation also includes a mechanism to incentivise the uptake of zero- and low-emission vehicles, in a technology-neutral way.

1.2.3.2. Light duty vehicles (cars and vans). Regulation (EC) 443/2009, set mandatory emission reduction targets for new cars from 2015 onward. Respectively, regulation (EU) 510/2011 set mandatory emission reduction targets for new vans from 2017. On April 17, 2019, the European Parliament and the Council adopted Regulation (EU) 2019/631 [143] which introduced CO_2 emission performance.

The Fuel Quality Directive (2009/30/EC) has dual implications for biofuel blending. On the one hand, the 6% reduction target for GHG emissions from fuels provides an incentive for using more low carbon fuels, such as biofuels, in the transport sector. On the other hand, the fuel specifications set out in the Directive define maximum levels for the biofuel content in petrol and diesel. The maximum content of ethanol in petrol is 10% (E10) while the maximum content of biodiesel (fatty acid methyl ester (FAME)) is 7% (B7).

Annex III provides information for advanced biofuel standards.

2. Challenges and policy related gaps

This section analyses policy relevant challenges that prohibit market uptake of advanced biofuels, discusses associated policies and performance [144] towards three competitive priorities: flexibility [145], reliability, and cost [146]. Flexibility is required in advanced biofuel value chains for handling various feedstocks and/or adjusting conversion process parameters to produce a variety of products, in future multi-product biorefineries. Reliability focuses on feedstock and process consistency and fuel quality throughout the operational life of a value chain [147]. Cost is the most difficult challenge that advanced biofuels [148–150] face in their competitiveness with fossil fuels and renewable electricity-based energy carriers [151] which are (or are expected to be) available in the market during the 2020–2030 timeframe.

Table 2 provides an overview of policy relevant challenges across the value chain stages and grades their risk to hinder performance in terms of flexibility, reliability, and cost.

2.1. Biomass supply

Like all biomass value chains, advanced biofuels face challenges to secure year-round, sustainable feedstock supply [153–155]with quality that meets the conversion specifications and keep costs throughout the year reasonable [156]. Land use is the first planning step if the biomass feedstock (all or a part of it) derives from dedicated crops [157,158]. Decision making must consider challenges [159] for improving soil quality, maintaining, and increasing soil carbon [160], rehabilitating degraded land [161–163] and avoiding land use change [164,165] that may displace other existing land-based activities.

Soil quality & soil carbon: Several policies have aligned objectives for soil quality and soil carbon, including the Soil Thematic Strategy (COM 2012) [166], the Common Agricultural Policy [167], the Cohesion Fund [168], the Farm to Fork Strategy (2020) [169] and the Industrial Emissions Directive (IED) 2010/75/EU [170]. However more targeted actions are required, such as carbon farming [171], to integrate these policies in biomass supply chains for advanced biofuels [172].

The challenges of soil quality and soil carbon apply to both harvesting/collection of agriculture and forest residues and the cultivation of dedicated crops. They affect performance for: i) reliability for raw material sourcing without causing negative impacts to soil and ii) flexibility to use a mix of biomass feedstock and secure year-round feedstock supply.

Improvements of degraded land: The Delegated Regulation (EU) 2019/807 [173] suggests degraded land as an option to broaden biomass supply, however, there are still limited initiatives to rehabilitate such land types for biomass production and advanced biofuels and these are mostly research and demonstration activities [174–179]. There are also still gaps concerning i) the uniform definition [180] and classification [181] of degraded land types [182] as well as ii) planning [183, 184], financing, capacity building and awareness [185] interventions at local level.

The challenge of improving degraded land affects performance mainly in terms of cost (high capital costs for rehabilitation) and flexibility to produce biomass from a broader land base which has low

Table 2
Policy relevant challenges for flexibility, reliability and cost of advanced biofuels and their risk (low-green, moderate-yellow, high-red) towards market uptake for 2030.

	Flexibility	Reliability	Cost
Biomass supply			
Agriculture & forest residues	Soil carbon loss	Biodiversity loss	Disperse, low density, ununiform material [152]
	Competing markets	Nitrogen leaching due to overharvest	Competing markets
Lignocellulosic crops	Spread of invasive species	Direct & indirect land use change	Low yield (high production cost per unit) in degraded land
	Degraded land improvement		
Organic wastes & lipids	Limited bulk availability	Variable quality	Collection and sorting
Conversion pathways			
Fermentation	Co-location with existing infrastructure	Establishing adequate operational capacity by 2030	Establishing adequate operational capacity by 2030
			Process efficiency, especially for butanol production
			By-products utilisation (e.g., lignin fraction)
Gasification		Gas conditioning and clean up	
		Co-location	
		Capacity redundancy required for First-of-A-Kind plants	Uncertain production costs
Pyrolysis	Pyrolysis oil upgrading and/or coprocessing	Catalysts with improved selectivity and stability for pyrolysis oil upgrading are not yet commercial	Pyrolysis oil upgrading and/or coprocessing
Upgrading and hydrotreatment	Co-location with existing infrastructure	Establishing adequate operational capacity by 2030	Establishing adequate operational capacity by 2030
			Process efficiency, especially for butanol production
			By-products utilisation (e.g., lignin fraction)
End Use			
Aviation	SAF must be drop-in	Competition with biodiesel production	International competition with non-EU operators
	Blending restricted to 50% (safety and lubricity restrictions)	Fuel quality critical to ensure safety in the air – variations in fuel quality dependent on conversion and feedstock	Fossil kerosene cheaper than all certified SAF pathways
	Lower aromatics content in some of SAFs might lead to jet engine compatibility issues (older engines)		Upgrading of bio-oil/biocrude leads to increased final price
Marine	Competition with biodiesel production	International competition with non-EU operators	
	Existing fuel infrastructure, no engine modifications	Access to renewable raw materials	International competition with non-EU operators
	Ensuring compatibility of new fuels or their blends & blending behaviour	Fuel quality of less refined fuel should enable year-round operation	Low prices of HFO, MGO
	Dedicated infrastructure needed onboard as well as in harbour (in case of methanol or LBG)	High fuel volumes needed for single vessel – risk of advanced biofuel seasonal shortage	Loss of cargo space due to bigger fuel tanks
	Multi fuel blends increase complexity		
Road	Use of existing fuel infrastructure, no engine modifications	Access to renewable raw materials	International competition with non-EU operators
			Need of compensation for lower income end-users
	Infrastructure and engine modifications needed for higher alcohols or FAME blends.	Shortage of sustainable feedstock for HVO or ethanol production	Price gap between advanced biofuels and fossils
	Completely new infrastructure for DME or hydrogen		End-user choosing economically justified option

impacts to direct and indirect land use change [186].

Direct & indirect land use change [187]: although the Commission Delegated Regulation (EU) 2019/807 [188] encourages the production of biomass raw materials: '*under circumstances that avoid ILUC effects, by virtue of having been cultivated on unused, abandoned or severely degraded land ….* ', there are still limitations in estimating and monitoring the effects of direct and indirect land use change [189,190] and introducing robust sustainability governance within EU and at global level.

The challenge affects performance in terms of reliability of practices applied for the provision or production of biomass feedstocks.

If the feedstock used for advanced biofuels derives from the organic fraction of wastes and residual streams from agriculture and forestry, then a key challenge is the efficient mobilisation patterns for year-round, sustainable provision of raw materials [191,192]. Other challenges also include: i) biodiversity loss, soil carbon and soil erosion risk [193] from over-harvesting agricultural and forest feedstocks [194] and ii) collection and sorting of the organic fraction from variable quality wastes.

There is also slow progress in knowledge transfer from existing good practices and flagship initiatives at regional level which can point the way forward for sustainable, long term biomass supply practices to produce advanced biofuels.

These challenges affect performance in terms of flexibility to produce biomass feedstocks from a broader land base.

Biomass logistics (contracts with farmers, biomass handling up to the conversion plant gate, etc.), high raw material production costs and biomass price fluctuations are also critical for all advanced biofuel conversion technologies as they can constrain market uptake potential. In this case, the lack of regulatory framework and financing mechanisms for the biomass price fluctuations are also important and, can be considered as dominant gaps in policy that should be addressed.

The challenge of biomass logistics affects mainly costs for raw material which in turn may restrict the opportunities for scaling up First of A Kind (FoAK) projects.

2.2. Conversion pathways

Projections for future market uptake of advanced biofuels are uncertain and decision making for new plants, especially after the impacts of Covid 19 which led to *the first contraction in biofuels output in the last two decades* [195], is still considered high cost and risky [196]. The key challenges until 2030, as identified in this work are economic and technical.

Economic challenges relate to investment and operation costs and access to finance. There is also clearly a learning process in the advanced biofuel industry (i.e., based on the "learning by doing principle" which implies severe increase of production scales) and thus a need for financial instruments for the scale-up, operation and process design considerations of a new technology system.

These impact primarily the cost of the conversion and the flexibility to scale up new conversion pathways due to high costs.

Technical challenges still exist, mostly for scaling-up most advanced biofuel technologies, which mean engineering and equipment modifications. They relate to process design, construction of unit operations, operation and scale up [197]. They include process efficiency, catalyst development, product upgrading and cleaning, by-products utilisation, recycling, etc. For instance, although the thermochemical processes are close to technological readiness for large scale industrial implementation with stable process and higher feedstock conversion efficiencies [198,199] there is still great potential for technological improvement [200] that lies in assembling them into a new system in a successful way and avoid process failures. FT liquids is an exemption since it is characterised by low biomass to fuel efficiency due to the co/by-products (such as alcohols, acids, ketones, water and CO_2 are also produced [201]. For the pyrolysis pathway, the most important constraints are the upgrading steps of bio-oil which are in early development stage (i.e., lab to pilot scale), even though pyrolysis is a well-established technology. As for the biochemical pathways, barriers of lignocellulosic ethanol future technological solutions relate to increasing the overall conversion efficiencies (i.e., not only regarding ethanol yields but also with respect to the currently not optimally utilized biomass fractions of lignin and hemicelluloses), and further intensifying the pre-treatment processes and fermentation through advanced continuous operations, higher product concentrations, etc. (OECD/IEA, 2011 [202]).

These challenges impact mostly the reliability and the flexibility of the conversion pathway.

Co-processing and co-location of advanced biofuel plants in existing infrastructures (e.g. power plants, refineries, etc.) by taking advantage of existing energy infrastructures in and around plants, etc. poses lower economic and technical risks, for ramping up these fuels in short-term [203]. It can also create synergies with other parts of the energy and industrial sectors and capitalise on the existing knowledge for the supply and market structures [204].

To facilitate the market uptake of advanced biofuels, there is an urgent need for immediate and targeted policy actions with focus firstly on reducing their production costs and secondly, on reducing the financial risk of investing in capital-intensive advanced biofuel chains (for instance via long-term regulation stability and access to privileged financing).

2.3. End use

From the end-use perspective, challenges for future market uptake relate to economic (appropriate pricing) and technical issues such as i) fuel quality, ii) engine compatibility and iii) improvements required in infrastructure for processing, storing and selling such fuels.

2.3.1. Economic challenges

2.3.1.1. Advanced biofuel pricing. Despite current regulation to integrate advanced biofuels in transport, there is still a significant price gap with fossil fuels. Currently, in EU the average total taxation share in the end-consumer price for gasoline is 65% and for diesel oil 60% [205]. This includes value added tax, and indirect taxes such as excise duties, carbon tax and so on. Therefore, the share of the fuel price itself is about 40%. To facilitate market uptake a potential modified taxation regime can be considered to ensure at least the break-even point for the final fuel price. This could be achieved for example by increasing the carbon tax for fossil fuels and by reducing the VAT and/or excise tax for biofuels.

2.3.2. Technical challenges

2.3.2.1. Fuel quality. Advanced biofuels from emerging conversion pathways might encounter quality issues related to blending performance and are linked to priorities such as flexibility and reliability.

Fuel quality depends on physical properties and chemical composition and affects handling, storage, and final use in engines. High calorific content and, good oxidation stability are examples of desired properties while favorable end-use performance is characterised by low tailpipe emissions (such as NO_x or PM) and reduced fuel consumption. Drop-in fuels are the preferred option since no modifications in current infrastructure and engine technology are considered necessary. Usually, those high-quality fuels such as paraffinic diesel in road transport or SAFs in aviation are more expensive than fossil diesel or kerosene, respectively.

Fuel quality challenges also exist in marine, where mixing of various grade fuels might result in wax formation or high corrosiveness, which further lead to filter clogging, engine damage and other operational issues. The pyrolysis oil or various biocrudes could be mentioned as examples [206]. Therefore, proper monitoring and testing are needed before commercialisation. Low quality biocrudes from biomass liquefaction processes could be a subject to appropriate refining or co-processing as in case of crude oil [207] (Fig. 4).

The challenge of compatibility with fuel quality affects primarily performance in cost.

2.3.2.2. Engine compatibility. While introducing new fuels it is important to ensure that the reliability of the engine is not affected, all components are compatible and proper emission aftertreatment systems are in place to minimise local emissions. Additionally, the lifetime of alternatively powered vehicles and engines must be the same as for regular powertrains running on fossil fuel. Drop-in solutions like HVO/BTL in LDV and HDV transport or a few SAF options in aviation should fulfil the above-mentioned requirements.

At this point it is important to clarify that HVO has so far been the sustainable biofuel of preference due to its drop-in characteristics. However, the availability of resources to be used as feedstock in HVO production facilities are indeed limited when excluding palm oil. Considering the relatively lower cost for HVO and its exceptional characteristics the need here is for innovation in cultivation and crop management practices of non-edible oils crops [208] without adverse effects on food production such as double cropping/cover crops or rotation crops. Used cooking oils have limited potential but better efforts in their collection will increase their availability. Overall, new value chains are expected to come into commercial production which will foster improvements. Such technologies are cellulosic ethanol, co-processing pyrolysis oils in refineries and synthetic fuels from biomass gasification (ENERKEM- www.enerkem.com and VELOCYS- www.velocys.com).

Optimized engines could bring further benefits in terms of lower fuel consumption, higher thermal efficiency and minimized emissions [209–212]. However, engine optimisation needs extensive R&D and further actions from engine manufacturers, which are associated with increase of end-use costs.

2.3.2.3. Infrastructure. Many advanced biofuels require high upfront investments in completely new infrastructure or retrofitting of existing ones. Switch to new infrastructure is inevitable in case of gaseous fuels

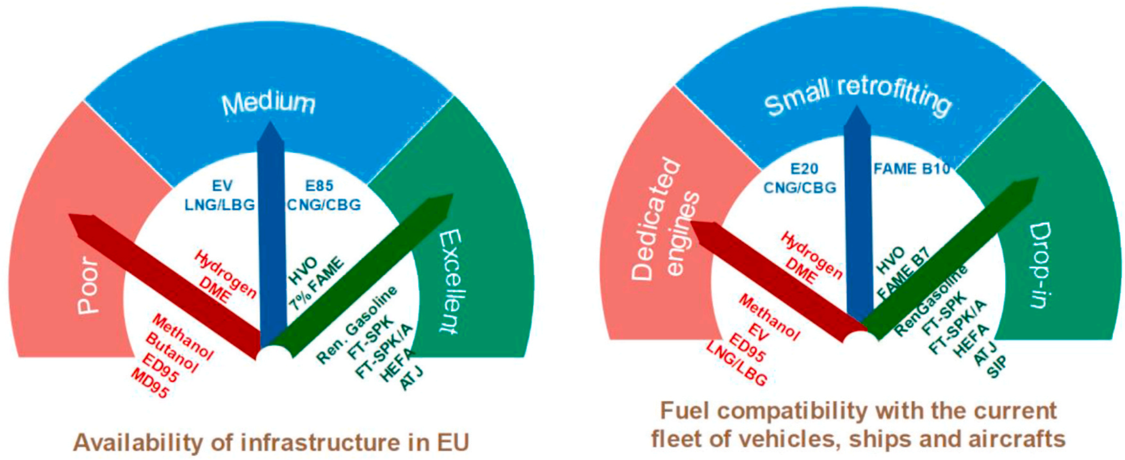

Fig. 4. ″Indicators of readiness level for considered alternative fuels: availability of infrastructure (left) and compatibility with current fleet (right).

such as LBG, DME, hydrogen or ammonia. In the marine sector, due to fast changing regulations and uncertain future, fleet operators tend to select the multi-fuel solutions that allow using various fuels including fossils and alternatives such as advanced biofuels. The shortage of infrastructure is an important barrier hindering uptake of new fuels.

It is worthwhile to mention that some of the technical challenges, especially infrastructure, also have strong economic components. There is also a potential difficulty of financing compatible infrastructure as a fuel is nascent or not yet widespread in the marketplace, which is the case of hydrogen. There are also other important concerns such as time needed for new investment, availability of retail stations, public/consumer acceptance, changes in the supply mechanism, effect on the landscape, or safety and reliability of the supply. Therefore, compatible biofuels (i.e. HVO) and minor retrofits (i.e. mid-level ethanol blends) are preferred options resulting in lower capital expenditure and re-use of the existing system.

Annex IV provides more details for challenges for the market uptake of individual advanced biofuels.

3. Future policy

Policy, integrated across the value chain, can facilitate future market uptake of good quality and sustainable advanced biofuels that are compatible with current vehicle engines and infrastructure for producing, storing, transporting, and retail stations. This section identifies potential interventions, which can be integrated across relevant existing policies, are linked to the Sustainable Development Goals and have strong potential to overcome the prevailing challenges.

Annex II provides detailed information of interventions per value chain stage and an initial suggestion for the sequencing (short- 5 years, medium- 10 years term) of policy interventions on the various challenges.

3.1. Biomass supply

To overcome challenges for ***soil quality*** [213] and ***soil carbon*** [214,215], contribute to the UN Sustainable Development Goals [216,217] and at the same time steer sustainable practices for biomass supply [218], targeted actions, such as carbon farming [219], use of biochar [220–222], etc., are required at regional level in close synergy with farmers/foresters and the industry. These actions can sequester carbon and/or reduce GHG emissions and include conservation tillage [223], cover cropping, rotational cropping that increases soil carbon [224,225] and agroforestry [226–229] which stores carbon in vegetation [230] and can offset effects of crop residue removals [231,232]. They are endorsed by the United Nations Framework Convention on Climate Change [233] (UNFCCC) and the United Nations Convention on Combating Desertification [234] (UNCCD) and other ongoing initiatives, like the '4 per 1000' [235] which demonstrate the crucial role that agricultural soils can play in food security and climate change [236,237].

Flagship and demonstration initiatives, including new business models [238–240] for biomass supply, with either industrial or regional cooperative lead, are needed to understand, implement, and monitor opportunities in different regional climatic and ecological zones within Europe. Such actions will inform on how domestic feedstock options can be best mobilised, which actors should be involved and under which contractual and business structures. Learning and communication will be improved, and the process will help establish reliable business relationships between the upstream and downstream part of the value chain.

Degraded land is perceived as a potential outlet to broadening [241] land availability [242,243] with land which has no conflict with food or feed and minimise competition between advanced biofuels and other land uses [244,245]. The concept does however have certain limitations as regards the cost-efficient rehabilitation [246,247] and the crop yield potential [248–250]. A number of initiatives have taken place or are ongoing which demonstrate the types of land, potential crops that can be suitable for different categories of degradation [251] and provide both top down modelling platforms [252,253] as well as regional case study examples [254–256]. Targeted policy interventions, including financing, which can improve the quality of degraded land [257,258], such as phytoremediation [259,260], etc. are required to improve infrastructure and compensate the high material costs that are needed to bring such land back to productivity. Since crop yields from degraded land might be low [261] in the beginning tailored financial support, in the form of feedstock premium is required. Such policy can increase opportunities for landowners, farmers, and foresters (to produce biomass feedstocks) but also for industry (to broaden their feedstock supply options, etc.).

Improved clarity and coherent sustainability governance [262] are essential when it comes to ***direct and indirect land use changes***. By introducing sustainable land use policies, the direct and indirect land use impacts (Van Stappen et al., 2011) [263] can be better addressed and monitored.

Spatially detailed guidance should be produced to identify areas and crop management practices suitable to produce advanced biofuels. This will increase confidence both in industry (for planning their future investments) and in public (reducing scepticism over sustainable biomass practices and improve social acceptance).

Increase mobilisation of organic wastes and residual biomass [264] to foster large scale feedstock production, support the development of biomass trade centres and ease supply chain flows. These will benefit the industry as they will provide uniform, good quality material with contractual arrangements but also facilitate biomass supply flows at the given geographical setting. Ensuring the quality and developing standards for the mobilisation of residual and biogenic waste biomass streams will mobilise otherwise unused biomass and reduce the pressure on land and diversity the source of biomass production.

Financial support interventions from the European Structural and Investment Funds (ESIF), including the European Regional Development Fund (ERDF), the Just Transition Mechanism, etc. could account for capital costs related to the development of infrastructure for the logistics related to waste and residues collection, as well as large scale energy crop production, supply and logistics.

The roll-out of innovations, especially in dedicated biomass cropping, such as carbon farming, phytoremediation [265–267], etc. can be further supported via the European Innovation Platform for Agriculture (EIP-Agri), knowledge sharing through the European Network for Rural Development (ENRD), and provision of funding from ESIFs, namely the ERDF, Cohesion Fund, and funding for farm diversification under the European Agricultural Fund for Rural Development (EAFRD).

The following policy interventions could improve year-round, low impact feedstock production for advanced biofuels by 2030 (see Fig. 5).

- Financial support for flagship & demonstration initiatives [268–270] with cooperative and/or industrial lead focusing on broadening domestic biomass supply [271]. Selected SDGs aligned with this intervention include:
  - o ***SDG6- Clean Water & Sanitation:*** Demonstrate carbon farming practices to reduce leaching of nutrients and pollutants, and thus improve management of organic compounds in soil and groundwater [272]
  - o ***SDG13: Climate Action:*** The use of biomass for advanced biofuels will facilitate the transition to 'low' and 'zero' carbon economies.
  - o ***SDG15: Life on Land:*** Demonstrate innovative carbon farming strategies will support the restoration of degraded land [273–276].
- Regional infrastructure for biomass supply hubs related to waste and residue collection, as well as large scale dedicated crop production. Selected SDGs aligned with this intervention include:
  - o ***SDG 8- Decent work and economic growth:*** Increasing the number of jobs in biomass production and logistics will result to additional income for local farmers and local population and will improve their knowledge base on sustainable agriculture [277].
  - o ***SDG9- Industry, Innovation, and Infrastructure:*** Development of innovative entrepreneurship by producing biomass for advanced biofuels.
- Uniform definition and classification of degraded land in relevant regulations. The abovementioned links to SDGs are in principle relevant for this suggested intervention as well.

3.2. Conversion pathways

Providing financial support for new, highly efficient conversion pathways will improve access to capital and reduce risk for industries and SMEs. The additional cost from public policy funding however is transferred to European citizens and can affect their quality of life. Future policy interventions therefore should be based on analysis and benchmarking of the technology status, resource availability and the time needed to bring innovative concepts from the lab to the market. A step-by-step approach in which reliable conversion pathways with not very expensive sustainable fuels are prioritised before innovative -but not yet commercially mature-ones with very expensive sustainable fuels should be considered. This approach will stimulate market uptake while

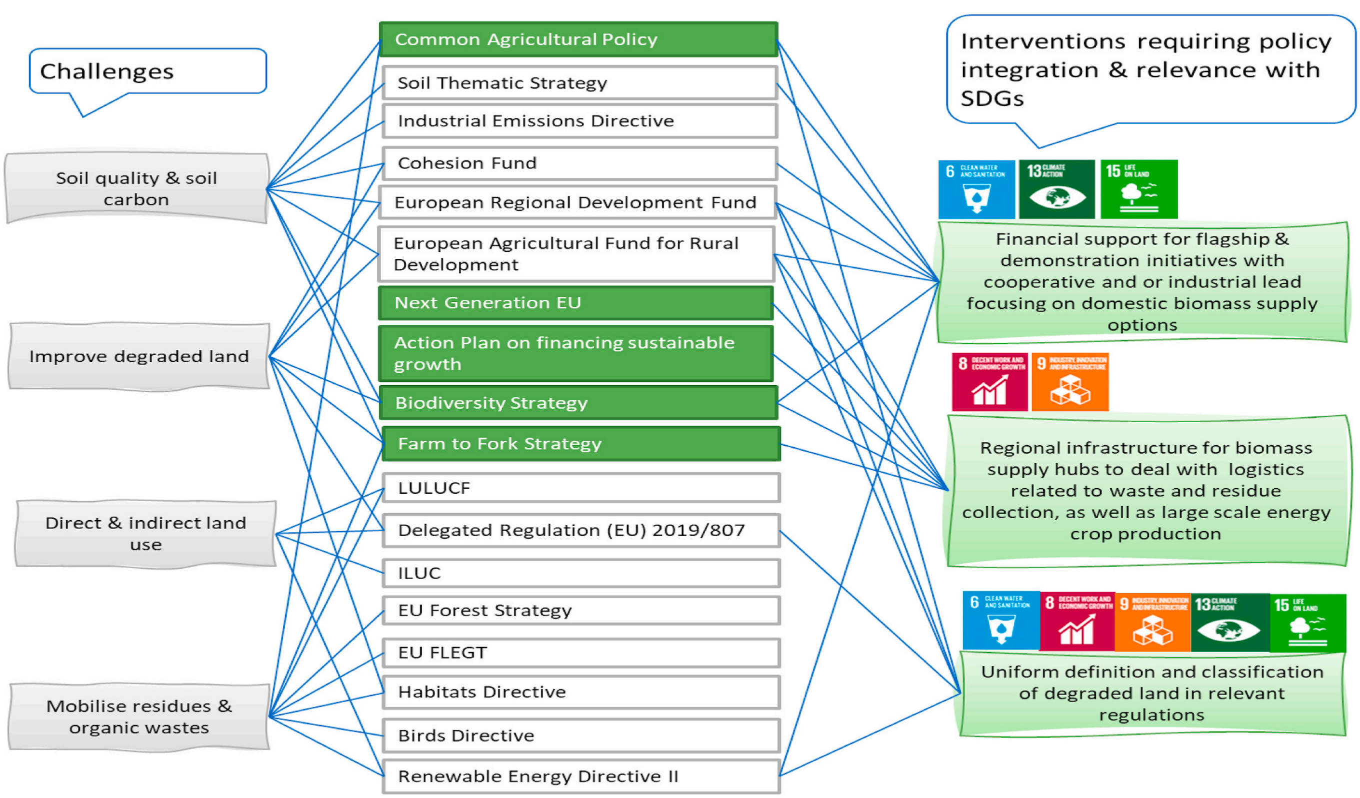

Fig. 5. Challenges for biomass supply for advance biofuels, current policy, future interventions requiring policy integration (in green boxes the Green Deal relevant policies) and relevance to SDGs.

allowing time for innovative technologies to develop out of the valley of death.

Fig. 5 provides an outline of challenges for biomass supply, current policy, future interventions requiring policy integration and relevance to SDGs.

Support for new technologies with improved efficiency will also address the competition though resource and energy efficiency and steer deployment to aviation, marine and heavy-duty transport sectors.

To improve investment attractiveness, future policy interventions can consider reducing risk premium in financing First-of-A-Kind (FoAK) plant investments (e.g. EU-ETS [278], Just Transition Fund [279], Invest EU [280], Cohesion Policy funds [281], etc.) and encourage participation of large private and public companies (with diversified business portfolio in low carbon, green technologies) to joint partnerships.

First-of-A-Kind (FoAK) plants will improve scale up by 2030. There are however trade-offs between the urgency of need for climate action (beyond particular targets) and potential for stranded assets or unfavorable technology lock-in. These can be relieved by the presence of more than one technology provider in the market creating healthy competition that moves innovation forward. This is the case with cellulosic ethanol where at present there are more than one technology developers (Clariant, Versalis, Praj Industries, etc.) active in FoAKs and optimising them. Fast pyrolysis is another pathway where significant progress has been reported recently (BTG, ENSYN, Fortum et al.).

The following policy interventions should be considered to facilitate the required innovations within the conversion pathways employed for advanced biofuels and steer their market uptake (see Fig. 6):

- Financial support for scale up innovative technologies – target co-location with existing biorefineries. Selected SDGs aligned with this intervention include:
  - o ***SDG7- Affordable & Clean Energy:*** Production of advanced biofuels through innovative conversion technologies will increase the affordability of low carbon fuels in aviation, marine and road transport.
  - o ***SDG 8- Decent work and economic growth:*** Production of advanced biofuels will improve progressively, till 2030, resource efficiency in consumption & production & decouple economic growth from environmental degradation.
  - o ***SDG9- Industry, Innovation, and Infrastructure:*** Co-location of advanced biofuels facilities with existing industries/refineries will facilitate to upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.
- Promote targeted integration of green funds to improve process efficiency, product quality and scale up. Selected SDGs aligned with this intervention include:
  - o ***SDG7- Affordable & Clean Energy:*** If the innovative components of Advanced biofuels conversion technologies are improved the renewable energy share in the total final energy consumption of the transport sector will be increased.
  - o ***SDG9- Industry, Innovation, and Infrastructure:*** Improved efficiencies and scale up will increase sustainable industrialisation of innovative Advanced biofuel conversion technologies.
  - o ***SDG13: Climate Action:*** Fund integration will strengthen sector integration in climate change measures.

Fig. 5 provides an outline of challenges for conversion to advanced biofuels, current policy, future interventions requiring policy integration and relevance to SDGs.

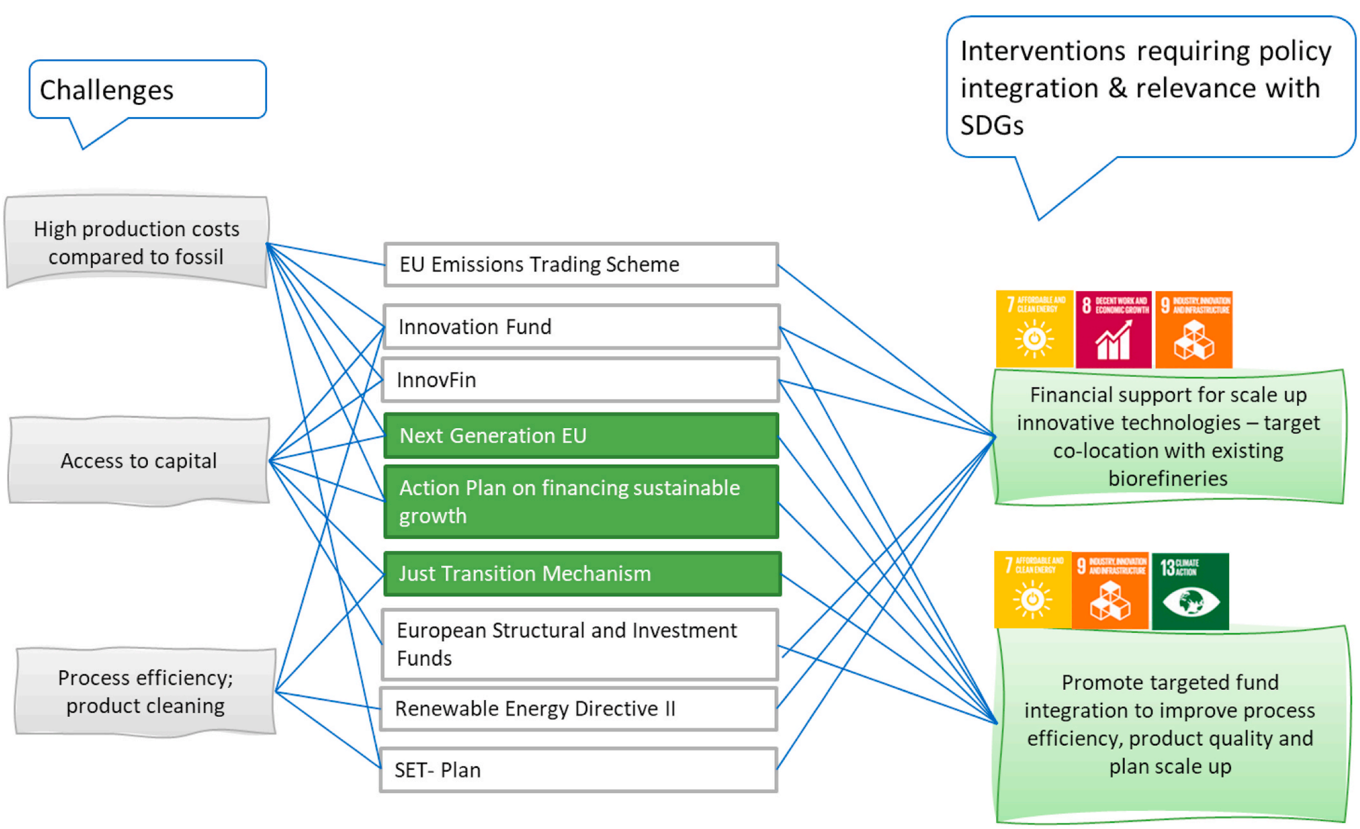

Fig. 6. Challenges for conversion to Advanced biofuels, current policy, future interventions requiring policy integration (in green boxes the Green Deal relevant policies) and relevance to SDGs.

3.3. End use

The significant price gap between fossil fuels and advanced biofuels makes their market roll-out very challenging but can be regulated with targeted policy interventions which include:

- Carbon taxation for fossil fuels. Selected SDGs aligned with this intervention include:
  - o ***SDG7- Affordable & Clean Energy:*** Efficient market roll out of Advanced biofuels will increase substantially the share of renewable energy and the proportion of population with primary reliance on clean fuels and technology.
  - o ***SDG9- Industry, Innovation, and Infrastructure:*** Advanced biofuels market uptake will lead to greater adoption of clean and environmentally sound technologies and industrial processes.
  - o ***SDG13: Climate Action:*** Taxation in favor of Advanced biofuels will foster the integration of climate change measures into national policies, strategies, and planning.
- Financial support for cost reduction of Advanced biofuels– target co-location with existing biorefineries. Selected SDGs aligned with this intervention include:
  - o ***SDG7- Affordable & Clean Energy:*** Financial support for cost reduction of Advanced biofuels will increase substantially the share of renewable energy in the energy mix of transport for road, aviation and ***marine.***
  - o ***SDG9- Industry, Innovation, and Infrastructure:*** Co-location with existing biorefineries will upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies.
  - o ***SDG13: Climate Action:*** Financial support in favor of Advanced biofuels will foster the integration of climate change measures into national policies, strategies, and planning.
- Promote targeted fund integration to improve Advanced biofuels infrastructure. The abovementioned links to SDGs are in principle relevant for this suggested intervention as well.

Fig. 7 provides an outline of challenges for end use of Advanced biofuels, current policy, future interventions requiring policy integration and relevance to SDG.

4. Conclusions

Current policy mechanisms have established targets and monitoring frameworks for low carbon fuels and improved car engine performance but have not yet been adequate to facilitate the market uptake of advanced biofuels. Their efficient market roll-out must be immediate if the 2030 targets are to be met. Analysis within this paper reiterates that their future deployment, in market shares that can lead to decarbonisation, still depends largely on the integration of tailored policy interventions that can overcome challenges and improve upstream and downstream performance.

Tailored policy interventions integrated along the advanced biofuels value chain (feedstock production, conversion, end use) are essential for future policy formation at all governance levels. These must on one hand target challenges that have been identified as hurdles to the sustainable development of the value chain stages and individual market sectors and on the other facilitate sector integration and alignment with the principles of Green Deal and the Sustainable Development Goals. This will increase investors' confidence and allow the industry to improve their technical and financial performance.

Sustainable biomass feedstocks are present in Europe, but their efficient and timely mobilisation remains a challenge which requires synergies with agriculture, forestry, and rural land-use planning. Flagship and demonstration initiatives, including new business models, for biomass supply with either industrial or regional cooperative lead are

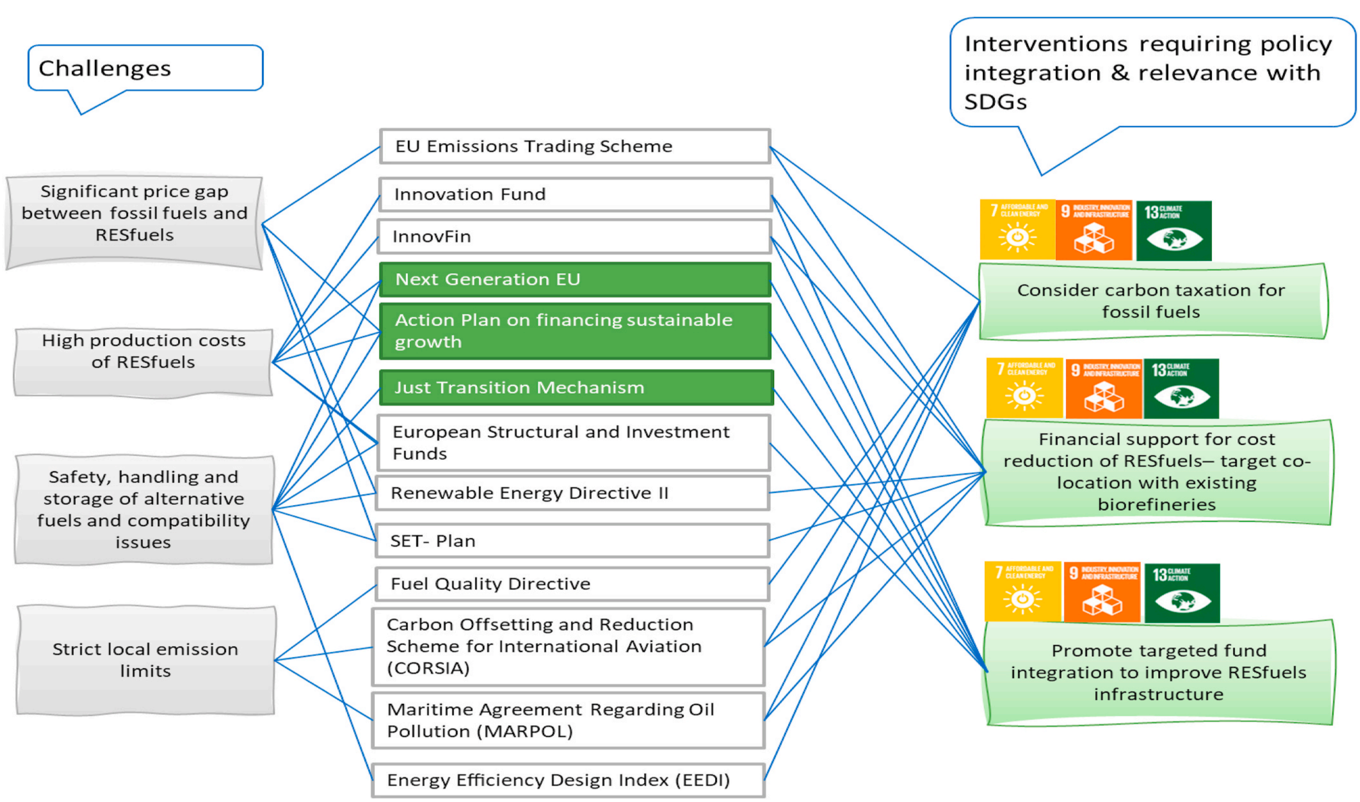

Fig. 7. Challenges for end use of Advanced biofuels, current policy, future interventions requiring policy integration (in green boxes the Green Deal relevant policies) and relevance to SDGs.

needed across different regional climatic and ecological zones within Europe. Such actions will provide clarity and evidence on how domestic feedstock options can be best mobilised, which actors should be involved and under which contractual and business structures. Learning and communication will be improved, and trustworthy business relationships between the upstream and downstream part of the value chain will be established.

Innovations in ***conversion*** pathways development involve high capital costs and thus high financial risk; measures to facilitate this must be introduced. Public and private funding bodies and financial institutions must increase budget shares for advanced biofuels in their investment portfolios. Tailored financing mechanisms (such as feedstock premiums, feed in tariffs and premiums, CO_2 taxes, etc.) are necessary to de-risk capital investment and ease uncertainties of production costs.

Since many of these fuels with strong future potential (i.e. methanol, DME), need dedicated powertrains engine and infrastructure modifications should be considered alongside fuel production costs. Changes associated with investments in dedicated engine's R&D, upscaling of production lines, distribution network, logistics, etc. are inevitable, therefore, consistent and long-term policy support is urgently needed.

Advanced biofuel value chains must be deployed before 2030 to ensure timely shift from fossil and achieve decarbonisation. Their market uptake in aviation, maritime and heavy-duty road, sectors with fewer alternatives and more challenging in terms of CO_2 emissions reduction, must be prioritised. Achieving this however necessitates appropriate taxation, incentives, and/or carbon credits to reduce the price gap with their fossil counterparts.

Raw materials for fossil fuels are a much more efficient form of energy than the ones for advanced biofuels. Therefore, aside from the specific short and medium-term policy interventions mentioned in this paper a longer-term perspective is still required. A carbon pricing intervention (fixed, like in Sweden, or market based, ETS, etc.) which will consider the external costs of fossil fuels is expected, with rare exceptions, to make advanced biofuels cost competitive. Such a mechanism will improve their market roll-out and meet the 2030 targets whist at the same time will allow other renewable fuels, such as electricity and hydrogen, increase their market shares and commercialisation rates.

Author contribution

Calliope Panoutsou: Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision; Sonja Germer: Resources, Writing – review & editing; Paraskevi Karka & Stavros Papadokostantakis: Resources, Writing – review & editing; Yuri Kroyan: Resources, Writing – review & editing; Michal Wojcieszyk: Resources, Writing – review & editing; Kyriakos Maniatis: Validation, Writing – review & editing; Philippe Marchand: Validation, Writing – review & editing

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.

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Appendix A. Challenges, policy relevant gaps and aim of policy interventions

Feedstock production.

Challenge	Policy relevant gaps	Aim for policy intervention
Soil quality and soil carbon Improve biophysically degraded land	Several policies have clear focus on soil quality and soil carbon however more efforts are required to develop targeted actions that integrate these policies to biomass supply chains for advance biofuels. There are still very limited initiatives to rehabilitate them for biomass production and advance biofuels and these are mostly research and demonstration activities There are still policy relevant gaps concerning i) the uniform definition and classification of marginal land types as well as ii) detailed planning, financing and awareness interventions within the national strategic action plans for the Common Agricultural Policy.	Uniform definition and classification of degraded land in relevant regulations Financial support for flagship & demonstration initiatives with industrial lead focusing on domestic biomass supply options
Mobilise residues and organic wastes	Despite the fact that several policies have aligned objectives for biomass production, the efficient and timely mobilisation of organic wastes and residues remains a challenge. There is still lack knowledge transfer from existing practices and flagship initiatives at regional level which will demonstrate the feasibility of sustainable, long term biomass supply practices to produce advanced biofuels.	Regional infrastructure for biomass supply hubs to deal with logistics related to waste and residue collection, as well as large scale energy crop production

Conversion.

Challenge	Policy relevant gaps	Aim for policy intervention
Lack of awareness in SMEs and industries for transition pathways to bioeconomy (Bonfante et al., 2017) [282] Lack of optimized multi-purpose/product biorefineries	Only a few SMEs and industries are aware of potential biomass opportunities and most of them have limited access to capital that will allow them to invest in new technologies (Access to project finance) Lack of harmonized framework for sustainability assessment (lacking in RED II and bioenergy targets) of biorefineries/multi-output biorefineries that produce next bio-based materials	Improve access to finance, regulatory support and information to SMEs and industries to share risks and facilitate decision making in biorefinery innovation.

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Challenge	Policy relevant gaps	Aim for policy intervention
To meet the Paris Agreement targets consumption reduction and increase in energy efficiency is considered absolutely crucial. Advanced and efficient technologies are not supported enough to improve the efficiency [283].	Lack of dedicated policy support for advanced biofuels with a focus on increasing efficiency. Lack of orientation about existing financial options and financial instruments as current legislation is often ambiguous [284].	Provide guidance on the cost-effectiveness of resource efficiency investments and the opportunities of new technologies per value chain. Address competition through resource efficiency.
Technology development and deployment is capital intensive therefore it results in high production cost of RES fuels, including for feedstock which represents a large share of total production cost, creating overall high financial risk.	Lack of tailored financing which addresses the varying scales of production and provides financial support. Varying scales of the applications are not addressed clearly within the financing mechanisms, thus R&D, design efforts and resources are lacking for production processes to move from pilot and demonstration scales to commercial scales.	Policy aim should significantly increase supporting the demonstration of innovative conversion technologies, their deployment and scale-up by reducing risk of financing in new carbon-reducing technologies
Integration into existing infrastructures	Only a few SMEs and industries are aware of potential opportunities and most of them have limited access to capital that will allow them to invest in new technologies	Improve access to finance, regulatory support and information to SMEs and industries to facilitate decision making for co-location of biorefineries in existing infrastructures

End Use (road, marine, aviation).

	Challenge	Policy relevant gaps	Aim for policy intervention
Road	Manufacturers (OEMs) not willing to change existing automotive production lines. No profit for OEMs when releasing dedicated engines/vehicles at the moment. Only few customers (end-users) interested in more expensive alternative powertrain. Good example is flexi fuel vehicle (FFV) and a cost of powertrain for OEM increases roughly 8% (180 EUR) compared to regular gasoline powertrain [285].	Lack of support for OEMs. Specific emission targets for OEMs - the EU fleet-wide average emission target for new cars will be 95 g CO_2/km in 2021. But no credits for advanced biofuels and it does not support new investments in internal combustion engine (ICE) development.	FFVs and optimized engines for biofuels contribute to significantly lower average CO_2 emissions for the whole fleet of the OEM. For example, minus 60–70% of CO_2 emission value for FFV intended for advanced bioethanol compared to only tank to wheel (TTW) emissions. Mid-level ethanol blends, (up to 20% or 30% of volumetric concentration) must also be prioritised as they need less engine modification and result in significantly lower retrofit costs than FFV (and still can bring improvements in efficiency).
Road	Personal decisions of consumers follow various aspects. End-users willing to choose cheaper option or rich consumers tend to buy oversized vehicles like SUVs.	Lower taxes for EVs but lack of concrete support for powertrains intended for advanced biofuel use.	Tax exemptions to make the price of alternative powertrain equal to regular powertrain. Incentives for mid-level ethanol blends, biofuel intended engine + downsized vehicle, which should bring significant CO_2 emission reductions from the fleet perspective. Higher carbon taxes for luxury cars or SUVs.
Road & other sectors	Fair comparison of LCA emissions of various powertrains (i.e. biofuels vs BEVs).	Mainly TTW emission assessment. EVs regardless of electricity origin treated as zero emission. Origin of liquid fuels including advanced biofuels not taken into account from OEM perspective.	Current TTW assessments replaced by more sophisticated methods. New targets for EU fleet-wide average emission for new cars should take into account also the average fuel intended for the vehicle and changes over the time in the fuel market (fuel mix evolves while renewable fuels are introduced to the pool gradually). Origin of the feedstock such as biofuel or electricity should be definitely considered based on LCA or even cradle-to-grave basis.
End-use (road and other sectors)	Infrastructure adaptation while switching towards advanced biofuels.	Fuel producers need to meet renewable fuel share in the fuel mix according to RED or REDII Directives.	More ambitious targets for advanced biofuels in the future fuel mix. Reconsidering of double-counting idea, which does not reflect the real share of advanced biofuels in the market.
End-use (road sector)	Introduction of new fuel with separate fuel standard. Retail stations with limited number of fuel distributors, generally not more than 6–8 fuel batches.	Retail stations can offer various products but no obligation to provide renewable fuels/blends.	Each retail station obliged to provide at least one renewable fuel batch (E20, E85 or BTL100) + support for infrastructure upgrade for retail station owner.
	Challenge	Policy relevant gaps	Aim for policy intervention
Marine	High volumes of advanced biofuels needed, even for the demonstration tests.	H2020 projects and EU financial support in the development stage.	More attention and funding on implementation of the pilot-scale solutions and construction of demo-scale plants. Logical and coherent continuation of Horizon 2020 programs.
Marine	Infrastructure and availability of fuel in big ports globally.	Supervised by IMO but no specific recommendations about future potential and availability of low carbon fuels in the ports.	New clear and strong recommendation from IMO indicating which low carbon fuels should be treated with highest priority in the short-term. Those should be based on comprehensive studies focusing on the current infrastructure and future potential.
Marine & all sectors	Rapidly changing regulations	Unstable environment for future investments in the whole advanced biofuel infrastructure.	Long-term stable policies promoting the production and utilisation of renewable fuels. Public-private ventures to invest in advanced biofuel value chains.
Aviation	Significantly higher cost of Sustainable Aviation Fuels (SAF) compared to fossil Jet A1	Absence of regulatory mechanism to bridge the price gap between renewable and fossil based fuels. Lack of a regulatory framework which impacts biomass price fluctuations (D3.5).	Commercialisation of advanced biofuels and RESfuels requires significant push from the policy, therefore, the future policy should aim to provide financial support which will reduce their market price making them competitive with fossil fuels. Existing subsidies

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	Challenge	Policy relevant gaps	Aim for policy intervention
			for fossil fuels must end and increased cost of fossil fuels can drive implementation of biofuels.
Aviation	Competition between aviation and on-road transport for feedstocks	Absence of the policy support and incentives for sustainable aviation fuels.	Reduction of the competition for feedstock and enabling the equal chances for decarbonis ation of both on-road transport and aviation.
All sectors	Lack of coordination, cooperation and synergies between all actors of the biofuels value chain, including the land related (agriculture, forestry, conservation/natural resources/environment) and the energy/fuel sectors.	Weak level of communication with the energy sector that does not cover all involved or affected by the law entities.	Fast and effective feedback on regulations from the energy industry. Providing the platform, for energy industry that will accelerate the collaborations and open new possibilities for effective decarbonisation. Increasing the democracy in policymaking process. Increasing the satisfaction of energy industry entities and their involvement in shaping the future of their sector.

Appendix B. Policy mechanisms that can facilitate the aim of future policy, timeline for action and their expected added value

Feedstock production.

Aim for future policy	Relevant mechanisms (*S: short term action until 2025; M: medium term action: after 2025)*	Added value
Improve logistics and access to sustainable biomass feedstocks	Financing in the form of loans or credit lines for biomass trade centres. **(S)** Capacity building for biomass suppliers and local communities. **(S/M)**	Increased feedstock options to provide year-round biomass supply.
Ensure quality of residual and biogenic waste biomass streams.	Standards and certification procedures. **(M)** Feedstock premiums with higher support for currently unused residues and biogenic waste streams. **(S)**	Increase mobilisation of unused resources streams and reduce competition. Reduced competition for commonly used biomass feedstocks such as wood.
Create a uniform standardised methodology for data collection on SOC levels and use it as standardised indicator for examining the impact of cropping and harvesting practices.	Uniform reporting requirements on the SOC levels for different harvesting practices **(M)**	Increase a scientific understanding of the impacts of innovative cropping practices and its impact on the soil.
Financial policy instrument which support the biomass production stage (Bitnere and Searle, 2017) [286] for the financial viability of the whole value chain.	Financial supports through loans and subsidies to reduce the burden of initial investment in infrastructures required for biomass production. **(M)**	Increase interest among farmers who would be willing to adopt the biomass production practices in their marginal lands.
Future policy should aim to educate and train all stakeholders who are concerned or interested in biomass production.	Information provisions which highlights and disseminates the benefits of replacing fossil fuels with RESfuels and advance fuels. **(S)**	Acceptance from the farmers and landowners

Conversion.

Aim for future policy	Relevant mechanisms	Added value
Address competition through guidance on cost-effectiveness of resource efficiency and promote the conversion technologies which have the higher efficiency	Capacity building and awareness activities for SMEs and industries. **(S)** Capital investment grants for higher efficiency technologies should focus on maximum utilisation of resulting by-products (e.g., tars), and reduce loss of carbon atoms to CO_2 emissions (e.g., by innovative CCU pathways). **(S)**	Provide opportunity for industries, SMEs and local actors to adopt new technologies and increase biomass market uptake. Increased mobilisation of process residues and biogenic wastes.
Policy should be supporting the demonstration of innovative conversion technologies and its deployment to increase the scale of biofuels production and overcome process design considerations.	Funding support for R&D projects and Innovation funds which are near to practice and need a push to reach to market from demonstration scale. **(S)** R&D for intensifying the processes to continuous operations and aggregate process components **(M)**	Provide opportunities for businesses and industries to deploy their innovative technologies with less risk.
Need of a regulatory framework to promote greening of fossil-fuel infrastructures by co-location of biofuels processes with existing industrial infrastructures	Premiums and reduced taxation **(S)** Capacity building **(S/M)**	Provide opportunities from a technical point of view with respect to integration of material and energy flows, for businesses and industries to deploy their innovative technologies with less risk.
Establishment of attractive biofuel market conditions in order to be competitive with fossil equivalents and to meet high production costs, respective uncertainties, biomass price fluctuations, etc.	Sufficient tax (or other CO_2 penalty) for using fossil fuels. **(M)** Feedstock premiums to biomass suppliers for low cost biomass **(S)**	Provide opportunities for biofuels to become sustainable, achieve maturity levels from continuous operation and achieve an appropriate market share
Establish sectoral collaboration in the value chain between biofuels production and engine development and reduce the technical barriers (e.g. biofuels quality/composition, blending ratios, engine modifications) especially for those fuels that	Regulations and Green procurement **(S)** Standardization**(M)** R&D grants (e.g., related to the dedicated to ethanol powertrains) **(M)** Introduction of tax incentives for using biofuels **(S)**	Provide opportunities for businesses and industries to deploy their innovative technologies (both on production and end use level) with less technical (e.g. blending ratios, fuel composition/quality etc.) and market risk.

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Aim for future policy	Relevant mechanisms	Added value
have been tested successfully and are close to commercialisation in transport sectors	Increasing the refuelling infrastructure **(M)** Comprehensive LCA studies are essential for comparing alternatives **(M)**	
Aim for future policy	Relevant mechanisms	Added value
Incorporate more specific sustainability goals in renewable fuel EU directives goals e.g. include CO_2 emission targets per sector, and CO_2 taxation.	Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors **(M)** Comprehensive LCA studies are essential for comparing alternatives. **(M)**	Establish a "green" profile for biofuels industrial plants and for end use markets (e.g. (enviro-economic aspects such as CO_2 emissions, carbon footprint, and life cycle assessment aspects (cradle-to-grave perspective) Provide information on what externalities are lowered using biofuels and possibly which ones are added (e.g., from negative impact on other sustainability development goals such as biodiversity)
Improve access to finance, regulatory support and information to SMEs and industries to share risks and facilitate decision-making in biorefinery innovation.	Tailored financing for resource efficient technologies. **(M)** Joint ventures between public and private institutions. **(S)** Harmonized regulation for multi-product biorefineries **(S)**	Reduce risk of financing in new technologies and at the same time improve their market uptake and respective carbon reductions. Create synergies across bio-economy sectors
Reduce risk of financing in new technologies and at the same time improve their market uptake and respective carbon reductions.	Funding support for R&D projects which are near to practice and need a push to reach to market from demonstration scale. **(M)** Capital grants and Innovation funds **(S)** Capacity building and training for investors and industry on the needs of this sector **(S/M)**	Provide opportunities for businesses and industries to deploy their innovative technologies with less risk.

End Use.

Aim for future policy	Relevant mechanisms	Added value
Fuel cost and taxation To make renewable fuels competitive against the fossil fuels price on the European market.	Higher carbon taxes for fossil fuels. **(S/M)** Elimination of the carbon tax for 1st generation biofuels. **(S)** Optionally; reduction of the excise duties and VAT for renewable fuels. **(S)** Each retail station obliged to provide at least one renewable fuel batch (E20, E85 or BTL100) + support for infrastructure up-grade for retail station owner. **(M)**	Renewable fuels cheaper or at least of the same price as fossil fuels. Price drop will trigger the higher demand for renewable fuels, which will consequently drive the investments in fuels production facilities. Accelerated growth of the refuelling infrastructure for renewable fuels. Economic growth in agriculture branch. Jobs for local communities.
Cost of the novel powertrains Price equalization for new, more efficient and clean powertrains intended to renewable fuels with the regular SI and CI powertrain vehicles powered by gasoline and diesel respectively.	Tax exemptions to make the price of alternative powertrain equal to regular powertrain. Incentives for renewable fuel intended engine. No purchase tax and VAT, lower annual road tax, no registration tax. **(S)** Downsizing vehicles and engines, which should bring significant CO_2 emission reductions from the fleet perspective. **(S)** Purchase grants. **(S)** No parking fees. **(S)** Higher road taxes for larger cars such as SUVs equipped with regular diesel/gasoline powertrains. **(S/M)**	Novel, more efficient and clean powertrains especially those compatible or dedicated to renewable fuels, cheaper or at least of the same price as regular SI and CI powertrains powered by gasoline and diesel respectively. Accelerated market uptake of technologies with significantly lower WTW based GHG emissions than electric vehicles and regular ICE vehicles. Improvement of local air quality (much lower emission levels), positive impact on human health.
Aim for future policy	Relevant mechanisms	Added value
Environmental impact assessment method Bringing the real reductions in GHG emissions. Current tank-to-wheel (TTW) approach is outdated. TTW approach does not consider majority of the emissions produced within the value chain, and misleads the assessment of real environmental footprint of the technologies. TTW approach drives the unfair taxation, punishes and inhibits the progress and commercialisation of cleaner and more sustainable technologies on the Well-to-Wheel (WTW) basis.	With the current TTW approach, EU state members will never achieve their climate targets. There is a clear need of taking into the consideration GHG emissions within the entire value chain according the Well-to-Wheel (WTW) approach or cradle to grave (CTG). **(S/M)** New targets for EU fleet-wide average emission for new cars should take into account also the average fuel intended for the vehicle and changes over time in the fuel market (fuel mix evolves while renewable fuels are introduced to the pool gradually). Origin of the feedstock such as biofuel or electricity should be considered based on LCA or even cradle-to-grave basis. **(S/M)** Additionally, emissions related to the production of the powertrains and related compounds including batteries should be incorporated in the assessments. **(S/M)**	Ensuring the changes towards the right direction, meaning a real reduction of the GHG emissions. Honest comparison, taxation and incentives for various alternative and sustainable technologies competing on the market. New clean technologies emerging on the market.
Feedstock for all transport branches Enabling the equal profitability for channelling the feedstocks towards the aviation sector and on-road transport.	Some sectors such as aviation struggle for feedstocks intended to SAF production, as it is cheaper to use them for on-road transport fuels. EU should provide the policy support and incentives for aviation industry and SAF producers like those for on-road transportation. This action would enable equal chances for decarbonisation within the transport sector. **(S)**	Reduction of the competition for feedstock within the transport sector. Higher feedstock demand. Fuel producers would be eager to invest in larger fuel production plants due to the higher demand for renewable fuels at various sectors of transport. Larger plants, tend to be more cost effective in fuel

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Aim for future policy	Relevant mechanisms	Added value
		production, which would boost the profitability of investments. Utilisation of all fractions from advanced biofuel production in various transport segments (less refined to marine and highest quality to aviation).

Appendix C. Advanced biofuel standards

CEN Standards for road transport

The Fuel Quality Directive [287] (2009/30/EC) has dual implications for biofuel blending. On the one hand, the 6% reduction target for GHG emissions from fuels provides an incentive for using more low carbon fuels, such as biofuels, in the transport sector. On the other hand, the fuel specifications set out in the Directive define maximum levels for the biofuel content in petrol and diesel of freely marketed fuels to make these fuels compatible with engines and aftertreatments in vehicles operating across the EU [288]. The maximum content of ethanol in petrol is 10% (E10) while the maximum content of biodiesel (fatty acid methyl ester (FAME)) is 7% (B7).

Standards for petrol & diesel

These limits are specified by the Technical Committee 19 “Gaseous and liquid fuels, lubricants and related products of petroleum, synthetic and biological origin” of the European Committee for Standardization (CEN) [289].

The EN228 “Automotive fuels - Unleaded petrol - Requirements and test methods” defines the quality requirements for unleaded petrol has been updated and the 2017 specifications [290]. This European Standard specifies two types of unleaded petrol: one type with a maximum oxygen content of 3,7% (m/m) and a maximum ethanol content of 10,0% (*V/V*), and one type intended for older vehicles that are not warranted to use unleaded petrol with a high biofuel content, with a maximum oxygen content of 2,7% (*m/m*) and a maximum ethanol content of 5,0% (*V/V*).

The EN 590 European Standard specifies requirements and test methods for marketed and delivered automotive diesel fuel. It is applicable to automotive diesel fuel for use in diesel engine vehicles designed to run on automotive diesel fuel containing up to 7% (V/V) Fatty Acid Methyl Ester.

CEN is also carrying out research work on behalf of the Commission on various biofuels blends. In particular for E20/25 the Commission has been supporting a series of research projects with CEN TC/19 since 2013 [291,292]. The results of the last contract were presented in a workshop on June 25, 2019 and concluded that According to the literature review, manufacturers suggest that the majority of cars produced in the EU from 2011 onwards are E20 tolerant [293].

Standards for HVO

Hydrotreated Vegetable Oils (HVO) is a paraffinic diesel fuel and it can be used directly in diesel engines as a drop-in fuel. The CEN standard EN 15940 [294] describes requirements and test methods for marketed and delivered paraffinic diesel fuel containing a level of up to 7,0% (V/V) fatty acid methyl ester (FAME). It is applicable to fuel for use in diesel engines and vehicles compatible with paraffinic diesel fuel. It defines two classes of paraffinic diesel fuel: high cetane and normal cetane.

Standards for biomethane

DG ENER issued on November 8, 2010 the mandate M/475 to CEN for standards for biomethane for use in transport and injection in natural gas pipelines. CEN/TC 408 ‘Natural gas and biomethane for use in transport and biomethane for injection in the natural gas grid’ was created in 2011 to deliver standards on biomethane used in transport and for injection.

Two standards were developed: EN 16723–1 ‘Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network — Part 1: Specifications for biomethane for injection in the natural gas network’, was approved by CEN on September 17, 2016. EN 16723–2 ‘Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network — Part 2: Automotive fuel specifications’, was voted positively in March 2017 and published in May 2017.

During the development of these 2 standards, technical barriers were identified by CEN/TC 408 and it proved difficult to achieve consensus on some parameters or analysis methods. These were related among others to the impact of siloxanes on engines and the impact of Sulphur on catalytic converters. The European Commission has provided a new contract to CEN to continue the research work. The work is led by the European Gas Research Group, (GERG).

Standards for pyrolysis oils

The European Commission, initiated by DG ENER, issued on July 27, 2013 the mandate M/525 [295] to CEN for standards on pyrolysis oils produced from biomass feedstocks to be used in various energy applications or intermediate products for subsequent processing. That resulted in two CEN deliverables fulfilling three of the original five elements of the mandate:

EN 16900:2017 - Fast pyrolysis bio-oils for industrial boilers - Requirements and test methods and EN 17103:2017 Fast pyrolysis bio-oil for stationary internal combustion engines - Quality determination.

A Technical Specification for a quality for pyrolysis oil suitable for mineral oil refinery co-processing was left for a later stage.

Appendix D. Challenges for the market uptake of individual advanced biofuels

HVO: it is an excellent drop-in fuel for road transport and a suitable alternative for compression-ignition (CI) engines powered by fossil diesel fuel, both in light and heavy-duty vehicles [296–299]. Pure HVO meets standard EN15940, however, it does not meet EN590 due to the slightly lower density [300]. In the case of Germany only EN590 compatible fuels are allowed, which limits the use of HVO to just 30% in blends with fossil diesel while in other countries, 100% HVO fuel is already sold at retail stations. Finland aims to expand the availability of HVO across the whole country [301]. Feedstock availability may also affect HVO quality but there is still limited room for optimized collection chains or broadening the raw material sources considering REDII [302].

Even though HVO performs very well in CI engines, there are important challenges for market uptake such as feedstock availability for upscaling the production capacities, the higher final product price compared to regular EN590 diesel and equality of regulation within the EU state members.

Other **paraffinic diesels, like biomass-to-liquid (BTL)** from lignocellulosic feedstock could mitigate the upscaling issues related to the feedstock availability, however, their production costs are higher than HVO [303].

For **Sustainable Aviation Fuels (SAF)** the situation is very similar; the type of feedstock affects the cost of production. In this case, the conversion pathway also plays a significant role. The production cost of HEFA from waste cooking oil is approximately 0.90 euro per litre, whereas production of ATJ from agricultural residues around 2.4 euro per litre - the same price as for power-to-x (PTX) renewable synthetic kerosene. On the high price range is the production of SIP from sugar cane which could reach nearly 4 euros per litre. The price of all mentioned above options, is well above the average production price of regular Jet A1, which oscillates around 0.4 euro per litre [304].

However, finding the cost-effective and feedstock-flexible upgrading processes, which produces suitable quality product, is very challenging and requires advanced R&D process [305]. At the end, the upgrading step is followed by the increased price of the final fuel product.

Bioethanol Ethanol can be blended with petrol at low concentrations of 10% on volume basis. Significant attention needs to be paid when informing the user of the introduction of E10. In Germany [306] there was considerable confusion caused by the information provided to the users while in France [307] the E10 was introduced smoothly. Overall E10 is safe to use in petrol engines [308]. The so-called 'blending wall' ensures the compatibility with the current engine and fuel systems. When considering ethanol and its drop-in solutions, the flexibility in replacing gasoline is limited to 10% by EN228 standard. Ethanol can also be used in a blend of 85% on volume basis (E85) in flexible fuel engines but its uptake has been rather slow in the EU [309]. Blends with higher ethanol concentration in regular vehicles affect negatively cold-start emissions, speed up the corrosion and wear of engine components [310,311]. That is why E85 fuel (gasoline blend with up to 85% ethanol concentration) requires flexi-fuel vehicles (FFV) equipped with spark ignition engines. There are differences in engine components between FFV and regular gasoline cars, i.e. some elastomers are replaced by more durable materials, corrosion resistant alloys of engine and etc. [312]. It adds extra cost, approximately 8% of regular gasoline powertrain [313]. In HDV segment, dedicated CI engines with high compression ratio (CR) can operate with ethanol in the form of ED95 fuel, which means 95% of ethanol, and 5% of ignition improvers [314]. Due to extra costs and lack of benefits for engine manufacturers, currently, there is a significant shortage of ED95 compatible vehicles and corresponding infrastructure in the EU.

Even lower blending limits are set for **methanol** fuel. Methanol can be utilized in HDV segment in dedicated diesel engines also in combination with ignition improvers in a form of MD95. Whereas MD95 is in the research and development phase, therefore, the technology is not ready yet for the commercialisation [315].

Traditional biodiesel, by convention mixture of fatty acid methyl esters (FAME), is another fuel for LDV and HDV road transport. In low blending concentrations with fossil diesel, traditional biodiesel (FAME) is an option, nevertheless the content should not exceed 7% on volume basis according to EN590 standard, which limits its flexibility in replacing fossil diesel. However, in France B10 has been used successfully without any major problem [316,317]. Furthermore successful operation of heavy duty engines with B30 have been performed [318]. In the US B20 is used successfully [319]. Higher blends of FAME have adverse properties such as cold flow properties, the oxidation stability, and increased corrosiveness [320]. High concentration of FAME in blends can additionally affect negatively microbiological growth, water solubility or cause oil dilution [321]. Modifications of engine components and fuel systems are needed to handle fuels such as B10 or B30 in diesel engines [322,323].

Unregulated emissions are important aspects to be reported in the research phase of new fuel blends. Engine type and fuel composition highly affect the characteristics of flue gases. Interactions between blending components can play an important role as well. Aldehydes can be mentioned as examples of unregulated emissions, valid for alcohol fuels [324–326]. In case of LBG, methane slip is a major issue [327]. To tackle the problem of local emissions from internal combustion engine, aftertreatment system tailored to its application should be always applied to ensure the reliability.

Methane is a good gaseous fuel but it requires dedicated engines, while it is not a drop-in substitution for gasoline or diesel. Biogas could be used in a compressed form as a CBG for the short-haul transportation, whereas for the long-haul in a liquefied form as LBG. Currently, there is a moderate bio-CNG and bio-LNG infrastructure and low number of compatible vehicles in Europe [328]. LBG is also very interesting option for marine application with growing infrastructure and fleet equipped with either dual fuel (diesel cycle) or spark gas (Otto cycle) engines [329]. The engine technology is mature and biggest challenge is foreseen in reliable supply of sustainable LBG in harbours globally at the moment.

DME: Good gaseous option for CI engine is dimethyl ether (DME). DME requires dedicated CI engines (especially injectors) as it is not a drop-in fuel for standard diesel engines [330]. The high cetane number of DME allow efficient combustion, which additionally leads to significantly reduced PM emissions, and lower engine noise [331]. DME was commercially proven in Sweden (Volvo trucks and city buses) [332], however the biggest challenges for the technology to enter the market are poor infrastructure, very limited amount of vehicles on the road, and low DME production capacities in EU. Therefore, public incentives are necessary for the technology to grow commercially and ensure reliable supply chain of the fuel.

Methanol: Methanol is very promising fuel option for marine sector with successfully demonstrated examples on the market [333]. Methanol performs well in retrofitted engines while using mixing controlled compression ignition combustion with pilot fuel [334]. Despite its good potential [335] the challenges refer mainly to the reliable supply chain of methanol in ports worldwide as well as price renewable methanol in comparison to currently used fuels.

Hydrogen: The use of hydrogen as a fuel in the road transportation is possible by special vehicles equipped with fuel cells [336]. Hydrogen has a very low volumetric energy density, therefore, the current technology stores the compressed hydrogen to 700 bars, which allows to achieve the lower heating value of 4,7 MJ/L. The LHV of such compressed hydrogen is still low compared to gasoline of about 32 MJ/L or diesel 36 MJ/L. Fuel cell light-duty vehicles powered with hydrogen bridge the benefits of electric vehicles such as zero tailpipe emissions and traffic noise reduction with the range of internal combustion vehicles [337]. However, there are challenges for the market uptake such as higher price of fuel cell vehicles compared to internal combustion engine vehicles (ICEV), and high production price of the hydrogen [338]. Additionally, durability of the polymer electrolyte membrane fuel cells (PEMFCs) applied in FCVs is still an issue [339]. The lifetime of an average FCVs is around 17000 h, which makes them less reliable than ICEV [340]. Therefore, hydrogen is very challenging for heavy-duty transportation, both from the safety issues related to storage but also from the technology maturity, availability and costs.

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