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Dear Editors,

Please find enclosed the manuscript *A review on biofuels for light-duty vehicles in Europe* to be considered for publication**.**

The review article gives an updated summary of the use of biofuels for light-duty vehicles in Europe. This work condenses information about the legislation framework, the types of biofuels, the production techniques, the state of the market and the environmental impacts. To better understand if biofuels are environmentally better than fossil fuels, a systematic review of the Life Cycle Assessment (LCA) studies recently published for the European context was carried out. The use of biofuels can reduce the emissions of greenhouse gases (GHGs), but can also increase other environmental impacts. Even the reduction of GHG emissions is not certain, because the reviewed LCAs rarely quantify the impact of land use change.

Currently, first generation biofuels dominate the energy crop mix. New generation feedstocks are really promising, but their relative scarcity does not make a complete replacement of fossil fuels plausible. However, if the feedstocks with high indirect land-use change-risk are banned, new generation biofuels could significantly reduce GHG emissions in the transport sector. The European legislation is pushing in that direction.

This review aims to provide the reader with an up-to-date view of the world of biofuels, as complete as possible. Moreover, the review tries to analyse which data sources and methodologies are used in recent LCAs, and what are the main findings of those studies. In the meantime, this paper discusses some peculiar aspects of biofuels' modelling.

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We hope the proposed article can be of interest to you, as well as to the readers of *Renewable and Sustainable Energy Reviews*.

Yours sincerely

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Title

A review on biofuels for light-duty vehicles in Europe

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Abstract

The European transport sector was responsible for more than 25% of the EU total greenhouse gas (GHG) emissions in 2017. 53% of these emissions came from the passenger cars and light-commercial vehicles segments. Biofuels are seen as one of the options to limit these emissions in Europe. To understand the recent evolution of biofuels and their future, this review gives an overview on the production, use, legislation, and environmental impacts of biofuels in Europe for light-duty vehicles. In 2017, biofuels made up 4.5% of the energy consumption in the road transport and non-road mobile machinery. Biodiesel in 2018 accounted for 62% of the biofuels consumed in the EU, followed by bioethanol (17.5%), HVO (16.6%), upgraded biogas (1.7%) and bio-ETBE (1.1%). A review of 86 LCA studies published between 2013 and 2020 indicated that the climate change impact of biofuels is generally lower than diesel and petrol, with average emission savings depending on the type of biofuel: 70% for biohydrogen, 63% for upgraded biogas, 41% for pure biodiesel, between 54% and 7% for bioethanol (depending on the blend percentage, between 100% and 10%). An important issue identified is the limited consideration of the land use change effects, which are rarely assessed and are of paramount importance, as the values found in this review were as high as 231 g CO_2eq/MJ in some cases and thus non-negligible. Biofuels perform generally similarly or worse than fossil fuels for most of the non-GHG-related impact categories, except for ozone, fossil resource and abiotic depletion. Currently, it is highly recommended to move towards non-edible feedstocks, waste and by-products which guarantee a lower risk of land use change. The European legislation, through the Directive 2018/2001 and the regulation 2019/807, is pushing in that direction.

Highlights

- The EU is encouraging advanced feedstock for biofuels
- The range of types of promising advanced biofuels is very broad and evolving
- Regarding the climate change, biofuels have generally a better conduct than diesel and petrol
- The land use change effects are rarely included in life cycle assessments

Keywords

Biodiesel; Bioethanol; Biofuel; Biogas; Biohydrogen; Biomethane; Biomethanol; Bio-SNG; Climate change; GHG; Life Cycle Assessment (LCA); Systematic review; Transportation; Vehicle.

Word Count

11798 (including table/figure captions)

List of abbreviations including units and nomenclature

B100 Neat FAME

B20 Diesel fuel with up to 20%$_{v/v}$ FAME content

B7 Diesel fuel with up to 10%$_{v/v}$ FAME content

BE Bioethanol

BEV Battery Electric Vehicle

BtL Biomass-to-Liquids

C2G Cradle-to-Grave

CEN European Committee for Standardization

CH_4 Methane

CIE Compression-ignition engine

CO Carbon Monoxide

CO_2 Carbon Dioxide

DLUC Direct Land Use Change

DME Dimethyl Ether

E10 Petrol fuel with up to 10%$_{v/v}$ bioethanol content

E100 Neat bioethanol

E20 Petrol fuel with up to 20%$_{v/v}$ bioethanol content

E85 Petrol fuel with up to 85%$_{v/v}$ bioethanol content

ETBE Ethyl-Tertiary-Butyl Ether

EU European Union

FAME Fatty Acid Methyl Ester

FCEV Fuel Cell Electric Vehicle

FFV Flexible Fuel Vehicle

FT Fischer-Tropsch

FTD Fischer-Tropsch Diesel

g CO_{2eq}/km Grams of CO_2 equivalent per kilometre

GHG Greenhouse Gas

GWP Global Warming Potential

H_2 Hydrogen

HVO Hydrotreated Vegetable Oil

IC Impact Category

ICEV Internal Combustion Engine Vehicle

ILUC Indirect Land Use Change

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Inventory Assessment

LDV Light-Duty Vehicle

LPG Liquified Petroleum Gases

LUC Land Use Change

MSW Municipal Solid Waste

MTBE Methyl Tert-Butyl Ether

N_2O Nitrous Oxide

NH_3 Ammonia

NO_x Nitrogen Oxides

O_2 Oxygen

OFMSW Organic Fraction of MSW

PEF Product Environmental Footprint

PME Palm Methyl Ester

RDE Real Driving Emissions

RED Renewable Energy Directive

RME Rapeseed Methyl Ester

SME Soybean Methyl Ester

158 SNG Synthetic Natural Gas

159 SO_x Sulphur Oxides

160 SRF Solid Recovered Fuel

161 SSF Simultaneous Saccharification and Fermentation

162 TAEE Tert-Amyl Ethyl Ether

163 TTW Tank-To-Wheel

164 UBG Upgraded Biogas

165 UCO Used Cooking Oil

166 UCOME UCO Methyl Ester

167 US United States

168 USDA United States Department of Agriculture

169 v/v volume percentage

170 w/w weight percentage

171 WLTP Worldwide harmonised Light-duty vehicle Test Procedure

172 WTT Well-To-Tank

173 WTW Well-To-Wheel

174 **1. Introduction**

175 The Paris Agreement, signed in December 2015, was a historic deal: 195 countries agreed on limiting the
176 increase of global average surface air temperature to "well below 2 °C", compared to the pre-industrial
177 levels, and on pursuing efforts to keep the global temperature increase within 1.5 °C [1]. Among the
178 different actions to contrast the climate change, it has become incumbent to reduce greenhouse gas (GHG)
179 emissions from transport systems: in 2017, transport was responsible for 25% of total EU GHG emissions
180 and for 31% of energy consumption[2]. In 2017, road transport was responsible for 72% of GHG emissions
181 from transport [3]. Light-duty vehicles (LDVs), defined as the sum of passenger cars and light-commercial
182 vehicles (vans) [4], account for 53% of GHG emissions from transport [3]. Passenger cars account for 88% of
183 light-duty vehicles (LDVs) sold in the EU, while 12% are light-commercial vehicles (vans) [5]. Passenger cars
184 are responsible for 44% of GHG emissions from transport [3] and 81.3% of passenger transport in Europe
185 [6]. Light-commercial vehicles are responsible for 9% of GHG emissions from transport [3]. Figure 1
186 graphically translates these statistical data [3].

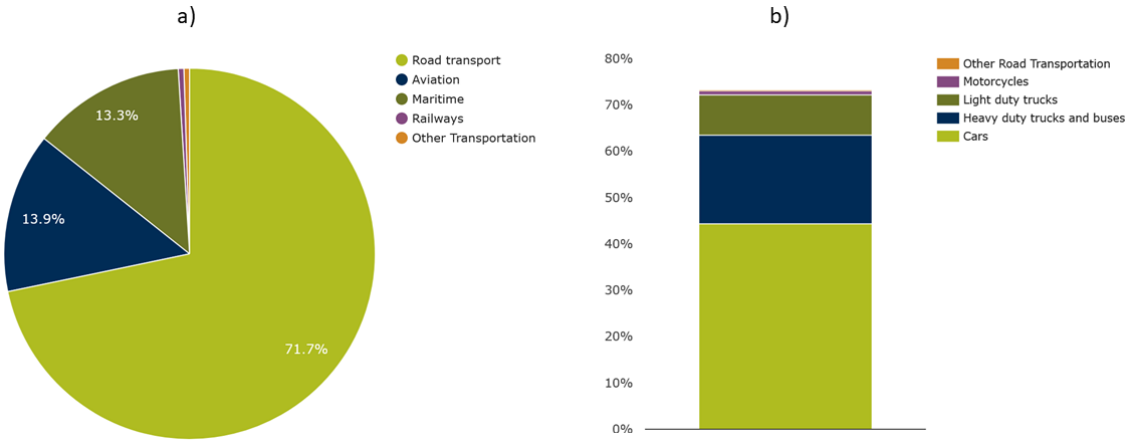


Figure 1: Share of transport GHG emissions in 2017 in EU (Reprinted with permission from [3]*). a) Share of transport GHG emissions. b) Share of road transport GHG emissions.*

The EU is promoting the use of biofuels, primarily due to the savings of GHG emissions that biofuels can potentially offer [7,8]. Biofuels can diversify the offer of transport fuel and are a way to rise the energy self-sufficiency, to diversify the production sites, and to strengthen the internal agriculture of a country. Lastly, they are suitable, in many cases, for being used in current powertrains and fuel infrastructures. In spite of their advantages, several problems regard biofuels, such as competition for land and water, conversion of carbon-rich ecosystems, and limited blending in current engines.

This work attempts to give an overview of the current status and the future perspective of both the commercially available biofuels and the most promising ones under development. The main goal of the work is to understand the recent evolution of biofuels in the light-duty sector in Europe and to use this knowledge to gain insights on their potential future.

The specific research questions this work tries to answer are:

- What types of biofuels are currently available for road transport and how they are/can be produced in terms of processes and feedstocks?
- What is the current state of biofuels for road transport in Europe, with regard to legislation, consumption and production?
- What do the most recent LCA studies tell us about the well-to-wheel environmental impact of the use of biofuels in LDVs in Europe?

The context chosen for the evaluation is Europe and the targeted vehicles are the LDVs. Previous works on biofuels can be found in [9–12], but these works each had a global scope, resulting in a more superficial discussion of the merits and drawbacks of biofuels. The added value of this review lies in the regionality (Europe) of the scope, which allows for a more in-depth discussion of markets, regulations and impacts, including quantitative analysis of these topics. Reviews about biofuel LCAs have been published as well in the last 10 years: [13–18], but the main focus is either on the period 2000-2010, or on a different geographic location. The work of Liew et al. (2014) also reviews LCAs, but only up to 2013. In the meantime, over 86 new European LCAs have been published and EU guidelines for GHG calculations have been changed [19], leading to a new understanding of the results. The added value of this review lies thus, next to its geographic scope, in an update of the state-of-the art in 2020. The plan of the review is as it follows. Section 2 provides a complete, but concise, description of all biofuel typologies. In section 3 the state of the

biofuel market is discussed, including an overview of the European legislation on biofuels. Section 4 is a systematic review on the life cycle environmental impact of biofuels. Section 5 discusses the results and in section 6 conclusions are drawn and recommendations are made.

2. Biofuel typologies

Because of the "chameleonic evolution" of biofuels, different classification methods are present in the literature and in the legislation. A common classification found in the literature subdivides biofuels into three generations [14,18,20–23]. The division presented here is inspired by the types of feedstock, the historical order of appearance on the market and the level of maturity and it is explained below:

- First generation: conventional biofuels made from food and feed energy crops (e.g., corn, palm oil, etc.). First generation production technologies are well established. The competition with the food supply-chain is however a matter of concern. The "food vs. fuel" debate has raised because it has been suggested that the increased use of food and feed crops for energy production might increase food prices [14], also causing food shortage. Also, it must be born in mind that, in the future, the effects of climate change could decrease the yields of food crops [24].
- Second generation: biofuels produced from non-food and -feed energy crops (e.g., straw, wastes, etc.). Second generation production technologies are relatively mature, but the complexity of processes and the scarce availability of raw materials is limiting their potential. Their production is more complex and expensive.
- Third generation: biofuels produced from algae. Among algae, microbial algae (or microalgae) are the most promising for biofuel production. Sometimes, other innovative biofuels which are still not commercialised are linked to the third generation. Two examples are biofuels produced from cyanobacteria [21] and higher alcohols.

Sometimes, in the literature, a fourth generation of biofuels is mentioned [12,20,21,23,25]: biofuels produced by genetically engineered micro-organisms and photosynthetic micro-organisms, from thermochemical processes, from waste CO_2, etc. Since the classification of fourth-generation biofuels is not unanimous and since these fuels are still under development, this review focuses only on the first, second and third generations. Figure 2 shows the reasons behind the evolution of feedstocks.

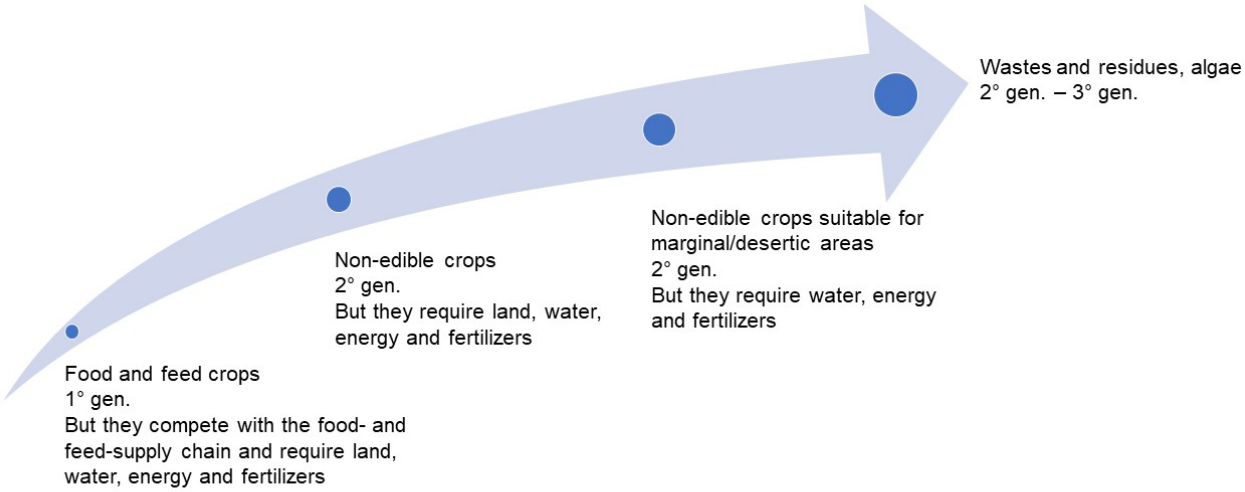


Figure 2: The evolution of feedstocks for biofuels.

Electro-fuels (often cited as "e-fuels"), are fuels obtained from captured CO_2 of different origins and, preferably renewable, electricity, that are not considered counted among biofuels for their non-biological nature [26]. Nevertheless, it is worth specifying that e-fuels could be produced also from CO_2 of biogenic origin [27]. For example, the production of methane from CO_2 separated during the biogas upgrading [28,29] and the use of electrolytic H_2 and O_2 to enhance the biofuel production [30] have been studied. As the classification of this kind of fuel is not clear yet, also due to their hybrid origin, they are not included in this review. Leaving aside the classifications, which struggle to encompass into categories the evolving world of biofuels, the main biofuels (liquid and gaseous) used for road transport are described below. Biodiesel from extractive method and bioethanol from fermentation are the principal biofuels produced globally. Figure 3 shows the main conversion pathways addressed by this paper.

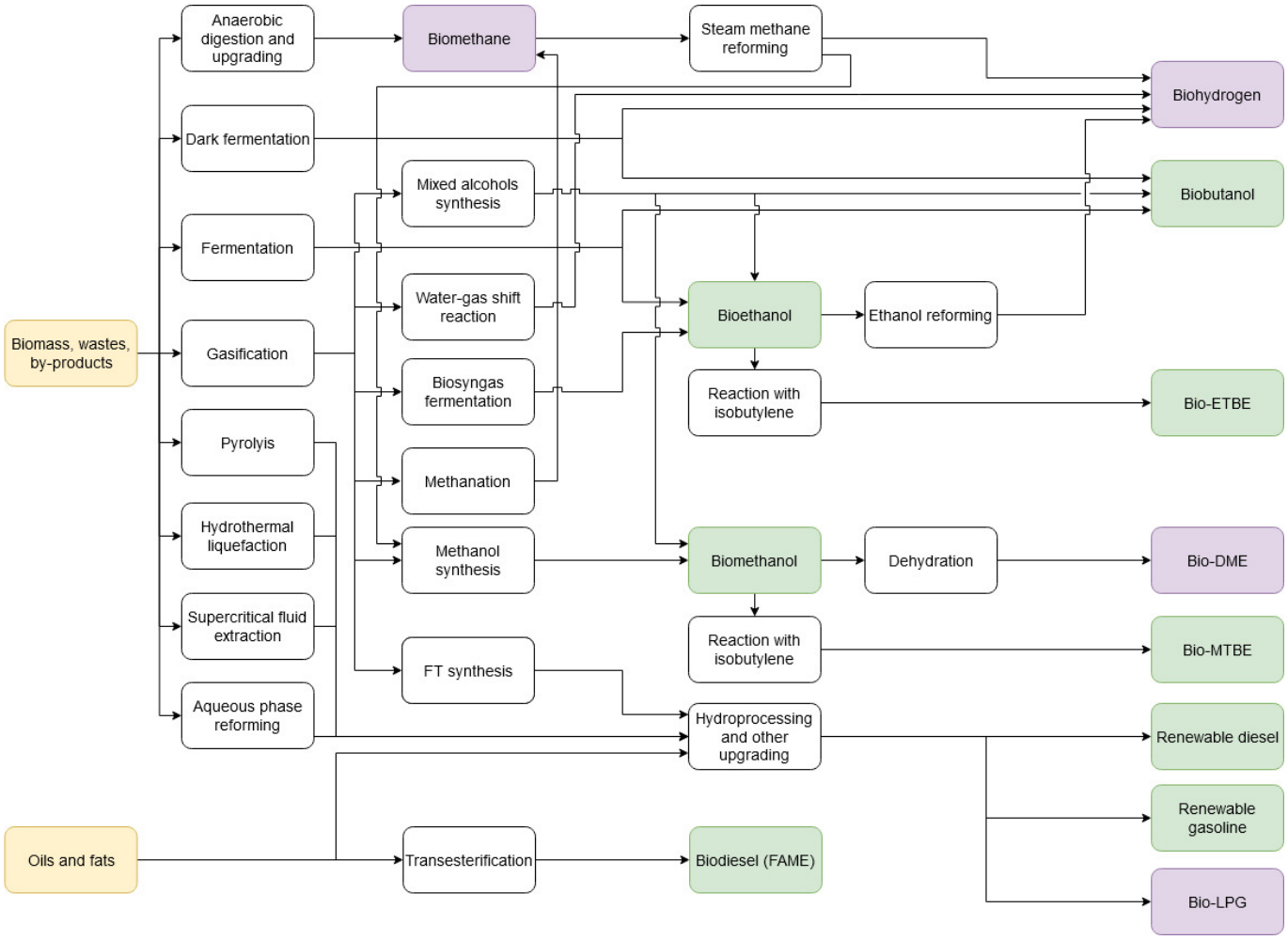


Figure 3: Simplified overview of the various possible biofuels processes (elaboration based also on [9–11,31,32]*). The green boxes are liquid biofuels, whereas the violet boxes are gaseous biofuels.*

2.1. Biodiesel

Biodiesel is a fuel produced from lipid feedstocks like vegetable oils or animal fats. To bring the oil properties closer to those of diesel, the process of transesterification is used [33] to give a fatty acid methyl ester (FAME) typically known as biodiesel. Biodiesel can be blended and used without modifications in compression-ignition engines (CIEs) [34]. Since stability and decomposition issues may arise, biodiesel is typically blended with conventional diesel up to 7-10%$_{v/v}$ (B7-B10 blends) [35–38]. To increase the blend percentages, engines have to be modified in order to optimise the operating parameters (injection timing, compression ratio, injection pressure) [39]. In Europe there are already examples of captive fleets using B20, B30 and B100 blending grades [40]. Detailed description of the production processes of biodiesel can be found in [41,42] while its technical advantages and disadvantages when combusted can be found in [20,21,46–48,33,34,39,41–45].

2.2. HVO

Hydrotreated Vegetable Oil (HVO), also named ‘green diesel’ by producers, is a paraffinic diesel derived from biomass. HVO is part of the “renewable diesels” group, which also includes the Fischer-Tropsch diesel (FT-diesel). Renewable diesel is a general term used for referring to new-generation diesels derived from biomass [49]. Two groups of technologies allow to produce renewable diesel: hydroprocessing (HVO) and

thermochemical processes like pyrolysis and gasification (see Section 2.4). These fuels can be used in conventional vehicles also directly without blending [46,50]. HVO does not contain oxygen, aromatics and sulphur [49] and it has better properties than FAME and diesel e.g. higher cetane number[1] and heating value, better oxidative stability properties. HVO does not have the FAME's advantage of being highly lubricant, though. More detailed information about HVO's properties and the distinction with biodiesel can be found in [46,51–54].

2.3. Bioethanol

Bioethanol is a liquid alcohol produced in two steps. In the first step, the fermentation of carbohydrates using yeasts produces the hydrous ethanol (water and maximum 95.6% of ethanol). In the second step, the residual water is removed using solid adsorbent, extractive distillation or membrane separation [55] to obtain anhydrous ethanol. Bioethanol is classified in three generations based on the feedstock used (see) and is blended with petrol in spark-ignition engines. In Europe, for conventional vehicles, the percentage of ethanol blended with petrol is limited to $10\%_{v/v}$ (E10) [56]. Flexible fuel vehicles (FFVs), which account for 0.1% of the EU passenger car fleet [57], can run with a percentage of blended ethanol up to $85\%_{v/v}$ (E85) [58]. Additional information about fuel properties and pollutants can be found in [11,20,21,34,59–62].

2.4. Synthetic liquid biofuels

Several thermochemical routes can convert biomass into synthetic fuels for transport [63]. An exact denomination for this group of biofuels is not in use yet [64]. According to the authors of this review, "synthetic liquid biofuels" was the most appropriate classification. The process of biomass gasification, which produces syngas, and subsequent thermochemical route is often referred to as 'biomass to liquids' (BtL) [49,65,66] Synthetic diesel, also named syndiesel and Fischer-Tropsch diesel, for example, is made from syngas by the Fischer-Tropsch process.The co-products of this process can be biogasoline, biokerosene or both, depending on the catalysts used and the process conditions [67]. Synthetic biofuels have similar or even superior properties to those of their fossil-equivalents. They practically contain no sulphur and aromatics [40], and can be used in existing engines without any modifications [68]. The available thermochemical production routes are gasification, pyrolysis, liquefaction, supercritical fluid extraction, and aqueous phase reforming. In addition, the steam reforming of biomethane can lead to the synthesis of biomethanol.

2.5. Biomethane

Biomethane produced from biomass is a sustainable alternative for feeding compressed natural gas vehicles, which in 2017 amounted to 0.4% of the passenger car fleet [57]. Biomethane can be produced by anaerobic digestion or methanation of biosyngas. The first process, a fully mature technology [66], produces biogas from organic matter. After that, biogas can be purified to biomethane (also named UBG: upgraded biogas) [69]. Bio-synthetic natural gas (bio-SNG) is the biomethane produced from biosyngas. The

[1] Cetane Number: measure of self-ignitability of a diesel fuel.

311 technology of SNG from biomass gasification, however, is not profitable yet [66]. Further information about
312 the use of biomethane can be found in [40,68–71].

313 **2.6. Other biofuels**

314 • Here a list of less common biofuels is described:Bio-DME: Dimethyl ether is an ether which can be
315 used as a fuel additive and it is also suitable as a fuel itself in CIEs. Bio-DME is produced by
316 biomethanol dehydration [72] or from biosyngas, along with biomethanol [73]. At ambient
317 conditions, DME is gaseous so it can be used only in adapted vehicles, like LPG, with a pressurised
318 fuel chamber [74]. More information is reported in [72,74].
319 • Bio-ETBE and bio-MTBE: Bioethers are a class of fuels normally used as additive to improve the
320 fuel's performance in the combustion chamber. The production of bio-ETBE/bio-MTBE requires the
321 reaction of isobutylene with bioethanol/biomethanol [20,70].
322 • Biohydrogen: hydrogen (H_2) can be produced from biomass and converted to electricity through
323 fuel cells (FCs). To produce biohydrogen, an H_2-rich biosyngas can be produced with the gasification
324 of biomass in the presence of water [73]. To further increase the H_2 content, the water-gas shift
325 reaction is employed [32,73,75]. For what concerns the resources to gasify, JRC [70] mentioned
326 woody waste, farmed wood and black liquor. Other possibilities to produce biohydrogen are
327 biomethane reforming, bioethanol reforming [75–77], dark fermentation and photo-fermentation
328 [12,78]
329 • Biopropane/Bio-LPG: Biopropane could replace fossil LPG (liquified petroleum gas) [79] and, for this
330 reason, is also called bio-LPG [66]. It can be produced with a one-stage catalytic synthesis of the
331 syngas resulting from biomass gasification [68], and also as a coproduct of HVO [53,79]. Bio-LPG,
332 albeit in low volumes, is already produced as a co-product from other processes of biofuels
333 synthesis [40,66].
334 • Higher alcohols: Long chain alcohols such as biobutanol and biopentanol have better properties
335 compared to lower alcohols (ethanol and methanol) [33]. They can be used as blending
336 components with diesel in a compression-ignition engine (CIE) [33,59]. Butanol and pentanol can
337 be obtained via fermentation of biomass, biosyngas conversion or via biosynthesis from glucose by
338 engineered micro-organisms and cyanobacteria [59]. The scientific research on how to reduce the
339 production cost is ongoing. Three recent reviews deal with this topic [33,59,80].
340 • Mixed alcohols: A mixture of methanol, ethanol, and butanol can be produced through the
341 conversion of biosyngas via chemical catalysis [31].

342 Table 1 gives an overview of the main feedstocks used for each of the described biofuel types.

343 *Table 1: Summary of biofuel types, production techniques, and feedstock typologies.*

Biofuel type	Technology	Biofuel generation	Feedstock used	Notes
Biodiesel (FAME)	Transesterification	First	• rapeseed methyl ester (RME) [15,35,81–83]	

			• palm methyl ester (PME) [48,84,85] • soybean methyl ester (SME) [48,84,85] • sunflower, corn, coconut, peanut, safflower, linseed oil, rice bran, and olive are also used [11,20,39,42,43,70,84,86].	
		Second	• used cooking oils (UCOs). FAME from UCO is called UCOME (UCO methyl ester) • tall oil, pine oil, animal fats (tallow, lard, fat, etc.), cotton seed, castor, madhuca or mahua, neem, jatropha, pongamia or karanja, carinata [9,16,87,88,20,39,41,42,46,48,84,86].	
		Third	Algae	The production of algal biofuel still under development [89,90] with improvement of harvesting, extraction and production techniques needed [12,89].
HVO (green diesel)	Hydroprocessing	First	Like biodiesel.	
		Second	UCOs, palm fatty acid distillate, animal fats, fish fats, tall oil and other unconventional sources [49,52,85,91].	
		Third	Algae	
Bioethanol	Hydrolysis and fermentation	First	• corn (or maize), wheat, barley, rye, rice, triticale, and cassava most popular starch based feedstocks [20,48,51,61,82,84,92,93]	

			• sugarcane [22,85,94,95] and sugar beet [85] most popular sugar crops • sweet sorghum one of the most promising new crops being usable on marginal lands [61].	
		Second	• wood-based material (residues from wood and paper industries, stalks, forestry residues, short rotation coppice waste wood, etc.) • perennial grasses (switchgrass, miscanthus, reed canary, giant cane, elephant grass, alfalfa stems, fiber sorghum, etc.) • agriculture by-products and waste (straws, stems, bagasse, hemp, husks, sugar beet pulp, corn stover, corncob, etc.) • organic waste (organic fraction of municipal solid waste, other industrial waste like food, etc.).	Main challenge in production is the release of simple sugars from the material since lignocellulose is recalcitrant [2] to the degradation [32,63,96]. This fact is limiting its commercialisation [11,32].
		Third	Algae	Albeit the content of carbohydrates in microalgae is quite low, under stress conditions they can amass up to 65% of carbohydrates per mass [89]. Microalgae can produce bioethanol by themselves as

[2] Lignocellulose's structure is the complex and intricate combination of a skeleton of cellulose chains, a cross-linked matrix of hemicellulose and a protective crust of lignin [45]. Lignin is unfermentable and makes cellulose and hemicellulose inaccessible to enzymes and chemicals [45,176,177].

				well, by means of dark fermentation [97].
Synthetic liquid biofuels (syndiesel, biogasoline, biomethanol, etc.)	Steam (bio)methane reforming	Second*, third**	Like biomethane and bio-SNG.	With the exception of biomethanol from biogas (SMR), synthetic biofuels are only produced at the pilot level [32,40].
	Gasification, Pyrolysis	Second*, third	Wood, municipal solid waste (MSW), energy crops, black liquor and crop residues, switchgrass, miscanthus, timber, straw, cardboard waste, forestry residue, waste wood, lignin from the Kraft process, lignin from the production of cellulosic bioethanol, etc. [32,98]. Algae [99]	
	Hydrothermal liquefaction	Second*, third	Wet biomass (e.g., OFMSW, algae).	
	Aqueous phase reforming	Second*, third**	Solution of sugars [31].	
Biomethane (upgraded biogas)	Anaerobic digestion	First	Dedicated energy crops (corn, sunflower, grasses, fodder beet, etc.) [84].	
		Second, third	Organic waste and residues, sewage sludge [84]. Algae [89,100–102].	
Bio-SNG	Methanation of biosyngas from gasification	Second*, third**	MSW, forestry and agricultural residues, sewage sludge and digestate, timber, miscanthus, and switchgrass [68,98,103].	Technology not profitable yet [66].
Bio-DME	Biomethanol dehydration	Second*, third**	Like biomethanol.	
	Synthesis from biosyngas	Second*, third**	Like gasification.	
Bio-ETBE/Bio-MTBE	Reaction of isobutylene with bioethanol/biomethanol	Second*, third**	Like bioethanol/biomethanol.	

Biohydrogen	Gasification	Second*, third**	Woody waste, farmed wood and black liquor [70]	
	Biomethane reforming	Second*, third** *	Like biomethane and bio-SNG.	
	Bioethanol reforming	Second*, third**	Like bioethanol.	
	Dark fermentation and photo-fermentation	Second*, third**	Biowaste [78].	Low yield [78]
Biopropane/Bio-LPG	Synthesis from biosyngas	Second*, third**	Like gasification.	
	Hydroprocessing	Second*, third**	Like HVO.	Coproduct of HVO [53,79].
Higher alcohols	• Fermentation of biomass • Biosyngas conversion • Biosynthesis from glucose by engineered micro-organisms and cyanobacteria	Second*, third**	Sugary, starchy and lignocellulosic biomass feedstocks [59].	Scientific research on how to reduce the production cost is ongoing [59].
Mixed alcohols	Conversion of biosyngas via chemical catalysis	Second*, third**	Like gasification.	Low product yield [31].

344 * In principle this fuel can be produced from first generation feedstocks, but due to the recent emergence
345 of this pathway and the current focus on second generation feedstocks this is unlikely to occur.

346 ** In principle this fuel can be produced from algae, but no studies were found to actually have mentioned
347 this pathway.

3. The state of the European biofuels market

This section of the review supplies information about the EU legislative framework on biofuels and statistics about consumption and production of biofuels. Data on consumption and production were mainly retrieved from [91,104–106]. Data about biofuels consumption refer to the transport sector (Section 3.2), while data about biofuels production do not refer only to transport, unless specified (Section 3.3).

3.1. The European legislation on biofuels

To contribute to the goal of the Paris Agreement, the European Council adopted in 2014 the "2030 climate & energy framework" [107]. This framework follows the earlier "2020 climate & energy package" and defines new targets for 2030. According to the latest update from 2018, the minimum targets are:

- 40% decrease in GHG emissions, with respect to 1990 levels;
- 32% of gross final consumption of energy supplied by renewable energy (in 2018 it was 18.9% [108]);
- 32.5% increase in energy efficiency.

For what concerns the target of renewable energy share, the Directive 2018/2001/EC, known as RED II, established for the transport sector a minimum 14% share of renewables (in 2018 it was 8.3% [108]) [19]. A complementary document, Directive 2009/30/EC [109], known as Fuel Quality Directive, has set for 2020 that life-cycle GHG emissions, per unit of energy from fuel and energy supplied, must be reduced at least by 6%, compared to 2010 (in 2017 it was 3.4% [104]). Fuel quality Directive applies to fuels used in road transport and non-road mobile machinery [104]. Regulation 2019/631 sets mandatory CO_2 standards for new LDVs [110], forcing manufacturers to reduce the average tailpipe CO_2 emissions factors for the fleet average. The 2021 target of CO_2 for new passenger cars is equal to 95 g/km, and the target values in 2025 and 2030 are respectively -15% and -37.5% of the average fleet CO_2 emissions compared to the values calculated through the new WLTP (worldwide harmonised light-duty vehicle test procedure), starting from the data that will be collected in 2020 (which will be available in 2021). The 2020 target of CO_2 for new vans is equal to 147 g/km and the 2025 and 2030 targets for vans are respectively -15% and -31%. From 1992, the 'Euro' standards define the limits of tailpipe emissions for the type-approval of LDVs sold in Europe. The goal of the Euro standards is to gradually reduce the traffic pollution. Also following the recent "Dieselgate" scandal, the new LDVs have to undergo two testing procedures: RDE (real driving emissions) and WLTP tests [111].

Many definitions exist for the term 'biofuel'. Directive 2018/2001/EC states that "'biofuels' means liquid fuel for transport produced from biomass" [19]. Complementary to the biofuels, are the 'biomass fuels', defined as "gaseous and solid fuels produced from biomass". Another definition that is worth to report is 'bioliquid': "liquid fuel for energy purposes other than for transport, including electricity and heating and cooling, produced from biomass" [19]. Lastly, Directive 2018/2001 defines advanced biofuels as biofuels produced from feedstocks present in part A of Annex IX [19]. Advanced biofuels are those fuels, not belonging to first generation biofuels, that are produced from non-edible feedstocks having a low risk of indirect land use change (see below for an explanation of the land use change effect) [51,112,113]. Directive 2018/2001/EC sets up many targets referring to biofuels. A selection of the main features includes:

- Within the 14% target of renewable energies in transport, a maximum of 7% share is set for biofuels, bioliquids and biomass fuels used in road and rail transport and produced from food and feed crops. This target aims to limit the excessive expansion of cultivation area and the competition with the food supply-chain. The remaining 7% can be reached with advanced biofuels, renewable electricity (i.e. battery-electric vehicles), recycled carbon fuels[3], and renewable fuels of non-biological origin (e.g. hydrogen and electrofuels).
- The share of advanced biofuels and biogases, not derived from food crops, produced from feedstocks listed in Part A of Annex IX (e.g. algae, straw, biowaste, etc.), must reach at least 3.5% in 2030. The feedstocks present in the list of Part B of Annex IX (used cooking oils and animal fats) are capped to 1.7% in 2030 [91,114]. RED II establishes the feedstocks cited in Annex IX as double counting ones (in order to promote them, when calculating the contributions towards the 14% target, the used amount of advanced biofuels counts double [91]).
- RED II defined a series of sustainability and GHG savings criteria that biofuels must meet to be counted towards the 14% transport target. For example, it is forbidden to produce biofuels from biomasses cultivated on high biodiversity land and high carbon stock land (such as wetlands, peatlands, primary forests) [91,114]. Moreover, to be considered sustainable, biofuels must achieve GHG savings in comparison to fossil fuels of at least 50%, 60% and 65%, depending from the start date of the plant operation [19]. Voluntary schemes can certify that biofuels comply with the EU sustainability criteria [91,115]. Biofuels with "high indirect land-use change-risk", produced from food and feed crops, and for which a significant expansion of their feedstock production area into land with high carbon stock is observed, will be phased out by 2030. Two types of land use change (LUC) exist: direct LUC (DLUC) and indirect LUC (ILUC). DLUC is a transformation from one land use type into another. The conversion of a land to cultivation area may change the below- and above-ground carbon stocks, and substantial amounts of GHGs can be released or stored due to this process. The highest risk of additional GHG emissions (and biodiversity loss) occurs when DLUC affects areas with high-carbon stock, such as peatlands, wetlands, and forests. That risk can be excluded if the studied biofuel is certified as compliant with the EU sustainability criteria. DLUC can be beneficial if marginal lands or annual arable crops are converted to perennial crops [17,116,117]. On the other hand, ILUC occurs when a land, that was dedicated to another crop, is converted to crops for biofuel production. This determines indirectly a DLUC in other places to satisfy the unchanged global demand of the previous crop. The higher risk of ILUC was identified for oil crops such as palm oil, soy, rapeseed and sunflower [116,118,119]. It was estimated that when the expansion of a biofuel crop into lands with high-carbon stock exceeds 14%, the GHG emissions from LUC will negate the GHG savings resulting from the replacement of the conventional fuel [118]. Regulation 2019/807 established the criteria to determine which are the high ILUC risk feedstocks for which a significant expansion of their feedstock production area into land with high

[3] Recycled carbon fuels are "liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations" [19];

carbon stock is observed [120]. The European Commission communicated that only the oil palm could be proven to belong to this category, whereas for many crops the lack of data makes it difficult to draw conclusions [118]. Regulation 2019/807 also set the criteria to certify a biofuel as low ILUC-risk. However, at the present, the certification rules are not developed yet.

In closing, the fuel standards developed by the European Committee for Standardization (CEN) define the test methods to be used and introduce more technical requirements for the use of biofuels in road transport [37,38,50,56,58,121–124].

3.2. Transport biofuels consumption in EU

As a result of the legislative push, the consumption trend over 2017-2018 has grown (Figure 4). The new period of development after a stagnation from 2012 to 2016 is mainly due to the increase of blending targets for countries and, to a lesser extent, to tax incentives [91,105]. The stagnation was due to adjustments to national blending targets, high import duties, and to the shift towards double-counting biofuels (see Section 3.1) [91]. Regarding the latter, the growing use of UCOs and animal fats for the production of biodiesel and HVO reduces the volume of biofuels needed for reaching the renewable energy target [105].

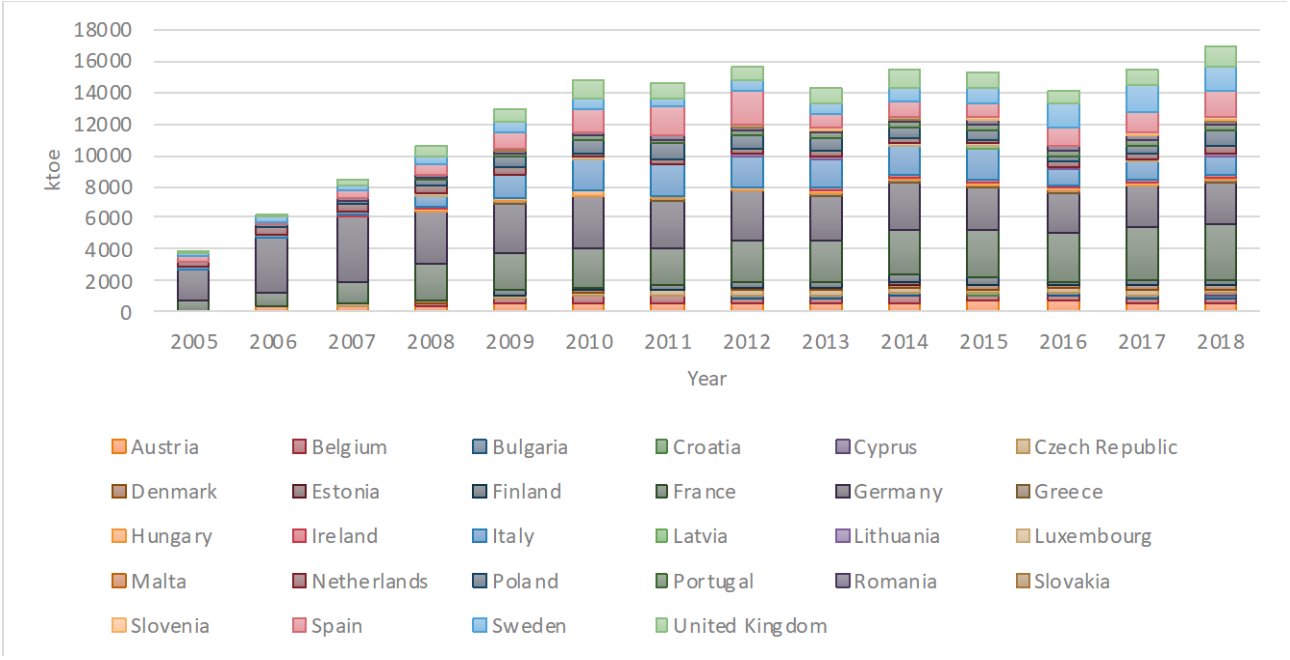


Figure 4 Consumption trends of transport biofuels in the EU (in ktoe) (Reprinted from [105]*).*

In 2017, biofuels reached 4.5% energy share in road transport and non-road mobile machinery [104]. As showed in Figure 5, biodiesel was the dominating biofuel (62.3% of total biofuels energy consumption), followed by bioethanol (17.5%), HVO (16.6%), upgraded biogas (1.7%) and bio-ETBE (1.1%) [104].

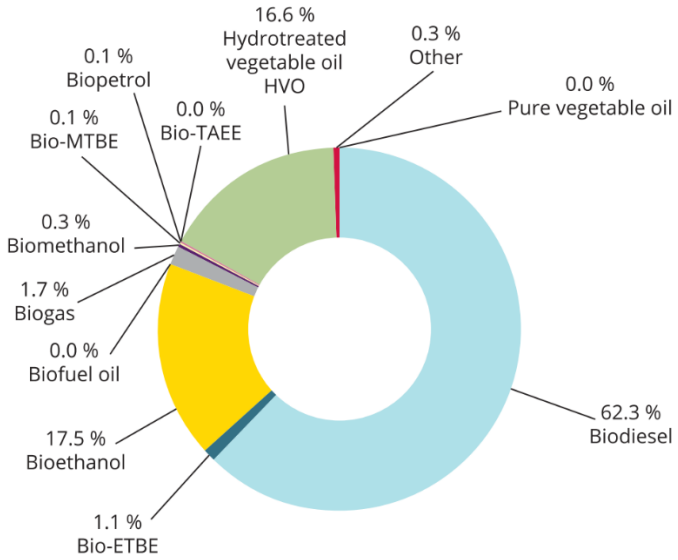


Figure 5: EU biofuel energy supply shares in 2017 in road transport and non-road mobile machinery (Reprinted with permission from [104]*). TAEE: tert-amyl ethyl ether.*

Country-level biofuels consumptions in 2018 are reported in appendix (Table A.1). 99.5% of the biofuels consumed in 2018 from the European transport sector was compliant with the sustainability criteria defined by RED II (see Table A.1), with France, Germany and Spain being the top three consumers of both biofuels and biodiesel and Germany, United Kingdom and France leading the consumption of bioethanol. 87.6%$_{v/v}$ of petrol sold and 100%$_{v/v}$ of diesel sold were labelled as containing biofuels (bioethanol and FAME, respectively) [104]. Figure 6 shows the blends that dominated the market in 2017. It should be noted that the number of a blend (x) must be understood as "with up to x%" in volume of that component. Therefore, for example, a diesel "B7" could also contain 0% of biodiesel, up to 7% maximum.

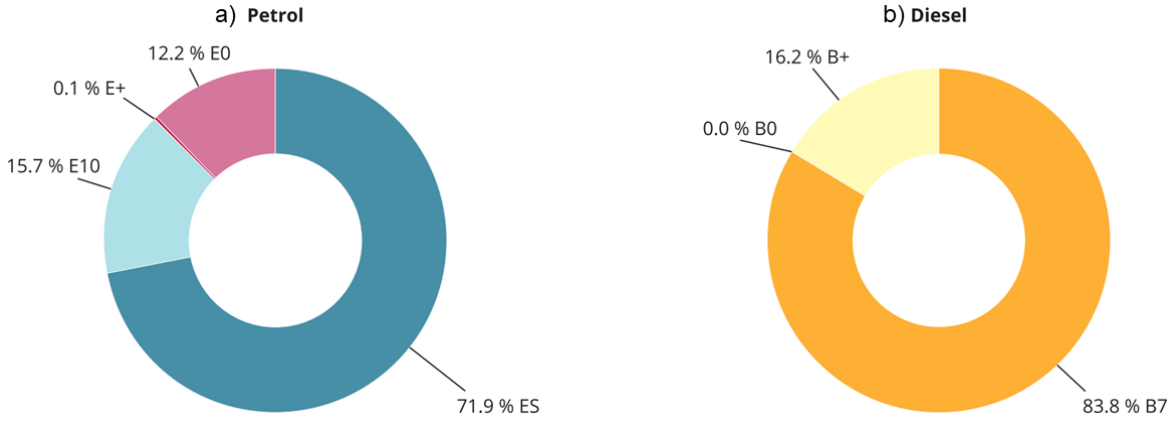


Figure 6: a) Biofuels blends in petrol sold in 2017 in EU for road transport and non-road mobile machinery (Reprinted with permission from [104]*). E0 = petrol; E5 = petrol with up to 5%$_{v/v}$ bioethanol; E10 = petrol with up to 10%$_{v/v}$ bioethanol; E+ = petrol with > 10%$_{v/v}$ bioethanol (i.e. E85). b) Biofuels blends in diesel sold in 2017 in EU for road transport and non-road mobile machinery (Reprinted from* [104]*). B0 = diesel; B7 = diesel with up to 7%$_{v/v}$ biodiesel; B+ = diesel with > 7%$_{v/v}$ biodiesel.*

3.3. Biofuels production in EU

In 2018, approximately 14.4 billion litres of biodiesel and HVO were produced in the EU, 3.4 were imported and 0.7 were exported [91]. HVO production corresponded to about 2.8 billion litres. Biodiesel was

produced in 188 biorefineries, while HVO in 12. Table 2 lists the production capacity of the main European producers of FAME and HVO in 2018. Top FAME-producing countries were Germany, Spain, France, the Netherlands and Poland, while the Netherlands and Finland produced the greatest amount of HVO. Domestically produced FAME is facing competition from EU-produced HVO and imported SME from Argentina and PME from Indonesia.

Table 2: Production capacity of FAME and HVO for the main producers in 2018 (in tons) [105].

Company	Country	Location of plants in Europe	Biodiesel and HVO production capacity (t)
Neste	Finland	Finland, Netherlands	2,700,000
Avril	France	France, Germany, Italy, Austria, Belgium	1,552,000*
Infinita	Spain	Spain	600,000
Verbio AG	Germany	Germany	470,000
Total Group	France	France	470,000
Eni	Italy	Italy	219,000*
Marseglia Group (Ital Bi Oil)	Italy	Italy	200,000

**Production and not capacity.*

Mostly used feedstocks for FAME and HVO were rapeseed oil (39% of total mass of feedstocks), UCOs (22%) and palm oil (19%). In addition, soybean, animal fats sunflower, pine/tall oils, and fatty acids. The majority of rapeseed oil is produced inside the EU [91,125]. 90% of UCOME was produced in the Netherlands, Germany, the United Kingdom, Portugal and Austria. Palm oil, almost totally imported from Indonesia and Malaysia [125,126], was mainly used in Spain, Italy, France and the Netherlands. Soybean was mainly used in Spain, the Netherlands and Germany. The majority of soybean oil is domestically produced by crushing of imported soybeans. The Netherlands was the largest user of animal fat, while Greece and Bulgaria were the largest users of sunflower. In 2018, approximately 5.4 billion litres of bioethanol (used as fuel, but not only in transport) were produced in the EU, 0.5 were imported and 0.09 were exported. Less than 0.2% of bioethanol produced inside the EU was cellulosic ethanol. Table 3 lists the main European bioethanol producers in 2018. Total refineries of first-generation ethanol were 58, while only two refineries produced cellulosic ethanol.

Table 3: Bioethanol production of the main producers in 2018 (in millions of litres). Modified from [105].

Company	Country	Location of plants in Europe	Bioethanol production (millions of litres)	Raw materials
Tereos	France	France, Czechia, UK, Italy	1,200	Sugar juice, wheat
Crop Energies	Germany	Germany, Belgium, France, UK	967	Sugar juice, wheat, corn, triticale
Vivergo	United Kingdom	UK	420	Wheat

Cristal Union	France	France	320	Sugar juice, wheat
Agrana	Austria	Austria	250	Wheat, corn

482

483 The top five bioethanol-producing countries were France, Germany, United Kingdom, Hungary and
484 Belgium, with the first three countries sharing more than 50% of the total [91,105]. Cellulosic ethanol
485 commercialisation is having difficulties to take off because of high investment costs. In 2018, the three
486 most used feedstocks for transport bioethanol were sugar beet (39% of total mass of feedstocks), wheat
487 (28%) and corn (25%). In addition, barley, rye, triticale and cellulosic biomass were also used. Focusing
488 instead on the total volume of bioethanol produced, and knowing that 82% was used as fuel, 43% of
489 bioethanol was produced from corn, followed by wheat (26%) and sugar crops (21%) [106]. In 2016, 65% of
490 the bioethanol consumed in the EU was produced from EU's feedstocks [125]. Corn is mainly imported
491 from Ukraine and predominantly used in Central Europe, the Netherlands and Spain. Wheat ethanol is
492 mainly used in Germany, France and the United Kingdom. Sugar beets are particularly used in France,
493 Germany, the United Kingdom, Czechia and Belgium.

494 Data about other biofuels is scarce. Only one plant in the EU produces biomethanol from biogas: BIOMCN
495 in the Netherlands [91,127].Biomethane for natural gas vehicles is available in 8 countries, with Sweden
496 being the largest consumer. No specific data was found about the origin of biomethane used for transport.
497 Bio-LPG (biopropane) is already produced, although indicatively only 0.1% of the produced LPG is bio-based
498 [66]. Bio-ETBE and bio-MTBE are already used on the European market (Figure 5).

499 Obviously, the commercialisation of a biofuel depends on the technology maturity, which can be measured
500 in terms of Technology readiness level (TRL). Table 4 summarizes the degree of maturity of several biofuels
501 presented in Section 2.

502 *Table 4: Degree of maturity of biofuels. In brackets the year of the source reporting the information.*

Biofuel/Technology	Degree of maturity
Algal biofuels	Immature technology, under research and development (2018) [89]
Aqueous phase reforming	TRL* 4-5 (2016) [31]
Biodiesel (FAME)	First generation: TRL 9 (2020) [66]. Second generation: TRL 9 (2020) [66]. Third generation: still under development [89,90].
Bio-DME	TRL 5-7 (2014) [68]
Bio-ETBE and bio-MTBE	Already on the market [104]
Bioethanol	First generation: Fully mature technology (2019) [91]. Second generation: already produced (2019) [91]. Third generation: still under development [89].
Biohydrogen from woody biomass gasification	TRL 7 (2016) [128]
Biomethane from biogas	Fully mature technology (2020) [66]. TRL 8-9 (2014) [68]

Biomethanol from biogas	Already produced (2019) [91,127]
Biopropane/Bio-LPG	Already produced as a co-product of HVO (2020) [66]
Bio-SNG from gasification	Not profitable yet (2020) [66]. TRL 6-7 (2014) [68].
Gasification + Fischer-Tropsch	TRL 5-6 (2016) [31]
Gasification + methanol	TRL 6-8 (2016) [31]
Gasification + mixed alcohols	TRL 4-6 (2016) [31]
HVO	TRL 9 (2020) [66]
Hydrothermal liquefaction	Immature technology, in an industrial pilot phase (2018) [63]. TRL 1-4 (2016) [31].
Lignocellulosic bioethanol	TRL 8-9 (2020) [66]. TRL 6-8 (2016) [31].
Lignocellulosic butanol	TRL 5-6 (2016) [31]
Pyrolysis	Immature technology not yet suitable to economically compete with conventional fuels (2020) [129]. TRL 4-6 (2016) [31].
Supercritical fluid extraction	At the laboratory scale [63]
Syngas fermentation	TRL 6-7 (2016) [31]

**Technology Readiness Level: (1-3) basic to applied research, (4) small-scale prototype, (5) large-scale prototype, (6) prototype system, (7) demonstration system, (8) first of a kind commercial system, (9) full commercial application* [65].

4. Environmental impacts of biofuels use

In the case of a crop-based biofuel, the life-cycle path includes multiple steps: agricultural phase, transport, industrial processing phase, transport, use phase. Life-cycle impacts on climate change of a biofuel must be assessed including all CO_2 emissions from all the stages, as well as other GHGs like nitrous oxide (N_2O) and methane (CH_4). Life Cycle Assessment (LCA) is a well-known technique that is used to evaluate the environmental impacts of a product or service over its life cycle. The International Standard Organization set a standardised methodology for carrying out an LCA [130,131]. With the aim of understanding the potential benefits and drawbacks of biofuels, this section includes a systematic review of the European LCA studies on light-duty vehicles (LDVs) running with biofuels. The literature review analyses which sources and methodologies are used in recent LCAs, what are the main findings of those studies, their most important assumptions and modelling approaches as well as their limitations. Other reviews about this topic have been published in the last 10 years: [13–17]. The systematic review followed the Standardized Technique for Assessing and Reporting Reviews of Life Cycle Assessment Data (STARR-LCA) developed by Zumsteg et al. [132]. The qualitative (i.e. methodological choices, assumptions modelling approaches and limitations) and quantitative (i.e. life cycle impact) results of the review are shown following the formal structure of an LCA.

4.1. Method

The literature review covers 86 publications issued from 2013 to 2020 (August). Earlier studies were not considered, as they have already been covered by previous reviews, as explained in the introduction. The studies where selected by means of a search in the “Scopus”, “Web of science”, and “ScienceDirect” databases [133–135]. The research was conducted among article titles, abstracts and keywords (selection

method and keywords are described in the supplementary material). 2643 documents were screened for eligibility. Other publications and case studies from the grey literature were identified from the references. To be eligible for the review, a study had to comply with four requisites:

- the production and use of the finished biofuel have to be in Europe, regardless of the feedstock's origin.
- the study must assess an LDV. The studies not reporting the vehicle's type, evaluating only GHG emissions and assuming neutral emissions during the use phase were eligible for the review, because in this case the type of vehicle was irrelevant.
- the study must include at least one scenario related to a vehicle fuelled by a liquid or gaseous biofuel.
- the study must be a full cradle-to-grave (C2G) LCA or at least a well-to-wheel LCA (WTW). The first type assesses the life cycles of the vehicle and the fuel, without neglecting any life-cycle stage. The second approach assesses only the life cycle of the fuel, including its combustion in the car's engine. WTW studies exclude from the analysis the manufacture and the end-of-life of the vehicle.

A detailed spreadsheet with the main qualitative results of the analysed LCAs is provided in the supplementary material. Studies using a well-to-tank (WTT) system boundary that explicitly assume zero combustion emissions or that compare directly to a WTW benchmark of fossil fuels were also included. They were marked WTT* in the supplementary material, but were considered WTW for the analysis.

4.2. Goal and scope definition

The first stage of an LCA defines the context of the study, the reason for carrying it out, the description of the system, the functional unit, the system boundaries, the impact categories, the category indicators, the method to account for coproducts, the type of data, the assumptions, the limitations and additional information.

4.2.1. Biofuel pathways and feedstocks

The majority of the reviewed LCAs studied the environmental performance of bioethanol (41/86), FAME (27/86) and upgraded biogas (26/86), as can be seen in Figure 7.

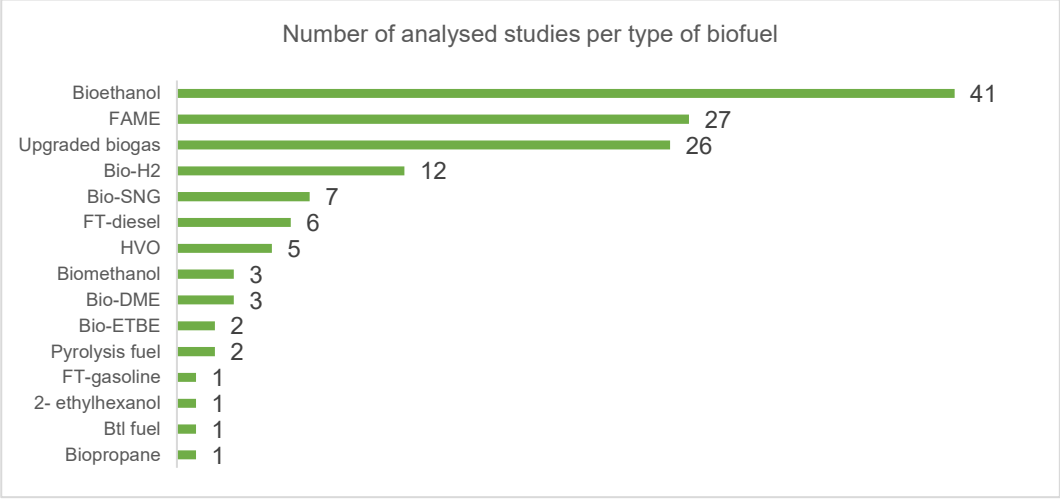


Figure 7: Number of analysed studies per type of biofuel. Bio-SNG = bio-synthetic natural gas; DME = dimethyl ether; ETBE = ethyl tert-butyl ether; FAME = fatty acid methyl ester; FT = Fischer-Tropsch HVO = hydrotreated vegetable oil.

The European scientific community has been directing its efforts towards first, second, and third generation feedstocks (Figure 8). Figure 8 shows the most evaluated feedstocks.

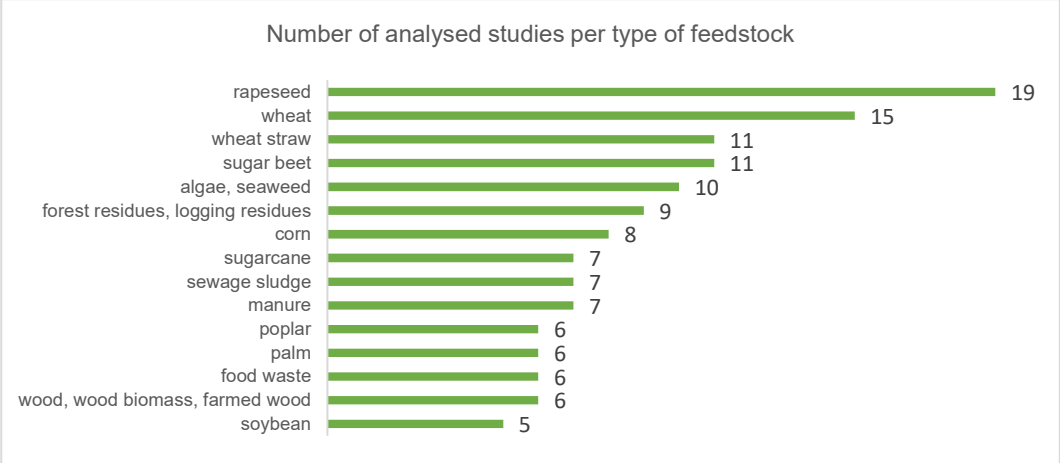


Figure 8: Number of analysed studies per type of feedstock (only the feedstocks mentioned by more than 4 studies were included in the chart). Functional unit

The functional unit is a measure chosen to describe the function of the system, a common measure to which the results of an LCA are expressed. The choice of functional unit depends on the goal and scope definition. For example, for WTW and C2G studies, the most chosen functional units are "1 MJ" (38/86) and "1 km" (32/86). WTT* studies (see Section 4.1) typically choose "1 MJ of finished fuel delivered to the vehicle tank" or another unit to express a quantity of fuel (ton, liter, kg). The use of different functional units in studies with similar scope is not problematic as long as they are convertible into each other. Blend composition, density, energy content and fuel consumption of the considered fuels are therefore crucial values to be reported by each biofuel LCA, but these are currently often lacking. 46/86 studies did not mention the required data for harmonization. In those cases, sometimes general values from literature can be used if at least the fuel blend is known.

4.2.2. Geographic location and system boundary

Most of the studies are dispersed among 17 different countries, while 15 studies are set more generically in the European continent. The reviewed LCAs are almost all WTW studies (71/86). The choice of neglecting the life cycle of the vehicle is mainly due to the comparative nature of vehicle-related LCAs. For example, when the aim of an LCA is to assess the differences in using bioethanol over petrol, the impacts generated during the vehicle production, recycling and disposal are practically the same in both cases. In this case, the exclusion of the vehicle life cycle is a widespread practice. Anyway, if different powertrains are compared (e.g., an EV versus an ICEV), the vehicle life cycle should be assessed. In the few cradle-to-grave LCA founded (16/86), where it was possible to isolate the data about the vehicle life cycle, the GHG emissions ranged from 14-37 g CO_{2eq}/km for ICEV [136,137] to 67-72 g CO_{2eq}/km for FCEV [138].

4.2.3. Time horizon

In the majority of the studies (66/86), the time horizon was not explicit. However, it is quite clear that time horizon is affected by the age of data collected in the life cycle inventory (LCI). 14 studies chose to analyse a

583 future timeframe. , 5 LCAs assumed future developments of the vehicles technology. .Normally, for
584 assessing the impact on climate change, a time horizon of 100 years is chosen. After 100 years, the long-
585 term effects due to the emissions of GHGs are cut off (although 20% of CO_2 will remain in the atmosphere
586 for other thousand years) [139]. When a biofuel is produced from long-lived bio-products, for example
587 poplar or willow, the LCA study could include the calculation of temporary carbon storage, a correction flow
588 which lowers the climate change impact of the biofuel, due to the delay of the emission [139]. The short-
589 term carbon storage is irrelevant when considering the long-term effect on the climate change (e.g. 500
590 years) but could be valuable when assessing the impacts on shorter time horizons (e.g. 20 years). Dynamic
591 LCAs are relevant for assessing climate impacts of long-life cycles and the results can considerably differ,
592 compared to those provided by a static LCA [140]. Shimako et al. performed a dynamic evaluation on
593 bioenergy from microalgae. They found that microalgae, due to the short time between the CO_2 capture
594 and the CO_2 release, did not lead to carbon sequestration [101]. Singh et al. reported all the results on a
595 100-years base (the rotation time of the studied forest), considering the long-term effects of clear-cutting a
596 forest [141]. Using customized characterization factors for biomass derived CO2, they found that GHG
597 savings were less than those calculated by other LCAs who used the assumption of carbon neutrality (see
598 Section 4.3.3).

599 **4.2.4. Impact categories and impact assessment methods**

600 Every LCA aims to assign the LCI results to one or more impact categories (ICs) that reflect the
601 environmental issues of the product system being studied. While recognizing the GHG emissions as the
602 main legislative stimulator, other environmental impacts should be assessed: the main environmental risk
603 for human health is the air pollution. Road transport contributes significantly to the emissions of air
604 pollutants and is the main responsible source for air pollution in cities [142,143]. Road transport
605 contributes to high concentrations of CO and particulate matter (PM) [144], and NO_x emissions from the
606 transport sector represents 46% of the total EU28 emissions [144]. Instead, SO_x emissions from road
607 transport are nowadays negligible because the fuels sold in Europe have to meet the limit of 10 mg/kg of
608 sulphur content [109]. Other key issues concerning biofuels, especially during the agricultural phase, are
609 water use, soil degradation, deforestation, eutrophication, acidification, spread of invasive species and loss
610 of biodiversity [25,85,145]. It is common in an LCA to use already existing impact assessment methods
611 available in the software packages. The most used impact assessment methods resulted CML (16/86) and
612 ReCiPe (13/86). The impact on climate change was calculated using characterization factors by the IPCC
613 assessment reports or following the RED methodology [19]. The software used for the calculations were
614 disparate, ranging from self-made models running on Excel to commercial software like SimaPro [146] and
615 GaBi [147]. Climate change (and similar denominations) was the most considered impact category (85/86),
616 followed by eutrophication (mentioned in 28/86 studies), acidification (27/86), and energy use (26/86).
617 Only 7 studies included a water use IC and only 11 studies included an IC about the land use. The lack of
618 attention towards such key categories, ascertained by Shonnard et al. and Van Der Voet et al. [13,16],
619 persists.

620 **4.2.5. Modelling principle**

621 Two LCA modelling principles are used. In the attributional modelling, the system is modelled as it is (or
622 was, or forecasted to be, depending from the time horizon) [148]. In consequential modelling the system is

modelled as it is expected to change as a consequence of the analysed decision [148]. The indirect land use change is a suitable example of consequential modelling (see 1.12.2). 82/86 LCAs seem to follow an attributional modelling [148]: the study is used to support a decision (e.g., use of biofuel vs use of fossil fuel) that does not lead to large-scale consequences in terms of installed capacity in the background system or other systems. In fact, it can be stated that a biofuel has a limited share of the total production of its sector (see Section 3). Moreover, also in LCAs that set as time horizon the 2020-2030 decade, the substitution of fossil fuels is plausible up to a limited level [70]. Anyhow, only 7/86 studies explicitly claimed to follow a consequential modelling principle (though only 27/86 explicitly claimed to follow the attributional modelling principle).

4.2.6. Multi-functionality

It is common, when assessing a biofuel chain, that a life-cycle stage has multiple outputs. The environmental impacts linked to the LCI results must be subdivided between the main product (the biofuel) and the co-products, in order to isolate the impacts of the function under study. When applicable and reported (61/86), the used procedures for solving multi-functionality in the base scenario were the substitution approach (system expansion) (24/61), the energetic allocation (19/61), the economic allocation (6/14), the exergetic allocation (5/61) and mass allocation (2/61). In addition, 5/61 studies used a mixed approach for their base scenario, which means that for some co-products the substitution method is used and for other co-products the allocation method. The energetic allocation was always used in studies according to the RED methodology [19], whereas the ISO standards and other scientists promote the use of the substitution approach rather than the allocation [70,131]. Although the specific nature of the LCA and of the system under study may justify a deviation from the recommended hierarchy [14]. In any case, trying different allocation approaches is a widely recommended practice that six LCAs adopted.[75,149,150]More widely, changing the procedure for solving the multi-functionality has a great influence on the results, therefore, a sensitivity analysis should always be included [13]. For example, using the substitution approach with the production of biogas from anaerobic digestion, all the impacts are allocated to biogas but the digestate replaces the use of fertilisers and the impact of the system is reduced. When using energetic or economic allocation, on the other hand, all the impacts are allocated to biogas because the LHV and economic value of digestate is practically zero, thus no displacement effects are accounted for. This effect has been investigated by nine studies. In the majority of cases (31/42 estimates), the difference between the results obtained with substitution and allocation is more than 10% and in almost half of the case (18/42) the difference exceeds 50%. The substitution approach often leads to lower results, as credits for co-products can be larger than the impact related to the production process itself. The biggest difference between the methodologies in absolute terms was reported by Jeswani et al. who found that ethanol from forest residues leads to -200 g CO_{2eq}/km according to the substitution method and to 347 g CO_{2eq}/km according to economic allocation [151].

4.3. Life-cycle inventory (LCI)

The second phase of an LCA is the collection and the organisation of input/output data about the analysed system (flows of energy and material, solid wastes, emissions in air, water and soil).

4.3.1. N_2O

It is recommended to estimate the emissions of N_2O from soil during the growth of the biomass due to its high global warming potential [152] and its relative importance in the context of biofuels [85]. N_2O can originate from the usage of fertilisers and manure or also, subsequently, from NH_3 deposition and nitrate leaching [149]. 14/86 authors neglected the N_2O emissions when the feedstocks did not require fertilising (e.g., waste and residues, algae, by-products, etc). In the remaining studies, 43 authors included the N_2O emissions in the LCI, whereas 29 authors did not mention them.

4.3.2. Land use change

The assessment of the LUC effect, already discussed in Section 3.1, is recommended [17,153–155]. The PEF Guide suggests the assessment of DLUC only, because an agreed methodology for the estimation of ILUC is still lacking [154]. Nevertheless, reliable documents provide emission factors for ILUC that can be used [19,79,116,119]. Although the inclusion of the ILUC into an attributional LCA is not coherent with the attributional modelling principle [156], it is an effect which was proved to be possible and should not be overlooked. Unfortunately, only 18/86 studies explicitly wrote to have included the DLUC effect and only 10/86 to have included the ILUC effect. Focusing now on the debated ILUC, Yan and Boies added 14 g CO_{2eq}/MJ to their bioethanol from wheat grain and wheat straw, leading to the diminution of GHG savings (with respect to the fossil fuel comparator of RED) from 39-60% to 22-43% [157]. Lantz et al. added 12 g CO_{2eq}/MJ for wheat bioethanol, which is the emission factor suggested by RED II [156]. For FAME from palm, Johnson chose to add 55 g CO_{2eq}/MJ (RED II value) but also reported the leading estimates for LUC/ILUC in the literature: 44-231 g CO_{2eq}/MJ for FAME and HVO from palm oil, 9.5-28.4 for corn ethanol, 4.7-17 for sugarcane ethanol, 14.5-180.5 for rapeseed FAME, and 29.1-198 for soy oil FAME [79]. D'Avino et al. used 55 gCO_{2eq}/MJ for their FAME from rapeseed and carinata [88]. The addition of ILUC, in this study, made the biodiesels more impacting than diesel when using the energy allocation, while, when using system expansion, the biodiesels still guaranteed GHG savings. Gabrielle et al. added 53 g CO_{2eq}/MJ for rapeseed FAME, 37 for wheat bioethanol, 16 for sugar beet bioethanol, and 27 for miscanthus bioethanol [158]. The inclusion of ILUC lead to nullify the GHG savings for the first two biofuels, and to halve the GHG savings for the last two biofuels. Boldrin and Astrup estimated the ILUC effect for FAME produced by Danish rapeseed, adding 29-79 g CO_{2eq}/MJ, but also they found in the literature a range of 33-67 g CO_{2eq}/MJ [155]. Herrmann et al. calculated for their B20 blend (from rapeseed) an increase of 107-173 kg CO_{2eq}/1,000 km [83]. In 13 cases, DLUC and ILUC were rightly neglected because the plantation was marginal or in operation before 2008 and beyond (10/13), or because the feedstock was a residue or an alga not leading to LUC (3/13). However, with a more precise approach, it must be specified that the removal of crop or forest residues may alter the soil organic carbon balance, affecting the DLUC [85,116,145,159]. Further, the use of wastes and residues which are already well-utilised for other purposes, could create a supply shortfall to be met with other materials [160]. In 2 cases, an additional justification for not taking into account the ILUC was the increasing yields of crops.

4.3.3. Carbon neutrality

The attribution of the value "zero" to the characterization factor of biogenic CO_2 is a widespread practice in LCA studies. Nevertheless, doubts are mounting about the scientific soundness of this hypothesis. The example of a forest represents the emblem of the distrust towards the carbon neutrality approach. Taking

the case of an old-growth forest cut down to produce biofuel, the combustion of the biofuel instantly generates CO_2 just like a fossil fuel. To repay the carbon debt, accentuated by the LUC effect, several decades will be required for re-growing the biomass and absorbing CO_2 again in plant biomass[141,145,161]. But, if the breakeven point is too much far, the use of biofuels paradoxically could worsen climate change through XXI century. Further, if an energy crop replaced a high-carbon stock area, the carbon debt could be never repaid [162]. In order to achieve a carbon credit, the biomass should be harvested after having planted new trees [85]. Following such observations, it is recommended by Rabl et al. [163] to abandon the practice of considering biogenic CO_2 as "neutral" (49/86 LCAs explicitly did not abandon the practice). The emission and removal of CO_2 should be evaluated at every life-cycle stage, just like any other flux (17/86 studies explicitly adopted this practice). In 20/86 LCAs the approach regarding the biogenic CO_2 was not reported or sufficiently clear. Summing up, it seems that there is greater attention to the subject than in the past, given that a review of 2010 complained that 85% of LCAs had not explicitly indicated the choice made [13].

4.4. Life-cycle impact assessment (LCIA)

The inventory flows are assigned to one or more impact categories. After that, the LCI flows are converted to common units and summed to obtain single results of potential environmental impact for each IC. Optionally, the results of single ICs can be normalized, grouped and weighted to obtain a few numbers of scores and, ultimately, a single score. For this analysis, all the WTW results regarding the climate change IC (244 observations, from 67 studies, expressed as a single digit or as a range) were collected and conveyed in "box and whisker" plots (Figure 10), to roughly understand if a rank among the different biofuels can be determined. The climate change was chosen because it was the most representative and analysed IC among the selected studies. Only the available explicit results were included in the chart. In cases where a WTW result was expressed as a range (uncertainty analysis, multiple scenarios, etc.), the data conveyed in the plot was the mean of the range. The GHG emissions were analysed as g CO_{2eq}/km. The results were grouped in families of biofuels, admitting that the quantity of selected articles did not allow evaluations to be made on the individual feedstock (e.g., sugar beet), but rather on the biofuel family (e.g., bioethanol). The results were compared to the use of diesel and petrol, which are the most used fuels for road transport in Europe. The number of articles and of results greatly affects the strength of the consideration that can be done; therefore, the reader should take care of the number of studies and results reported on the chart for every fuel.

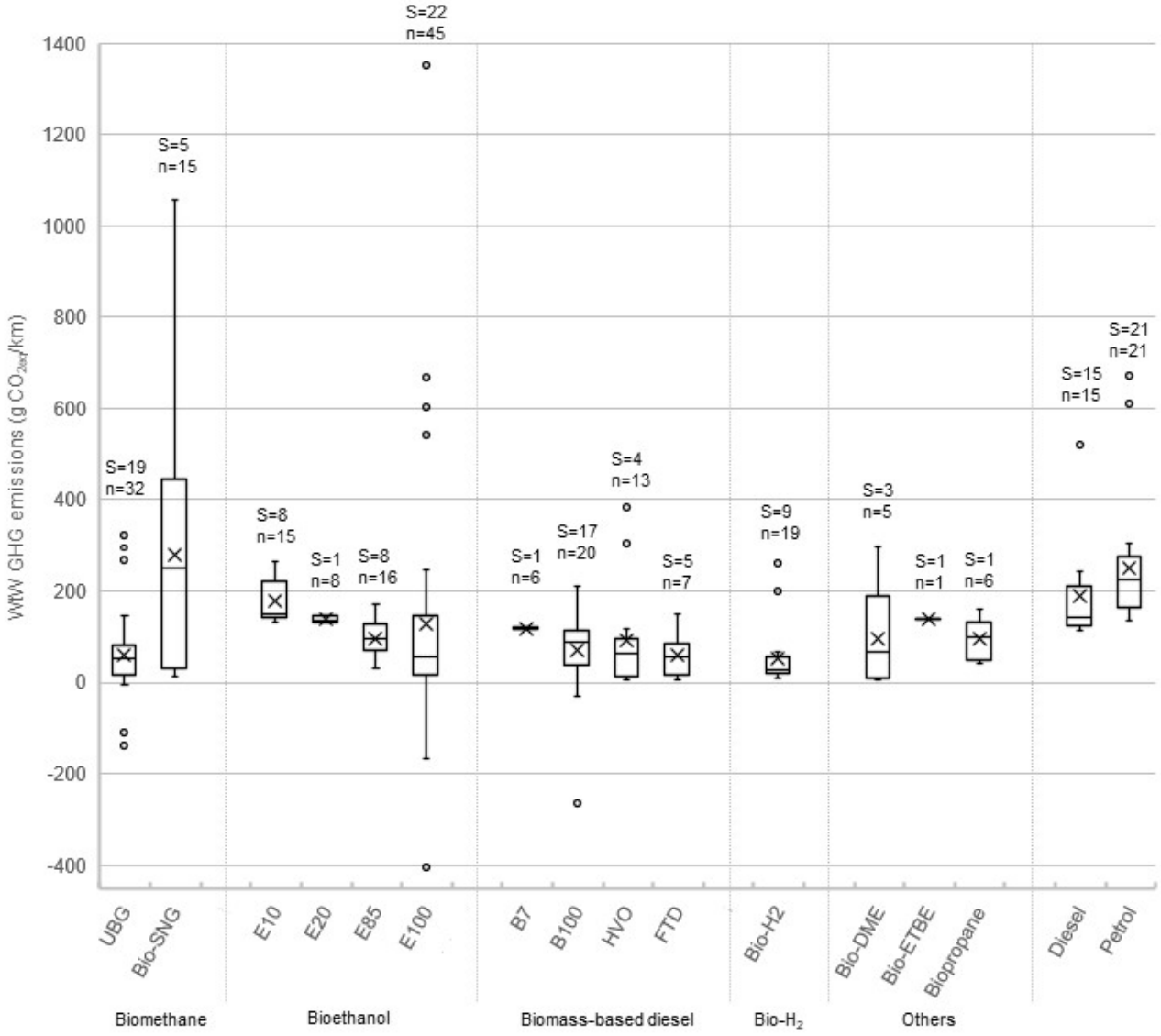


Figure 9: WTW GHG emissions (g CO_{2eq}/km) values grouped for type of biofuel (neat or blended). S = number of studies; n = number of results; Bio-H_2 = biohydrogen; Bio-SNG = bio-synthetic natural gas; DME = dimethyl ether; ETBE = ethyl tert-butyl ether; EXY = XY% of bioethanol + (100-XY)% of petrol; BXY = XY% of FAME + (100-XY)% of diesel; FTD = Fischer-Tropsch diesel; HVO = hydrotreated vegetable oil.

4.5. Interpretation

In the present paragraph the results are explored and analysed.37/86 LCAs performed a sensitivity analysis on various assumptions, e.g. the choices for solving multifunctionality, methane leakage, electricity source, transport distance, ILUC, , the time horizon of the global warming potential (GWP), , etc. 20/86 studies performed an uncertainty analysis and 12/20 applied the Monte Carlo analysis. The uncertainties of the results (ranges of results) were included in Figure 10, whereas the results coming from sensitivity analyses were not included. Therefore, the pool of results solely comprises those related to assumptions and parameters considered as the most common by the authors.

Figure 10 suggests that biofuels generally perform better than diesel and petrol, except for bio-SNG. The results for this biofuel are somewhat biased, as 9/16 estimates are from the same study that used various unconventional assumptions, in particular: a) gasification of feedstocks with high moisture content, leading

to a low process efficiency b) inclusion of ILUC. This explains the high results for bio-SNG. In fact, the mean of the results for the other biofuels is less than those for diesel and petrol. However, there is not a clear rank between the six considered families. To formulate some indications, only the most represented fuels should be taken into account. In fact, the more the number of authors included in the samples, the more the robustness of the interpretation. For this reason, fuels to be discussed are upgraded biogas (whose results were retrieved from 19 studies), E10 (8), E85 (8), E100 (22), B100 (17), bio-H2 (9), diesel (15), and petrol (21). The GHG savings for the chosen biofuels can be calculated taking diesel as the less impacting fossil comparator, and using the mean of each sample of results, after removing the outliers. Bio-H_2 results in -70% of CO_{2eq}/km compared to diesel, followed by upgraded biogas (-63%), E100 (-54%), B100 (-41%), E85 (-36%), and E10 (-7%). These positive results are counterbalanced by not negligible uncertainties. The range of results is particularly wide for E100 (from -167 to 247 g CO_{2eq}/km) and B100 (from -30 to 212 gCO_{2eq}/km). Many variables, inside and among the LCAs, can increase or decrease the environmental impact for biofuel production and use [14,16,83,98,145,164]:

- Agricultural phase: nature of biomass feedstock, climate, biomass yield, fertiliser application rates, estimation of N_2O emissions from soil, DLUC, ILUC, data quality and uncertainty.
- Conversion from biomass to biofuel: scale of production, efficiency of the process, source of processing energy, data quality and uncertainty.
- Use phase: type of powertrain, type of vehicle, flue gas emission control technologies, driving cycle, considered tailpipe emissions, vehicle lifespan, data quality and uncertainty.
- LCA: system boundaries, assumptions on biogenic carbon, carbon debt, functional unit, time horizon, modelling principle, methods to account for coproducts, kind of substituted product, impact categories and indicators, LCA software packages (LCI databases, impact assessment methods, how the recycle and the coproducts are modelled).

The use of bio-hydrogen in FCEVs seems promising, although one should keep in mind that the production of a FCEV is responsible for more GHG emissions than the production and end-of-life of an ICEV (from 30 to 58 g CO_{2eq}, as seen in Section 4.2.2). It is interesting to point out that the impacts of bioethanol decrease when the percentage in the blend increases. Another interesting indication is that when the use of a biofuel guarantees an emission credit (negative impact) the feedstock is always a second-generation one: manure, poplar, miscanthus, forest residues, wheat straw, lignocellulosic waste, biowaste, carinata, and ley crops. A negative impact implies that the method of substitution was used for co-products (see Section 4.2.6). Looking at the disaggregated data accessible in the supplementary material and exploiting the sufficient number of values concerning UBG (32 results) and E100 (45) it was tried to find if second generation feedstocks guarantee better results than first-generation ones. The review collected 9 results for first generation UBG, 16 for second generation UBG, 16 for first generation E100 and 25 for second generation E100. Third generation biofuels were excluded from this last comparison because the collected values were only 3 for UBG and 1 for E100. Considering also the outliers of Figure 10, it was found that second generation feedstocks averagely perform better than first generation feedstocks for E100 (59 g CO_{2eq}/km vs. 265 g CO_{2eq}/km), but similarly for UBG (61 g CO_{2eq}/km vs. 58 g CO_{2eq}/km).

It would be erroneous to consider these box plots as a real representation of the hierarchy among biofuels, but the effort made gives a valid and comprehensive idea of the impacts of the use of biofuels on the climate change. For what concerns the other environmental categories, it was evaluated how biofuels

behave compared to conventional fuels among the reviewed LCAs. A selection of the most studied ICs, plus water use, is reported in Table 5. It can be stated that the use of biofuels indirectly consumes less abiotic resources, fossil resources, and ozone layer than conventional fuels. For the other 10 impact categories reported in Table 5, biofuels have a worse or similar performance than fossil fuels.

Table 5: Environmental performance of biofuels compared to fossil fuels (petrol, diesel, natural gas) on a WTW basis for non-GHG-related impact categories. Red arrows mean higher impact for biofuels, green arrows mean lower impact for biofuels, question marks mean a mixed picture. The most appropriate symbol was chosen basing on the results of the reviewed LCAs that reported a comparison with fossil fuels.

Biofuel	Abiotic depletion	Acidification	Ecotoxicity	Energy use	Eutrophication	Freshwater eutrophication	Marine and terrestrial eutrophication	Fossil resource depletion	Human toxicity	Land use	Ozone depletion	Particulate matter formation	Photochemical oxidant formation	Water consumption
Bioethanol	?	↑	↑	?	↑	↑	↑	↓	↑	↑	↓	?	?	↑
Bio-H_2		?		?	?							↑		
Bio-SNG		↑			↑							↑		
FAME	?	↑		?	↑	?	?	↓	↑	↑	?	?	↑	?
FT diesel	↓	?		?	?						↓	?	↑	
Upgraded biogas	↓	↑	?	?		?	?	↓	?	↑	↓	?	?	↑

4.6. Limitations of the LCA review and assessment of bias

In some cases, the results were approximately inferred from a chart. The variability in data, method and accuracy of each study included in Figure 10 limits the validity of the comparisons that arise from the graph. However, the grouping of all results has the advantage of providing the entire range of possibilities. Such an approach can lead to robust conclusions that go beyond the uncertainty and bias of a single study (e.g. based on the reviewed literature, biohydrogen always causes less GHG emissions than petrol and diesel). For this reason, bias within studies were not assessed. The bias regarding the search of LCAs were minimised repeating the search in three different databases (Section 4.1). The potential bias regarding the selection of LCAs were reduced because two persons worked on this task. Although the search in titles, abstracts and keywords was done carefully, some studies may not have been selected due to the erroneous perception that the study was not relevant or compliant to the requested requirements (see Section 4.1). There was no financial conflict of interest that could have influenced the selection of studies.

5. Discussion

From section 2 it became clear that a variety of biofuels currently exist and are new feedstocks, pathways and fuels keep emerging. Each fuel can be produced from different feedstocks and sometimes even via different technologies, leading to hundreds of potential production pathways [70]. The classification and terminology of fuels and feedstocks, however, are often ambiguous and unanimous. Words as “third generation”, “fourth generation”, “biomethane”, “synthetic fuels” and “renewable diesel” are used frequently, but in an inconsistent manner. Therefore, the importance of the work of Ridjan et al. 2016 on the terminology of liquid and gaseous renewable fuels is stressed here [64]. Their work, however, is not yet

finished and standardisation of terminology and classification remains a topic to be worked on. Until more harmonisation is reached, it is of utmost importance that studies on biofuels explicitly explain what is meant by the different terms.

Section 3.1 examined the current European legislation. The EU is gradually increasing the targets regarding the decrease in GHG emissions, acting both on the WTT and TTW parts of the life cycle of an LDV. Transport biofuels produced in plants which started operation after January 2021 shall guarantee a 65% of GHG savings [19]. Average tailpipe CO2 emissions of passenger cars shall be reduced from 95 g/km in 2021 to 59 g/km in 2030 [110]. The EU sustainability criteria, and the resulting certifications, ensure that the feedstocks production does not take place on high-biodiversity and high-carbon stock lands. In this way, the risk of negative DLUC is mitigated.

Regarding consumption and production, a much more homogeneous picture has been found. Over 95% of the biofuels consumed in the EU in 2017 was biodiesel, HVO or bioethanol. Very similar figures were presented for biofuels production and the feedstocks used. In fact, there is still a large share of first-generation feedstocks being produced, even though legislation and research has shifted the focus to waste streams and algae. This shows that there are still economic and legislative barriers to close the gap between the actual production and the technical potential. An example of such a barrier is the double counting rule of RED towards advanced feedstocks. The purpose of this rule is to push for higher production volumes of advanced biofuels, but one of the results is that biofuels production volumes have been stagnating, as the advanced fuels displaced twice the amount of first-generation fuels. Biohydrogen is the biofuel family with the highest average GHG savings (Section 4.4) and the interest of LCA scientists is often addressed to it (Figure 7). Besides the production of bio-H2 still being at a demonstrative scale, the diffusion of bio-H2 also depends on the development of fuel cell electric vehicles (FCEVs). FCEVs are currently sold on the market but are still a niche in the transport sector [57]. The technologies for hydrogen are still in an early commercial stage [165]. The high costs of fuel and vehicle, combined with the lack of refuelling infrastructure, are the main obstacles to the widespread diffusion of this technology [66]. Another biofuel that seems promising is upgraded biogas. UBG is a fully mature fuel (Table 4), has received a lot of attention in research recently (Figure 7) and has overall the best environmental profile of the biofuels investigated (Table 5) and comes just after biohydrogen in terms of GHG emissions.

To reduce GHG emissions of transport, not only biofuels but also other measures are being applied in Europe, such as efficiency improving, light weighting, car-sharing, traffic management, alternative powertrains, electric vehicles, alternative fossil and renewable fuels [166]. Several studies claim that electric mobility, including battery electric vehicles, has more potential than biofuels to reduce the impacts of a vehicle during its life cycle [22,167–169]. An electric engine has high efficiency (up to 95%), while an internal combustion engine reaches 40%, depending on conditions [170]. However, the environmental effects of an EV are highly dependent on the electricity mix of the country [171]. Nevertheless, a decarbonization of the European electricity mix is in progress, because in 2016 the 86% of newly installed electricity power plants were from renewable sources [165]. Some residual constraints (i.e. limited range, affordability, and lack of recharging points) still limit the widespread diffusion of electric vehicles, but recent improvements in all such aspects are very promising. Electrically-chargeable vehicles still amount only to 0.2% of the passenger car fleet [57]. In the long term, however, the mentioned constraints will be probably eliminated. Until that moment, biofuels can be a promising alternative to conventional fuels.

Nevertheless, biofuels do not appear as a definitive solution to completely displace fossil fuel used in transport, due to several concerns regarding their environmental direct and indirect effects. The use of biofuels can reduce the GHG emissions but can also increase other environmental impacts (see Table 5), including land use and water consumption. Even the reduction of GHG emissions is not always certain, because the LCAs rarely quantify the impact of LUC. Indirect land use change, as explained in Section 3.1, is a central problem inside the discussion about biofuels. RED II provides three provisional values for the estimation of ILUC for non-advanced feedstocks: 12 g CO2eq/MJ for starch-rich crops, 13 g CO2eq/MJ for sugar crops, and 55 g CO2eq/MJ for oil crops. However, as reported in Section 4.3.2, the literature suggests a broader range of values, especially for oil crops. Johnson in 2016 reported that the leading estimates of LUC/ILUC for palm oil and soybean oil were, respectively, 44-231 g CO2eq/MJ and 29.1-198 g CO2eq/MJ [79]. ILUC alone can negate the reduction of GHGs achieved by the use of bioenergy [145], as reported by two studies cited in Section 4.3.2. Another reviewed LCA, Tonini et al., reported that LUC emissions overwhelm the GHG savings if biofuels are produced from annual crops and residues for feed [172]. Other documents stated that the ILUC linked to the production of palm oil causes GHG emissions that alone exceed the complete life-cycle emissions of diesel [116,118,173]. Since it was proven that ILUC emissions could have the same importance as the direct emissions, it is recommended to include ILUC emissions (when applicable), trying to use the most updated emission factors. Currently, first generation biofuels dominate the energy crop mix (see Section 3.3). Summing rapeseed, palm, soybean and sunflower, almost 70% of the feedstock used for FAME and HVO was first generation in 2018 [91]. Analogously, bioethanol was almost totally produced from cereals and sugar crops [91,106]. New generation/advanced feedstocks (such as lignocellulosic materials, UCOs, etc.) are very promising, but their limited availability, also caused by geographical dispersion [174] and competing purposes, represents a constraint to the complete replacement of fossil fuels. However, if high ILUC-risk feedstocks are banned, new generation biofuels could significantly reduce GHG emissions in the transport sector, displacing large amounts of petroleum-based fuels. The European legislation is pushing in that direction [19,120].

6. Conclusions and recommendations

- A literature review was performed to understand the state of biofuels in Europe for road transport and their potential to contrast the climate change. Based on the physical state and on the relevance on the market, biofuels can be grouped in six categories: biodiesel, HVO, bioethanol, synthetic liquid biofuels, biomethane, and other biofuels. Biodiesel, HVO, bioethanol, and upgraded biogas are most relevant biofuels in Europe. A great variety of production techniques exist, allowing to convert to biofuel any kind of biomass.
- EU regulation is pushing for more sustainable biofuels, by setting increasing GHG emissions savings targets for production and decreasing tailpipe emission targets for passenger cars. After a stagnation from 2012 to 2016, the consumption of biofuels in Europe has grown during 2017 and 2018. 4.5% energy share in road transport and non-road mobile machinery was supplied by biofuels. France, Germany, Spain, United Kingdom and Italy accounted for about 70% of the EU consumption of biofuels in 2018 [105].
- A systematic review of the LCA studies about biofuels for LDVs was performed. The main assumptions and results of 86 studies were summarised and commented. The use of biofuels can averagely lower the WTW emissions of CO2eq/km, comparing to diesel and petrol. Biohydrogen

and upgraded biomethane were identified as the most promising biofuels in terms of greenhouse gas emissions savings, although the market diffusion of the first is hindered by technical and economic barriers. The convenience of biofuels for climate change is questioned by the uncertainty surrounding the land use change effects, however rarely assessed. The use of biofuel often leads to higher impacts on non-GHG-related impact categories, compared with fossil fuels.

- Until electric mobility has become mainstream, biofuels can be a promising alternative to fossil fuels, provided they are produced from advanced feedstocks. In particular, feedstocks that lead to land use change should be avoided, as this process alone could lead to the same amount of GHG emissions as fossil fuels. To move towards new production technologies, great efforts and investments are needed. A more solid knowledge of the real effects of the use of biofuels on a global scale is needed. The methods and models used in the LCAs must be improved. Further research on the effects of land use change and carbon debt are required. The development of a common sectorial method, following the same logic of the "Product environmental footprint category rules" [175], could help to reduce the number of variables among the LCAs.

Declarations of interest: none.

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Appendix

Table A.1: Biofuels consumption for transport in the EU in 2018 (in ktoe). Modified from [105].

Country	Bioethanol	Biodiesel	Biogas fuel	Total consumption	Of which advanced biofuel	% compliant with Articles 17 and 18 of Directive 2009/28/EC
France	586,0	2.812,0	-	3.398,0	21,3	100,0%
Germany	756,0	1.929,0	34,0	2.719,0	n.a.	99,2%
Spain	160,0	1.568,0	-	1.728,0	2,4	100,0%
Sweden	96,6	1.342,6	118,0	1.557,2	n.a.	99,7%
United Kingdom	376,8	897,1	0,4	1.274,3	n.a.	100,0%
Italy	32,6	1.217,0	0,1	1.249,7	65,0	100,0%
Poland	173,0	770,0	-	943,0	3,0	100,0%
Netherlands	170,7	330,5	7,2	508,4	n.a.	99,5%
Austria	57,9	423,1	0,3	481,3	1,4	97,1%
Belgium	93,6	381,0	-	474,6	5,0	100,0%
Finland	80,7	315,6	0,3	396,7	n.a.	100,0%
Czechia	61,3	247,4	-	308,7	-	100,0%
Romania	91,1	206,2	-	297,2	-	100,0%

Denmark	-	286,0	0,3	286,3	n.a.	85,2%
Portugal	7,6	272,3	-	279,9	-	100,0%
Greece	-	169,0	-	169,0	-	100,0%
Bulgaria	26,7	139,6	-	166,2	-	100,0%
Ireland	27,3	127,0	-	154,2	4,1	100,0%
Slovakia	19,6	129,9	-	149,5	-	100,0%
Hungary	40,0	108,4	-	148,4	-	100,0%
Luxembourg	10,1	109,5	-	119,6	-	100,0%
Lithuania	8,0	69,8	-	77,8	-	100,0%
Slovenia	8,6	34,7	-	43,3	-	100,0%
Latvia	7,9	1,4	-	9,3	-	100,0%
Cyprus	-	9,0	-	9,0	-	100,0%
Malta	-	9,0	-	9,0	-	100,0%
Estonia	1,0	-	-	1,0	-	100,0%
Croatia	0,2	0,3	-	0,5	-	100,0%
Total EU28	2.892,9	13.905,6	160,6	16.959,1	n.a.	95,5%

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