AMF Annex 58 /
IEA Bioenergy Task 41 Project 10

A Report from the Advanced Motor Fuels TCP and IEA Bioenergy TCP

Technology Collaboration Programme on Advanced Motor Fuels

IEA Bioenergy
Technology Collaboration Programme



The Role of Renewable Transport Fuels in Decarbonizing Road Transport

Production Technologies and Costs

Adam Brown
Energy Insights Ltd

Mahmood Ebadian
Jack Saddler
University of British Columbia

Nils-Olof Nylund
Päivi Aakko-Saksa
VTT Technical Research Centre of Finland Ltd

Lars Waldheim
Waldheim Consulting

Edited by Dina Bacovsky
BEST — Bioenergy and Sustainable Technologies GmbH

November 2020

Summary / Abstract

*This report constitutes Part 2 of the report on "**The Role of Renewable Transport Fuels in Decarbonizing Road Transport**". In this report the term decarbonization includes all options to reduce GHG emissions and make road transport cleaner, including low(-fossil)-carbon energy carriers such as biofuels, e-fuels, and renewable electricity. This part of the report deals with all aspects of the production and use of renewable transport fuels.*

Since the early 2000s, renewable transport fuels have been introduced in many countries around the globe. Biomass is a renewable source of carbon and its use for bioenergy and biofuels contributes to a circular economy. Biofuel production not only produces biofuels but also valuable by-products, and provides value to the local biomass producers.

While our assessment of the development of the transport sector in selected countries shows clearly that the required full decarbonization can only be reached with a combination of biofuels, electric vehicles and eventually also e-fuels, the question arises whether there will be sufficient renewable transport fuels available to support national and global needs. A large number of different renewable transport fuels exists, produced from a variety of feedstocks through a range of different production technologies. Some of these fuels are compatible with existing engines, others have to be used in low blends with fossil fuels or in dedicated engines. The multitude of options makes it difficult for policy makers to decide which fuel options to go for to decarbonize their transport sectors.

Low-carbon fuel technologies and their development status

Low-carbon transport fuels can be produced from:

- biogenic feedstocks or biogenic fraction of wastes ("biofuels")
- energy and carbon contained in fossil wastes and residue streams or the fossil fraction of such materials ("e.g. recycled carbon fuels")
- energy from other renewable sources, sometimes in combination with carbon atoms from biogenic and fossil sources (CCU) ("renewable fuels")

The technology readiness levels (TRL) of the production technologies for these fuels vary, as depicted in the figure on the following page.

Technologies for the production of **established biofuels** such as ethanol from sugar and starch crops, biodiesel from triglycerides and lipids, hydrogenated triglycerides and lipids, and biomethane from upgrading of anaerobic digestion biogas are at TRL9.

	Raw material	Technology	Fuel	Technology Readiness Level (TRL)								
				1	2	3	4	5	6	7	8	9
Established biofuels	**Sugar**	Fermentation	Ethanol									
	Starch											
	Vegetable oils & lipid waste	Transesterification	FAME/Biodiesel									
		Hydrotreatment	Drop-in hydrocarbons									
	Crops, sludges, manures etc.	AD biogas upgrading	Biomethane									
Emerging Biofuels	**Raw material**	**Technology**	**Fuel**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Lignocellulosic feedstocks	Enzymatic hydrolysis + fermentation	Ethanol									
			Other alcohols									
	Lignocellulosics' biogenic fraction of RDF etc., non-lignocellulosic biomass or by-products	Gasification + fermentation	Ethanol									
		Gasification + catalytic synthesis	Drop-in hydrocarbons, Alcohols, Biomethane									
	Lignocellulosics' biogenic fraction of RDF etc., non-lignocellulosic biomass or by-products	Pyrolysis + upgrading	Drop-in hydrocarbons									
		HTL + upgrading	Drop-in hydrocarbons									
	Lignin from lignocellulosic ethanol or forestry liquors	HTL and/or chem. treatment + upgrading	Drop-in hydrocarbons									
	Sugars from sugar and starch crops or lignocellulosic	Fermentation	Drop-in hydrocarbons									
			Various alcohols									
		Chem. conversion	Drop-in hydrocarbons									
	Non-LC biomass fractions or by-products	Various	Various									
Recycle Carbon Fuels	**Supply of fossil waste or by-product gases**	**Technology**	**Fuel**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Steel industry & chemical industry off-gases	Fermentation	Ethanol									
		Catalytic synthesis	Methanol									
			Methane									
	Wastes, waste plastics, non-bio fraction of RDF	Gasification + catalytic synthesis or fermentation	Drop-in hydrocarbons, Alcohols, Biomethane									
	Waste plastic fraction	Pyrolysis + distillation	Drop-in hydrocarbons									
E-fuels	**Supply of H2**	**Technology**	**Fuel**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	RE electricity	Electrolysis	Hydrogen									
		Electrolysis and carbon capture + catalytic synthesis	Methanol									
			Methane									
			Drop-in hydrocarbons									

Overview of technology pathways and their technology readiness level (TRL)

Emerging biofuel pathways include ethanol from lignocellulosic feedstocks, gasification-derived biofuels, pyrolysis-derived intermediates, hydrothermal liquefaction-derived intermediates, lignin-derived intermediates, sugars to biofuels, and biofuels derived from non-lignocellulosic biomass such as microalgae. TRLs for these technologies range from 3 to 8.

Recycled carbon fuels include ethanol, methanol and methane produced from industry off-gases, and fuels derived from the gasification or pyrolysis of non-biogenic wastes or fractions of wastes, with TRLs ranging from 4 to 9.

E-fuels include hydrogen, methanol, methane and Fischer-Tropsch liquids. While the production of hydrogen through electrolysis is at TRL9, the other pathways are at TRL 4-6.

Terminology for different low-carbon fuels is not consistent globally. In the EU fuels are classified by feedstock, in the USA by pathway, and in Brazil by the carbon intensity of the fuel. In particular, the term advanced biofuel has different meanings in different jurisdictions.

Terminology used in this report

In this report a distinction is being made between **established biofuel pathways** and **emerging biofuel pathways**. This is to avoid terms like first and second generation, 1G, 2G, conventional and advanced, as these terms have no homogeneous definition and are used differently in different regions and jurisdictions. Further fuel types mentioned in the report include recycled carbon fuels and e-fuels. Further descriptions of these categories are provided in **Figure 1** and the explanatory text below.

The same figure also provides the linkage between fuel production pathway, i.e. feedstock and conversion technology used, and the chemical nature of the resulting fuel. When applied in engines it is the chemical composition of the fuel that matters, not the feedstock. Thus, some fuels are grouped, e.g. **FT-liquids** and **HVO**[1] into **drop-in hydrocarbons**[2].

The linkage between these fuels and the marketed fuel qualities is provided in

Table 6, which also describes the applicability of these fuel qualities in different engines.

[1] *HEFA (Hydroprocessed Esters and Fatty Acids), also called HVO (Hydrotreated Vegetable Oil), is a renewable diesel fuel that can be produced from a wide array of vegetable oils and fats. The term HEFA or HVO is used collectively for these biogenic hydrocarbon-based renewable biofuels. HVO is free of aromatics and sulfur and has a high cetane number.*

[2] "Drop-in" biofuels are defined as liquid hydrocarbons that are oxygen-free and functionally equivalent to petroleum transportation fuel blendstocks.

Availability and costs of sustainable bioenergy feedstocks for biofuels production

The theoretical availability and cost modelling indicate that large volumes of sustainable feedstock could be made available for biofuels production, sufficient to meet likely future demand as indicated in low carbon scenarios. Most of the material necessary could be supplied from wastes and residues, and from sustainable forestry practices. Agriculture can also be an important source of raw materials, with feedstocks produced in ways which complement traditional agricultural production through co-cropping and through use of less productive land.

Estimates of the potential available biomass and other uses vary significantly in the literature. While the theoretical potential is high, the economic availability can vary greatly, depending on numerous factors including yield and regional parameters (e.g. location and size of crop/forest lands, local infrastructure, etc.). There is a wide range of biomass availability globally, from as low as 95 Exajoule (EJ)/year to as high as 350 EJ/year.

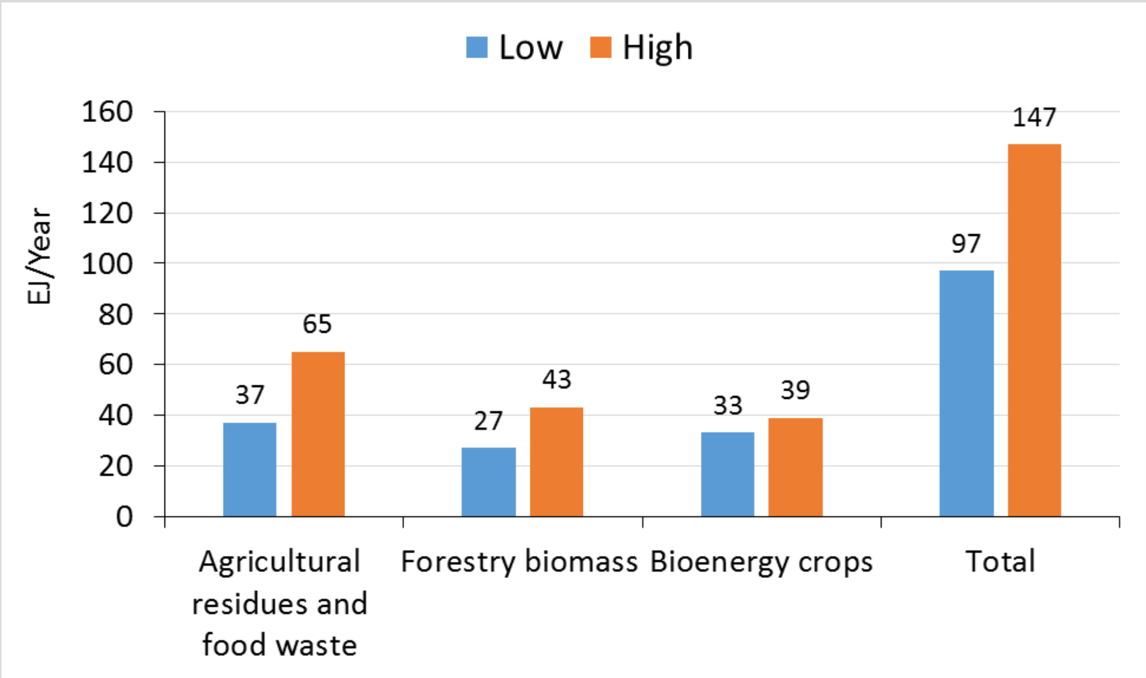
National studies indicate that much of the raw material could be produced and delivered to users at costs of between 3 - 6 EUR/GJ. More information from real projects is needed to test the costs of procuring suitable feedstock in the real world.

The overall biomass cost is highly case dependent and successful management of biomass supply chains will be critical if future investments in biofuels are to be realized. Despite efforts to reduce the cost of biomass and associated logistics, it is anticipated that increasing competition for commercial quantities of biomass will result in an increase in the price of the biomass feedstock.

National and regional assessments are very helpful in providing insights into likely long-term availability and costs of feedstocks for bioenergy production, including for the production of advanced biofuels. However, in order to be useful for estimating long term global availability such assessments need to be done in a very transparent way, with clear classification of the various resources and of the assumptions made in defining how much material could in practice be available, and around the sustainability considerations applied.

A useful step in harmonizing such approaches would be the development of some best practice guidelines for such studies, including some standardization and rationalization of the classification of the various potential feedstocks, and of the sustainability constraints which are applied. Such measures could facilitate the development of more consistent resource estimates, which could be more easily compiled to give a global estimate, at least for key producer and user regions.

As shown in the figure on the next page, IRENA estimates the global biomass energy supply potential in 2030 to be in the range of 97 to 147 EJ/year. Feedstocks considered include energy crops, agricultural residues, processing residues, animal and food wastes, fuel wood, forest biomass and wood waste. Largest supply potentials stem from Asia, Europe and North America. Growth in biomass supply potential will be (among other factors) supported by increased plantation areas both for food/feed crops as well as for forests, higher yields of energy crops, and higher recovery of agricultural and processing residues.



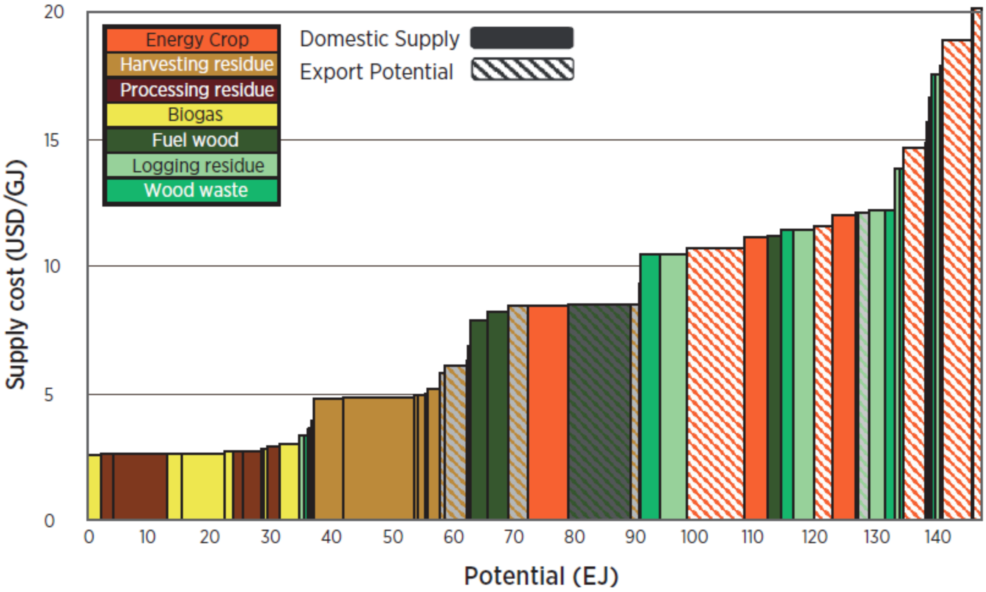
Potential global biomass supply in 2030 (Adapted from IRENA, 2014)

Domestic biomass resources can be classified into three supply cost groups:

- < USD 5 per GJ: processing residues and wastes
- USD 5-8 per GJ: harvesting residues
- > USD 8 per GJ: bioenergy crops and fuel wood

As depicted in the figure on the next page, the average, global cost of biomass is about USD 8.3 per GJ, with the cost of domestic biomass ranging from as low as USD 3 per GJ in Africa (agricultural processing residues) to as high at USD 17 per GJ for bioenergy crops in more developed parts of the world. The amount of exportable biomass available in regions with surplus biomass is estimated to be about 26% of the total global supply potential. However, the costs associated with transporting this biomass to different world regions are estimated to add an average of USD 3 per GJ to domestic prices.

The overall biomass cost is highly case dependent and successful management of biomass supply chains will be critical if future investments in bioenergy and biofuels are to be realized. Despite efforts to reduce the cost of biomass and associated logistics, it is anticipated that increasing competition for commercial quantities of biomass will result in an increase in the price of the biomass feedstock.

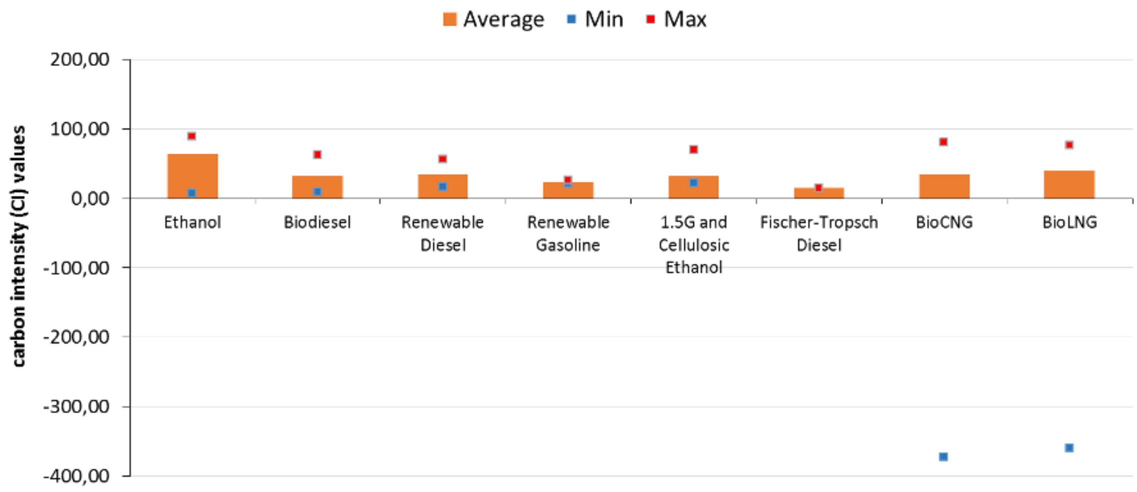


Projected annual global supply for primary biomass in 2030

GHG emissions of emerging biofuel pathways

Current legislation in the USA and the European Union require advanced biofuels to show at least 50% / 65% reduction in GHG emissions respectively, as compared to their fossil fuel equivalents. The carbon intensity of a fuel is measured in gCO_2e/MJ using Life Cycle Assessment (LCA) and represents the GHG emissions emitted across the full life cycle of a product system, from feedstock acquisition to production, use, and final disposition. Carbon intensity of gasoline and diesel is about 95 gCO_{2e}/MJ.

Emerging biofuels, termed advanced by either USA or EU legislation, do not automatically have lower carbon intensity values than those of established biofuels. However, among the various pathways that have been certified under California Low Carbon Fuel Standard (LCFS) program, the average carbon intensity values of advanced biofuels are typically, sometimes significantly, lower than those of established biofuels, see figure below for details. The current average CI values of biofuels (both established and emerging pathways) provided to California range from 15 to 65 gCO_{2e}/MJ, and can also be negative when obtaining credits for avoided GHG emissions from waste disposal or if combined with CCS.



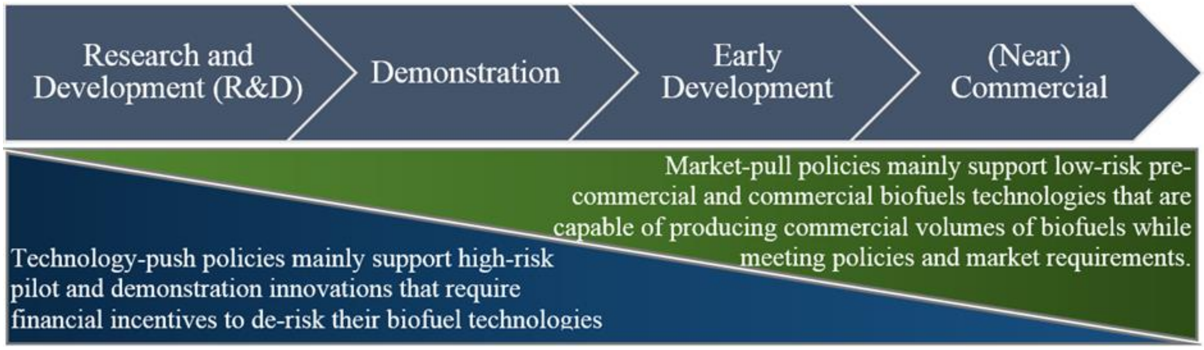
Minimum, average, and maximum carbon intensity (CI) values of some of the fuel pathways certified under California LCFS program in 2019

The location/region where the biofuel production facility is located will be a key component of the final carbon intensity of the fuel. This is due to factors such as access to low carbon intensity energy sources for heat and power, the potential to co-locate with other biofuel plants or oil refineries to develop efficient biofuel production and supply chains, the type of biofuels and co-products produced, the type of feedstock and associated logistics, land type used for crop/biomass cultivation and agronomic practices, the local regulations on the use of feedstock, and carbon accounting mechanisms for biomass.

As LCFS-type policies become more common in increasing numbers of jurisdictions, the carbon intensity of current and emerging biofuels is expected to decrease.

Role of policy on production and use of emerging biofuels

Policies have been and will continue to be essential to foster the growth of the advanced biofuels used to decarbonize transport, particularly long-distance transport. Policies used include blending mandates, excise tax reductions or exemptions, renewable or low carbon fuel standards, as well as a variety of fiscal incentives and public financing mechanisms. Countries that use a mixture of market-pull and technology-push policy instruments have been most successful at increasing biofuels production and use and also at developing and deploying less mature emerging biofuels production technologies.



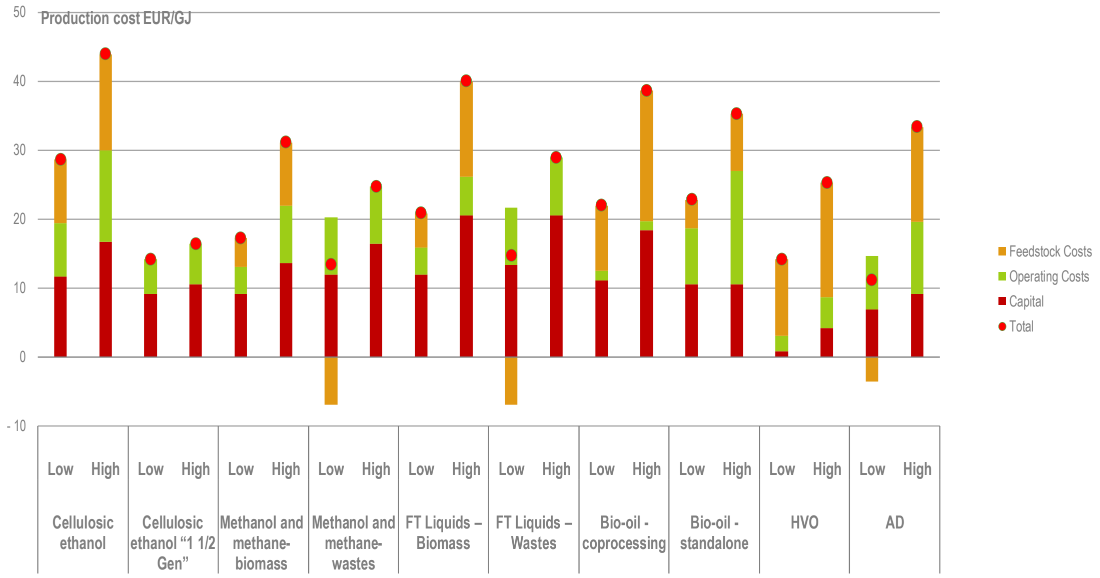
Technology-push and market-pull biofuel policies.

So far, most of the policies used to promote transport decarbonization have focused on road transport. Other transport sectors, such as rail, aviation and shipping, have, until recently, received comparably less policy attention despite being large energy consumers and GHG emitters. However, transport policies and industry efforts are increasingly focused on decarbonizing long-haul transport sectors (i.e., road, rail, aviation and shipping), where electrification is much more challenging.

While the production and use of transport biofuels has more than doubled over the last decade, progress in expanding biofuels production remains well below the levels required to decarbonize transport significantly. Several factors continue to impact the effectiveness of biofuels policies such as relatively low petroleum and fossil fuel prices, uncertainty about future policy and funding programs to support conventional and advanced biofuels, the inconsistent regulation of global trade of biofuels and continuing concerns related to food security, land use change and overall sustainability.

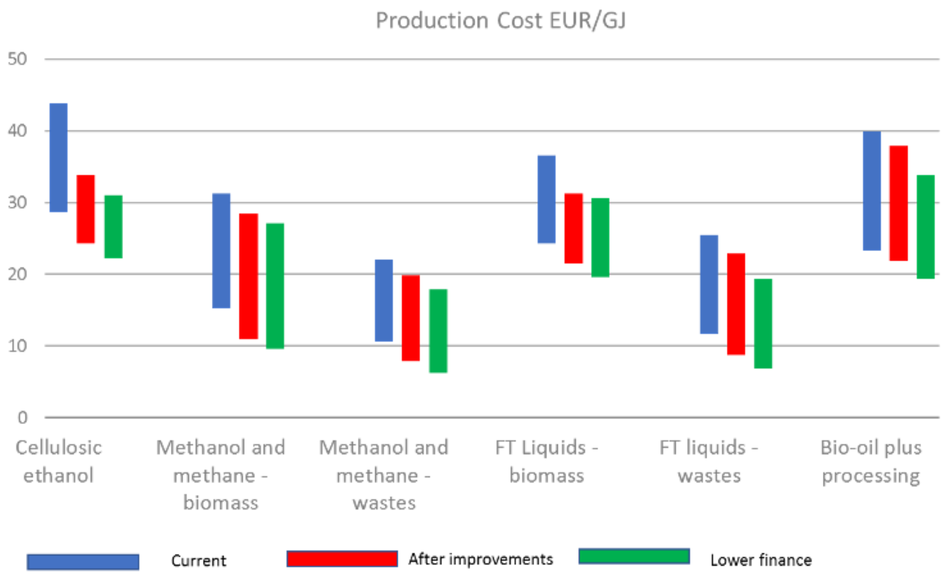
The likely costs of emerging biofuels production and the scope for cost reduction

The costs of producing emerging biofuels have been assessed in a recent IEA Bioenergy study. The costs are currently significantly higher than the current costs of fossil fuel equivalents, see figure below.



Summary of current cost ranges. Note: "Cellulosic ethanol", 1.5 Generation most frequently refers to the production of cellulosic (such as corn fiber) ethanol integrated into a corn-based ethanol plant.

There is significant potential for reducing the costs of the assessed range of emerging biofuels. In order to achieve these, projects must first demonstrate in practice that the current production objectives in terms of reliable production at high availability and efficiency can be achieved consistently. The reductions will only then be achieved if there are opportunities to build a significant number of further generations of plants which will allow experience to accumulate and provide the basis for learning, and for growing confidence in the technologies. The figure on the next page shows possible future emerging biofuel production cost ranges, after improvements in the process and after gaining access to capital at lower cost.



Potential costs of biofuels production after reductions

Large scale deployment will depend on continuing policy support. First, industry will need support during the demonstration and risky and costly early commercialization of the technologies, so as to bridge the "valley of death". And then, continuing strong support will be needed to offset the differences between biofuels and fossil fuel prices, and to incentivize low carbon transport fuels.

While the costs of the emerging biofuels and other fuels discussed above are an important factor, a broader range of issues also need to be considered when comparing these options and also when looking at other low-carbon options. These include the extent to which they can directly replace fossil fuels, the costs of any modifications or of distribution costs associated with fuels, the likely availability of feedstocks and the life-cycle GHG emissions associated with particular routes. The overall consideration of the future for emerging biofuels need to be seen in the context of these other factors, and based on an analysis of full system costs, feedstock availability and life-cycle GHG emissions.

Compatibility of fuels with existing engines

The compatibility of fuels with fuel infrastructure and vehicles includes the aspects material compatibility, tolerance, vehicle compatibility and vehicle compliance, i.e. fulfilment of all regulatory requirements concerning pollutant emissions and safe vehicle use. Biofuels can be used in low blends, as drop-in fuels with up to 100% substitution, or as special fuels in dedicated or adapted engines. The table on the next page provides an overview on fuels and their applicability in engines.

Application of transport fuels

Fuel	Application in road transport
Ethanol[3]	Gasoline blends (E5, E10, E85 in FFVs), stoichiometry and materials issues constitute blending walls in conventional vehicles Additive treated ED 95 for diesel-type engines (commercial), potentially also engines with assisted ignition (spark-plug, glow-plug, dual-fuel)
Methanol	Low-level blends with gasoline Heavy-duty engines as in the case of ethanol (additive treated fuel, engines with assisted ignition)
Various higher alcohols	E.g. butanol in gasoline blends
Ethers	E.g. MTBE (from methanol) and ETBE (from ethanol) in gasoline blends, preferred by the auto manufacturers over ethanol or methanol as such; blending wall stems from stoichiometry
FAME/Biodiesel	Diesel blends (B7, B10, B20, B30), neat B100 Neat B100 typically requires some vehicle modifications
Drop-in hydrocarbons	Gasoline-type components with limited octane for blending components Paraffinic HVO and Fischer-Tropsch diesel, drop-in, up to 100% substitution
Methane	Passenger cars (mostly bi-fuel methane/gasoline vehicles) Heavy duty vehicles with either mono-fuel or dual-fuel technology On-board storage either as compressed biogas (CBG) for LD vehicles or liquefied biogas (LBG) for HD vehicles
	Application in shipping
Biofuels	Various types of bioliquids, including some "biocrudes" less stringent fuel requirements than in the on-road sector
Methane	Mainly dual-fuel engines, fuel storage in liquid form, currently fossil natural gas, bio-methane could replace natural gas
	Application in aviation
Liquid renewable fuels	Current regulation allows up to 50 % renewable components, very stringent certification process, hydrotreatment (HEFA fuels), synthesis and e-fuels potential routes to aviation fuels

[3] Brazil: special case for ethanol, regular gasoline contains 27 % ethanol (E27), also hydrous ethanol (E100) on the market, special vehicles flex-fuel/bi-fuel vehicles combing gasoline/ethanol with methane available

The easiest way to introduce biocomponents is to operate within the framework of existing standards for gasoline and diesel fuel. Typically, standards allow blending of ethanol and FAME biodiesel corresponding up to an energy share 10 - 15 %. Some activities to introduce intermediate ethanol blends (E20, E25) are under way. However, for higher substitution and more substantial decarbonization of transport, complementary actions are needed.

Drop-in type fuels are fully fungible with conventional hydrocarbon fuels and compatible with existing vehicles and fuel infrastructure; no infrastructure or vehicle modifications are needed. Paraffinic renewable diesel fuel, whether from hydrotreatment of oils and fats (HVO) or Fischer Tropsch synthesis, can in principle completely substitute fossil diesel and for most performance criteria is superior to regular diesel.

B100 is not a real drop-in type fuel, as it requires some changes in calibration, engine hardware and maintenance schedules. Notwithstanding, some heavy-duty vehicle manufacturers allow the use of B100 fuel in present-day sophisticated vehicles.

In the case of gasoline, there are no superior renewable hydrocarbon drop-in components, as bio-gasoline hydrocarbon compounds tend to have low octane numbers. New blending components, such as pure hydrocarbons, higher alcohols or ethers, could alleviate this.

Finally, special fuels can be used as such or as high blends in dedicated or adapted engines. Such fuels are, e.g., gaseous fuels (methane, LPG), dimethyl ether (DME) and high concentration alcohol fuels (E85, ED95). These fuels have a merit in chemically simple structure, and in most cases, also inherently clean burning. However, the market introduction of such fuels has to go hand in hand with building up the refueling infrastructure and the vehicle fleet, requiring huge joint efforts.

The world population of natural gas vehicles exceeds 20 million units. Cleaned biogas, biomethane, is a drop-in substitute for natural gas. Ethanol flex-fuel vehicles (FFV) are still offered for the markets in North and South America, but have in practice vanished from the European market. FFVs are a cost-effective way of enabling the use of high concentration ethanol.

Regardless of the method to introduce biofuels, whether low-level blending, drop-in fuels or special fuels for dedicated vehicles, fuel quality, vehicle/fuel compatibility and vehicle compliance have to be maintained. Prerequisites are standards defining and securing fuel properties and vehicles adapted to and certified for the fuels they are using. The fuel is simply not a parameter that can be decoupled from the rest of the system, which comprises of engine, lubricant, exhaust after-treatment system, refueling infrastructure and regulation regarding safety and emissions.

Authors

This report constitutes Part 2 of the final report on the project "**The Role of Renewable Transport Fuels in Decarbonizing Road Transport**", which was initiated and carried out jointly by IEA Bioenergy and the Advanced Motor Fuels (AMF) TCP, with financial support of the European Commission. The project was Task 41 Project 10 under IEA Bioenergy and Annex 58 under AMF.

Participants in this project were the Contracting Parties of IEA Bioenergy from Brazil, the European Commission, Finland, and USA, the Contracting Parties of AMF from China, Finland, Germany, Japan, Sweden, and USA, and AMF Annex 28 and AMF Annex 59.

Further to this part "Production Technologies and Costs", the following report parts have been published:

- Key Strategies in Selected Countries
- Scenarios and Contributions in Selected Countries
- Deployment Barriers and Policy Recommendations
- Summary Report

This report part was written by Lars Waldheim (Waldheim Consulting), Adam Brown (Energy Insights Ltd), Mahmood Ebadian, Jack Saddler (both University of British Columbia), Nils-Olof Nylund and Päivi Aakko-Saksa (both VTT Technical Research Centre of Finland Ltd) and edited by Dina Bacovsky (BEST – Bioenergy and Sustainable Technologies GmbH).

The IEA Bioenergy TCP is an international platform of cooperation working in the framework of the IEA´s Technology Collaboration Programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use.
www.ieabioenergy.com

The Advanced Motor Fuels (AMF) TCP also is an international platform of cooperation working in the framework of the IEA´s Technology Collaboration Programmes. AMF´s vision is that advanced motor fuels, applicable to all modes of transport, significantly contribute to a sustainable society around the globe. AMF brings stakeholders from different continents together for pooling and leveraging of knowledge and research capabilities in the field of advanced and sustainable transport fuels.
www.iea-amf.org

Content

Introduction 9
Low-carbon fuel technologies and their development status 11
Overview of regulated fuel qualities 13
Technology pathways and status... 16
Established biofuel pathways 19
Ethanol from sugar and starch crops 19
Biodiesel from triglycerides and lipids (FAME)... 20
Hydrogenated triglycerides and lipids (HVO) 21
Biomethane from upgrading of anaerobic digestion biogas 23
Emerging biofuel pathways 25
Ethanol from lignocellulosic feedstocks 25
Gasification to synthesis gas and fuel production 26
Pyrolysis to bioliquid intermediates.. 28
Hydrothermal liquefaction (HTL) to bioliquid intermediates.................................... 30
Lignin to bioliquid intermediates 31
Sugars to biofuels.. 32
Non-lignocellulosic biomass 34
Low-carbon transport fuels from fossil waste sources 35
Steel industry & chemical industry off-gases 35
Waste plastics and the fossil fractions of wastes 36
Low-carbon transport fuels from other forms of renewable energy 37
Hydrogen.. 37
E-fuels (aka PtG or PtL) 38
Availability and costs of sustainable bioenergy feedstocks.. 40
Potential feedstocks and costs 41
Municipal Wastes... 42
Processing residues.. 43

Collectable residues 43
Internationally traded fuels 44
Energy crops 44
Price versus costs 45
Future Feedstock Cost 45
Summary – costs 50
Feedstock availability 51
Global estimates 51
Information at national and regional levels 58
Biomass availability and costs in USA 59
EU – S2Biom Study 59
Amounts of feedstock in Brazil 60
Conclusions 61
GHG emissions of emerging biofuels pathways 63
Current GHG emissions of Renewable Transport Fuels 63
Future GHG emissions of Advanced Renewable Transport Fuels 69
Role of policy on production and use of emerging biofuels 72
Current biofuel production volumes 72
Policies to increase biofuels production 76
Summary of the role of biofuels policies 81
The likely costs of emerging biofuels production and the scope for cost reduction 82
Background 82
Current Production Costs 83
Potential for cost reduction 86
Medium term cost reduction 87
Long-term cost reduction 89
Importance of feedstock costs 91

Benchmarking costs 92
Conclusions.. 92
Compatibility of fuels with existing engines 94
Introduction 95
Reasons for limiting the concentrations of certain components 98
Definitions for compatibility 100
Legislation, standards and recommended practices 101
Fuel quality marking for Europe 107
Examples of vehicle adaptation to special fuels 109
Effects of biofuels on tailpipe emissions 111
Additional information on fuel properties, performance and vehicle compatibility 114
Summary 116
Abbreviations 119

List of Figures

Figure 1: Overview of technology pathways and their technology readiness level (TRL)..... 18

Figure 2: Projected annual global supply for primary biomass in 2030[35]............................. 46

Figure 3: Typical cost ranges for biomass feedstocks 50

Figure 4: Summary of global biomass energy supply potential estimates in 2030 ,,,,,,,,,,,,,,,,,,.... 52

Figure 5: Potential global biomass supply in 2030 (Adapted from IRENA, 2014)................. 54

Figure 6: Breakdown of biomass supply ranges by regions (Europe includes Russia), 2030. Two columns for each region represent the high and low supply potentials. 55

Figure 7: Factors that will contribute to the annual growth in the world's potential biomass supply by 2030 [71] 57

Figure 8: The carbon intensity values of current fuel pathways certified under the California LCFS program Renewable Diesel is HVO/HEFA biofuels. 66

Figure 9: Minimum, average, and maximum carbon intensity (CI) values of some of the fuel pathways certified under California LCFS program in 2019.. 67

Figure 10: Summary of LCA values derived from oleochemical and lignocellulosic pathways to produce conventional and advanced drop-in hydrocarbons from various feedstock types68

Figure 11: World biofuels production from 2007 to 2017. Biofuels production increased at an annual growth rate of 11.4%, from over 37 Mtoe in 2007 to over 84 Mtoe in 2017 (Adapted from BP, 2018)... 73

Figure 12: Technology-push and market-pull biofuel policies. Countries that use a mixture of market-pull and technology-push policy instruments have been most successful at increasing biofuels production and use and also at developing and deploying less mature emerging biofuels production technologies. 77

Figure 13: Alternative low-carbon fuel volumes used in California 78

Figure 14: The market value of cellulosic ethanol in California in 2016 and 2018................ 79

Figure 15: Summary of current cost ranges 86

Figure 16: Potential costs of biofuels production after reductions....................................... 89

Figure 17: Examples of impact of learning in costs with increasing learning rates............... 90

Figure 18: Cost of feedstock in the overall cost of production.. 91

Figure 19: Prerequisites for technical compatibility, and in the end, consumer acceptance. 98
Figure 20: Current European fuel standards[7]. 102
Figure 21: The new fuel labelling system for Europe28. 108
Figure 22: Actual photos of fuel markings (truck fuel tank and fuel dispenser). 109
Figure 23: Flex fuel vehicle features. 110
Figure 24: Fuel effects on tailpipe emissions of light-duty vehicles. 113
Figure 25: Fuel effects on tailpipe emissions of heavy-duty vehicles[33]. 113

List of Tables

Table 1: Summary of sustainable biomass resources 58

Table 2: Greenhouse gas emissions savings thresholds in RED II 64

Table 3: Renewable fuel categories under the RFS program, (US EPA, 2017a; Gottumukkala and Hayes, 2018).. 65

Table 4: Summary of current production cost ranges. 85

Table 5: Potential costs of biofuels production after reductions in EUR/GJ 88

Table 6: Application of transport fuels 97

Introduction

Since the early 2000s, renewable transport fuels have been introduced in many countries around the globe. Biomass is a renewable source of carbon and its use for bioenergy and biofuels contributes to a circular economy. Biofuel production not only produces biofuels but also valuable by-products, and provides value to the local biomass producers.

While ethanol and biodiesel are the main biofuels so far, also other biofuels have come into focus recently, the most recent development being the introduction of e-fuels which may or may not be based on biomass. The term “renewable transport fuels” is used to cover all these alternative fuels.

Renewable transport fuels can be produced from many different feedstocks and through a multitude of conversion processes, and this causes large variations in the production costs and the associated well-to-tank greenhouse gas emissions. Also, some of these fuels can be used in internal combustion engines just as they are, while others need to be blended with fossil fuels, or need to be applied in adapted engines. Given this large variety, policy makers find it difficult to determine those fuels that would offer the most benefit to their societies while being technically and economically feasible and compatible with their legacy fleet. Also, large-scale deployment of renewable transport fuels will have effects on their costs and sustainability and thus constantly change the picture:

- increasing demand for certain feedstocks will cause a rise in feedstock costs;
- increasing demand for certain feedstocks may cause that they have to be sourced from less sustainable production areas, resulting in smaller greenhouse gas emission reductions;
- progress in production technologies will reduce both the capital and the operating costs
- infrastructure costs for dedicated vehicles and fuel stations will be more easily offset the larger the scale of their market introduction is.

This report provides the combined latest knowledge of IEA Bioenergy Task 39 and the Advanced Motor Fuels TCP on the production and use of alternative motor fuels. It aims to provide a sound basis for policy makers to take informed decisions with respect to the deployment of renewable transport fuels.

Terminology used in this report

In this report a distinction is being made between **established biofuel pathways** and **emerging biofuel pathways**. This is to avoid terms like first and second generation, 1G, 2G, conventional and advanced, as these terms have no homogeneous definition and are used differently in different regions and jurisdictions. Further fuel types mentioned in the report include recycled carbon fuels and e-fuels. Further descriptions of these categories are provided in **Figure 1** and the explanatory text below.

The same figure also provides the linkage between fuel production pathway, i.e. feedstock and conversion technology used, and the chemical nature of the resulting fuel. When applied in engines it is the chemical composition of the fuel that matters, not the feedstock. Thus, some fuels are grouped, e.g. **FT-liquids** and **HVO**[4] into **drop-in hydrocarbons**[5].

The linkage between these fuels and the marketed fuel qualities is provided in

Table 6, which also describes the applicability of these fuel qualities in different engines.

---

[4] *HEFA (Hydroprocessed Esters and Fatty Acids), also called HVO (Hydrotreated Vegetable Oil), is a renewable diesel fuel that can be produced from a wide array of vegetable oils and fats. The term HEFA or HVO is used collectively for these biogenic hydrocarbon-based renewable biofuels. HVO is free of aromatics and sulfur and has a high cetane number.*

[5] “Drop-in” biofuels are defined as liquid hydrocarbons that are oxygen-free and functionally equivalent to petroleum transportation fuel blendstocks.

Low-carbon fuel technologies and their development status

Low-carbon transport fuels can be manufactured from:

- biogenic feedstocks or biogenic fraction of wastes ("biofuels")
- energy and carbon contained in fossil wastes and residue streams or the fossil fraction of such materials ("e.g. recycled carbon fuels")
- energy from other renewable sources, sometimes in combination with carbon atoms from biogenic and fossil sources (CCU) ("e-fuels" or "renewable fuels of non-biological origin")

The technology readiness levels (TRL, see below) of the production technologies for these fuels vary.

Technologies for the production of **established biofuels** such as ethanol from sugar and starch crops, biodiesel from triglycerides and lipids, hydrogenated triglycerides and lipids, and biomethane from upgrading of anaerobic digestion biogas are at TRL9.

Emerging biofuel pathways include ethanol from lignocellulosic feedstocks, gasification-derived biofuels, pyrolysis-derived intermediates, hydrothermal liquefaction-derived intermediates, lignin-derived intermediates, sugars to biofuels, and biofuels derived from non-lignocellulosic biomass such as microalgae. TRLs for these technologies range from 3 to 8.

Recycled carbon fuels include ethanol, methanol and methane produced from industry off-gases, and fuels derived from the gasification or pyrolysis of non-biogenic wastes or fractions of wastes, with TRLs ranging from 4 to 9.

E-fuels include hydrogen, methanol, methane and Fischer-Tropsch liquids. While the production of hydrogen via electrolysis is at TRL9, the other pathways are at TRL 4-6.

Terminology for different low-carbon fuels is not consistent globally. In the EU fuels are classified by feedstock, in the USA by pathway. In particular the term advanced biofuel has different meanings in different jurisdictions.

Based on the market application, low-carbon transport fuels can be classified as drop-in fuels that can be blended into fossil fuels more or less without restrictions and also using the existing infrastructure, e.g. HVO, low-blend fuels such as FAME biodiesel or ethanol blended into diesel and gasoline up to a limited extent set by fuel standards ("the blendwall"), special

TRL scale

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment

fuels for dedicated vehicles, fleets and applications, e.g. DME, bio-gas for trucks or methanol for ships, as well as additives with a biogenic fraction such as the octane enhancers MTBE and ETBE that, apart of the energy provided, add to the functionality of the fuel.

Low-carbon transport fuels are in very general fuels manufactured from biogenic feedstocks or biogenic fraction of wastes ("biofuels"), fuels manufactured by recycling of the energy and carbon contained in fossil wastes and residue streams, or in the case of mixed biogenic and fossil materials, the fossil fraction of such materials ("e.g. recycled carbon fuels"), as well as fuels produced using energy from other renewable sources, sometimes in combination with carbon atoms from biogenic and fossil sources (CCU) ("e-fuels" or "renewable fuels of non-biological origin"). Of all these options, only ethanol, biodiesel (FAME) and to a lesser extent HVO are currently produced and used in significant quantities.

However, within these categories, there are a number of more detailed administrative regulations in different jurisdictions that give more detailed definitions on the requirements for different categories of low-carbon transport fuels in terms of eligible feedstocks and minimum GHG reduction requirements, determined by specific LCA methodologies.

For this reason, a specific conversion technology can yield differently defined fuel products depending on which feedstock or energy source is used, if the conversion is a dedicated facility or by co-processing, or from the GHG reduction obtained.

Overview of regulated fuel qualities

In the EU[6], there are "biofuels" "advanced biofuels" and "renewable liquid and gaseous transport fuels of non-biological origin" and as of 2021 "recycled carbon fuels" and "biogas in transport", the latter today being part of the "biofuels" and "advanced biofuels" categories. There is a target for the Member States for renewable energy in transport, i.e. also including renewable electricity with different multipliers, of 10% in 2020, to be increased to 14% in 2030. The obligated parties are the fuels suppliers in each Member State. Biofuels from "food and feed crops" (i.e. crops producing sugars, starch or vegetable oils) are since 2015 capped to 7%, this cap being maintained with some modifications in the period 2021-2030[7]. In addition, what is deemed as high iLUC feedstocks, e.g. palm oil, is subject by a delegated act to further qualification to be an eligible biofuel. In addition, there is a cap of 1.7% for fuels produced from feedstocks defined by Part B of Annex IX, used cooking oil (UCO) and certain animal fats.

"Advanced biofuels" (also including some biogas for transport) are biofuels produced from wastes and residues defined by Part A of Annex IX and has a separate target within the above renewable energy targets of 0.5% and 3.5% in 2020 and 2030, respectively. The Annex IX fuels, however, are counted at twice their energy content, if the Member States decide to use this option. Optionally, the Member States may also decide whether to account "recycled carbon fuels" towards their respective targets.

The GHG reduction requirements for new "biofuels" and "advanced biofuels" installations are 60% at present to be increased to 65% in 2021[8]. "Renewable liquid and gaseous transport fuels of non-biological origin" will require 70% GHG reduction as of 2021 while the methodology and threshold value for "recycled carbon fuels" will only be set by the Commission via a delegated regulation in 2021. The LCA methodology is defined in the legislation but a number of voluntary accounting and auditing schemes are also accepted after verification and approval.

6 See the iLUC directive, (EU) 2015/1513, now in force and the RED II directive (EU) 2018/2001 coming into force in 2021.

7 Defined as the minimum of 7% or the Member State actual consumption in 2020 of biofuels from "food and feed crops" plus maximum 1%.

8 However, the absolute change in reduction is less, as the fossil comparator is increased in 2021 from the present 84 to 94 g CO_{2e}/MJ.

At present, the Member States have implemented the EU-common directives in different ways, by tax exemptions, quota obligations, blend obligations, GHG reduction obligations or targets and trade certificate systems, and whether also to allow double-counting of the energy value or not. Different approaches will probably be present also after the implementation of REDII by the member states in mid-2021.

In the USA, the national policy to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel has resulted in a regulatory system, called Renewable Fuels Standard[9]. The current second phase, RFS2, was initiated in 2007 and continues to 2022. The target is to overall have 36 billion gallons/year (136 million m^3) of different renewable fuels in 2022, estimated to reduce the US GHG emissions by 138 million tons. The system is administrated by the Environmental Protection Agency (EPA), which sets annual Renewable Volume Obligations (RVO) for different fuel categories in advance, to be fulfilled by the obligated parties, i.e. refiners and fuel importers.

These annual requirements are divided among different categories of biofuel classified by "pathways" from feedstock over conversion to certain types of fuels.

"Renewable fuel", essentially crop-based (mainly corn-based) ethanol pathways, has at least 20% GHG reduction relative to the fossil fuel baseline on an energy basis.

"Advanced biofuel", a subset of "renewable fuel", is a renewable fuel other than ethanol derived from corn starch and which meet a 50% GHG reduction threshold. Within the category of "advanced biofuels" yet another two subcategories for specified feedstocks and conversion pathways are defined, "biomass-based diesel", of at least 50% GHG savings, and "cellulosic biofuel" of at least 60% GHG savings.

"Advanced biofuel" includes sugar cane ethanol and anaerobic digestion of certain wastes but also fuels produced by the non-cellulosic fraction of biomass, e.g. lignin and hemicellulose, as well as hydrogenated diesel (HVO, see also below) produced in co-processing with fossil fuels.

"Biomass-based diesel" includes FAME biodiesel and hydrotreated diesel (HVO) obtained from e.g. vegetable oils (but not including palm oil), algae oils, animal fats, UCO, industrial biogenic lipid residues and by-products greases, if produced in dedicated facilities (in the case of co-processing see above).

[9] www.epa.gov/renewable-fuel-standard-program

“Cellulosic biofuel” is fuel derived from lignocellulosic feedstocks e.g. forest and forest industry residues (including lignin), agriculture residues and the biogenic portion of wastes by either enzymatic hydrolysis, thermochemical conversion methods or anaerobic digestion of sludges, sorted wastes, manure but also of the cellulosic fraction of other wastes. In the case of MSW that has undergone a recycling and separation process, EPA can on a case-by-case basis rule that the entire residual fraction, i.e. not only the biogenic fraction, is renewable biomass.

Each of the renewable fuel categories are associated with tradeable certificates, Renewable Identification Number (RIN) issued per gallon produced of renewable fuel (D3), advanced biofuel (D4), biomass-based diesel (D5) and cellulosic biofuel, cellulosic ethanol (D6) and cellulosic diesel (D7), respectively. Refiners and importers have to provide RINs in relation to their share of the fuel market to meet the overall volume and category targets. RINs are primarily used to show compliance within its own category but can also for the category of which it is a sub-set. Thus, D5, D6 and D7 can be used to show compliance for advanced biofuels, D4, and in turn D4 can be used to show compliance for renewable fuels, D3. General pathways to the various renewable fuel categories are analyzed and approved by EPA and installations are audited to show that the actual production meets the requirements with regard to the feedstock and GHG reduction.

The Californian LCFS system, introduced in 2009, aims to reduce the GHG emissions in transport by 20% in 2030. The LCFS sets annual carbon intensity (CI) standards, or benchmarks, which reduce over time, for gasoline, diesel, and the fuels that replace them. Fuels and fuel blendstocks introduced into the California fuel system that have a CI higher than the benchmark generate deficits while credits are generated by fuels and fuel blendstocks with CIs below the benchmark and also from other projects in fossil upstream and processing GHG reduction and infrastructure. Annual compliance is achieved when a regulated party uses credits to match its deficits, these being obtained by trading of credits. A number of fuel production pathways have had their energy use and CI analysed, and there are calculation tools available for a large number of bio-, fossil-, waste- and RE- based pathways to transport fuels.

In Brazil, the support system RenovaBio has as its main objective to expand the biofuel production in the country. This regulation considers the following biofuels categories: FAME biodiesel blended into diesel, hydrous ethanol used as E100 and anhydrous ethanol blended into gasoline as well as biogas and bio-kerosene. In addition, there are also blending mandates for ethanol in gasoline and for biodiesel in diesel. The quantitative goal of the RenovaBio system is to gradually reduce the average GHG intensity in the Brazilian transport system, which are equivalent, in 2030, to 90.7 million CBIO that shall be acquired by the distributors. It is a certificate trading system (1 CBIO = 1 tonne CO2(eq)) that links producers of biofuels (generators) with the fuel distributors (obligated parties). Authorized institutions certify the production, and a LCA methodology is applied to ascertain the specific GHG emission reduction. The difference between the LCA from fossil fuel and biofuels is called the environmental energy efficiency rate, which is multiplied by the certified production commercialized with distributors, resulting in the number of CBIO generated. Each distributor has a reduction goal expressed as number of CBIO, which represents specific GHG emissions reduction in their fuel pool. The carbon intensity of their pool, multiplied with the energy of the fuels sold gives the number of CBIO to be rendered within the national CI reduction target.

Below, in the sections dealing with specific types of biofuels, only the EU and US classification of the fuels are mentioned. In California the classification is based on the carbon intensity of the fuel rather than exactly which category of fuel is produced. In Brazil biofuels are defined according to the feedstock, and the carbon intensity is used under the Biofuels National Policy - RenovaBio.

Technology pathways and status

Figure 1 provides an overview on the various pathways for the production of low-carbon transport fuels and on the technology readiness levels (TRLs) of these pathways. The main pathways are briefly described in the following sections. For a more detailed description of the technologies, their status and the cost of different biofuels, the references below provide further information[10, 11, 12, 13, 14].

From an end-use perspective, the above low-carbon fuel products can be classified as drop-in hydrocarbons, low-blend fuels and special fuels. Drop-in hydrocarbon renewable fuels include HVO diesel and HEFA kerosene as well as fuels produced via pyrolysis or HTL oils

---

[10] SGAB Technology status and reliability of the value chains: 2018 Update. 28 December 2018. Ed. I Landälv, L Waldheim, K Maniatis.
artfuelsforum.eu/news-articles/updated-sgab-report-technology-status-and-reliability-of-the-value-chains/

[11] Advanced Biofuels – Potential for Cost Reduction. A. Brown *et al*. IEA Bioenergy: Task 41: 2020:01

[12] ETIP Bioenergy

[13] IEA Bioenergy TCP Task Groups in variety of topical areas, see www.ieabioenergy.com/our-work-tasks/

[14] Global Potential of Biogas. World Biogas Association, June 2019.

and synthetic fuels (Fischer- Tropsch products) liquid intermediates, etc.. After upgrading these fuels are fractionated to gasoline, diesel or kerosene products in various proportions. These fuels in principle have similar properties and are to a large extent compatible with the gasoline, diesel and kerosene on the market and can be blended into these in a high ratio (typically well-above 10%), or in some cases even used neat. Low-blend fuels are ethanol, other alcohols and oxygenates as well as FAME biodiesel, where the fuel properties are quite different from marketable fuels and therefore these renewable fuels can only be blended into certain market fuels at a low blend rate, e.g. 10-20 % by volume ethanol in gasoline, 7% by volume of FAME, depending on local fuel specifications and vehicle OEM acceptance. Special fuels (e.g. bio-methane, B100 FAME, E85, ED 95, DME, H_2) are not compatible with the ordinary liquid fuels market infrastructure or vehicles, and have dedicated infrastructure and are used in vehicles specifically designed or adapted for the fuel in question (however in some case with dual-fuel capacity that also allows operation on conventional gasoline and diesel).

	Raw material	Technology	Fuel	Technology Readiness Level (TRL)								
				1	2	3	4	5	6	7	8	9
Established biofuels	**Sugar**	Fermentation	Ethanol									
	Starch											
	Vegetable oils & lipid waste	Transesterification	FAME/Biodiesel									
		Hydrotreatment	Drop-in hydrocarbons									
	Crops, sludges, manures etc.	AD biogas upgrading	Biomethane									
Emerging Biofuels	**Raw material**	**Technology**	**Fuel**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Lignocellulosic feedstocks	Enzymatic hydrolysis + fermentation	Ethanol									
			Other alcohols									
	Lignocellulosics, biogenic fraction of RDF etc., non-lignocellulosic biomass or by-products	Gasification + fermentation	Ethanol									
		Gasification + catalytic synthesis	Drop-in hydrocarbons, Alcohols, Biomethane									
	Lignocellulosics, biogenic fraction of RDF etc., non-lignocellulosic biomass or by-products	Pyrolysis + upgrading	Drop-in hydrocarbons									
		HTL + upgrading	Drop-in hydrocarbons									
	Lignin from lignocellulosic ethanol or forestry liquors	HTL and/or chem. treatment + upgrading	Drop-in hydrocarbons									
	Sugars from sugar and starch crops or lignocellulosic	Fermentation	Drop-in hydrocarbons									
			Various alcohols									
		Chem. conversion	Drop-in hydrocarbons									
	Non-LC biomass fractions or by-products	Various	Various									
Recycle Carbon Fuels	**Supply of fossil waste or by-product gases**	**Technology**	**Fuel**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Steel industry & chemical industry off-gases	Fermentation	Ethanol									
		Catalytic synthesis	Methanol									
			Methane									
	Wastes, waste plastics, non-bio fraction of RDF	Gasification + catalytic synthesis or fermentation	Drop-in hydrocarbons, Alcohols, Biomethane									
	Waste plastic fraction	Pyrolysis + distillation	Drop-in hydrocarbons									
E-fuels	**Supply of H2**	**Technology**	**Fuel**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	RE electricity	Electrolysis	Hydrogen									
		Electrolysis and carbon capture + catalytic synthesis	Methanol									
			Methane									
			Drop-in hydrocarbons									

Figure 1: Overview of technology pathways and their technology readiness level (TRL)

Established biofuel pathways

Ethanol from sugar and starch crops

Sugar crops are predominantly sugar cane, but also sugar beets and sweet sorghum are used. These plants produce sucrose, a dimer of C6 sugars such as mainly glucose and fructose. By milling and leaching at slightly elevated temperatures the sucrose is extracted into approximately 20 w% sugar juice, which is then pre-treated by clarification and a heat treatment. A sugar mill may produce only sugar, only ethanol, sugar and ethanol in parallel on a more or less equal scale or mainly sugar and some ethanol from molasses (concentrated syrup residue after sugar crystallisation) only. Yeast and nutrients are injected into the clarified juice and routed to fermenters where the sucrose is enzymatically split into the C6 sugars and then fermented to alcohol ("beer").

In the case of starch crops, mainly wheat, barley, corn (maize) but also e.g. cassava, the initial step is dry milling the crop grains, separation of the starch "meal" and addition of water and enzymes to obtain the starch as a thick gel slurry. There is also a wet milling process where the grains are soaked in a dilute sulphuric acid solution prior to milling and recovery of the starch, but also with possibilities for a range of valuable by-products. Starch is a polymer of C6 sugars - mainly glucose -, and enzymes are added to the slurry ("mash") to depolymerise the starch to release the sugars. The slurry is then heat treated and sent to fermenters where yeast and nutrients are added, and the sugars converted to alcohol.

The fermentation process takes 1-2 days to complete. In both cases (sugar crops, starch crops), ethanol is recovered from the "beer" by a typically two-stage distillation to produce approx. 94 w% ethanol hydrous ethanol (used as E100 in Brazil) followed by mol sieve dehydration to reach above 99 w% minimum ethanol content (dehydrated or anhydrous ethanol) for blending into gasoline.

In addition to ethanol (and sugar), by-products from cane ethanol are CO_2 from the fermentation, bagasse fiber used as fuels and vinasse recycled as fertiliser. By-products from the starch crop-based ethanol is in addition to CO_2, dry distillers grain solids (DDGS) used as cattle fodder and depending on the feedstock and milling technology, also technical corn oil, starch, syrup, gluten and bran. Due to increased requirements for GHG reduction and also because it is a revenue-generating by-product from a waste stream, AD technologies for residue streams are being more and more integrated into ethanol production.

In the EU, ethanol from these pathways is a biofuel and is subject to a cap, in the USA it is a renewable biofuel.

The global production of bio-ethanol was 108 000 billion liters[15] in 2018 (86 million tonnes, 638 TWh or 55 Mtoe, (tonnes of oil equivalents), of which over half was in the USA (some 200 plants) and one quarter in Brazil (close to 400 plants[16]), an 5% in the EU (some 50 plants[17]), with no other country producing above 5%. The feedstock used is 46% corn, 38% sugar cane, 5% wheat and then followed by molasses and other crops.

Biodiesel from triglycerides and lipids (FAME)

Biodiesel (FAME) is produced from vegetable oils, animal fats, used cooking oils (UCO), greases and other fats and oils. Oils and fats mainly consist of triglycerides, i.e. three long (C_{10+}) and straight fatty acid chain molecules linked to a glycerol (*aka* propantriol, glycerine) molecule via ester functionalities. The initial step in the FAME process is pre-treatment of the feedstock which for vegetable oils is more or less similar to refining of edible vegetable oils. Tallow, other waste lipids and UCO etc. also have other contaminants, in particular several percent of free fatty acids (FFA) and must undergo additional purification before use. The FFA is converted to FAME by acid esterification using methanol and sulphuric acid at approximately 9 bar pressure and 125 °C. This can be made in an integrated process unit upstream of the main conversion step or in a separate unit after separation of the FFA by stripping.

The pre-treated and purified triglyceride feedstock is processed by the transesterification reaction with an excess of dry methanol at atmospheric pressure and 60 °C in several steps, using a base catalyst[18], commonly sodium methoxide or KOH, at residence times of magnitude of hours. The transesterification reaction results in that the glyceride ester is reacted with methanol (approx. 10%w of the triglyceride) to form three separate FAME methyl esters and in exchange the glycerol is released into the reaction mixture. The glycerol, (approx. 10%w of the triglyceride) is separated by gravity or centrifuges for recovery. The separated crude FAME is treated by vacuum flashing or distillation to remove the unreacted methanol, which is recycled, and by decanting to remove residual glycerol. The crude FAME is then water-washed, followed by either vacuum-stripping or distillation to remove residual moisture and methanol and a final filtering step.

---

[15] ethanolrfa.org

[16] USDA Gains Report Brazil 2018

[17] USDA Gains Report EU 2018

[18] In addition, there are processes based on heterogenous catalysis and enzymatic reactions, but not in common use at present.

Glycerol can be a valuable by product, the glycerol/water/salt/methanol mixture is subject to treatment to recover both methanol for recycling and a glycerol product[19].

FAME biodiesel can be used as B100 but is more commonly blended into diesel, e.g. B7. Since the FAME chemical process has not affected the structure of the fatty acid chains, these are still straight and retain any unsaturation originally present, but also traces of glycerides that affects storage and use properties. For example, the choice of feedstock dictates the cold flow properties via the original triglyceride composition and must therefore be compatible with the climatic conditions of the intended market.

FAME biodiesel, subject to meeting the GHG reduction threshold, can in the EU be a biofuel or an advanced biofuel, eligible for double counting, depending on the feedstock used. Both categories can be produced in the same plant, if capable of using waste and residues materials. In the USA, FAME, subject to meeting the GHG reduction threshold, is bio-based diesel if eligible feedstocks are used.

Global production in 2017 was 36 billion liters[20] (328 TWh or 28 Mtoe). In 2016, the feedstock was 31% palm oil, 27% soybean oil, 20% rape seed oil, 10% UCO, 7% animal fat and the balance other sources[21].The EU (190 plants) is the main producer, 14 million liters production and with 21 billion liters installed capacity[22]. The second largest producer is the USA[23] (124 plants) 7 billion liters in 2017 based on 9 million installed capacity. Number three in production is Brazil (just over 50 plants) producing 5.9 billion liters but with 9.3 billion liters capacity[24], followed by Argentina and Indonesia providing 9 and 7 billion liters, respectively.

Hydrogenated triglycerides and lipids (HVO)

The HVO feedstocks are the same as for FAME biodiesel above, and the pre-treatment is in principal the same, with the exception that the HVO process can process FFA together with the triglycerides. HVO type of biofuels can either be produced in stand-alone facilities, by converting the existing oil refineries into HVO production or in co-production facilities.

---

[19] Glycerol products traded range from crude glycerol (typically 80% glycerol) to pharmaceutical grade (99.5-99.7% glycerol)

[20] OECD-FAO Agricultural Outlook 2018-2027. Biofuels. OECD FAO 2018.

[21] UFOP Report on Global Market Supply 2017/2018. Union zur Förderung Von Öl- und Proteinpflanzen e.V.

[22] USDA Gains Report EU 2018

[23] biodieselmagazine.com/plants/listplants/USA

[24] USDA Gains Report EU 2018

The first stage, the so-called hydrotreatment, takes place at 3-5 MPa (5-15 MPa for co-processing in fossil hydrotreater) pressure and at temperatures between 300 °C and 450 °C over a catalyst in a trickle column reactor, to which hydrogen is added with the liquid feed. The hydrogen is today mainly derived from fossil sources[25], but in the future it could be derived from the bio-LPG produced in the process or from RE power.

Initially, hydrogen saturates any double bonds of the triglycerides followed by a cleavage to fatty acids and the hydrogenation (hydrogen removes the acid group oxygen as H_2O) of glycerol to propane (i.e. bio-LPG) and water. Finally, the fatty acids undergo a combination of hydrogenation or decarboxylation (the acid group oxygen leaves as CO_2), the reaction split depends on the catalyst and operating conditions used. This results in straight chain alkane hydrocarbons.

The second stage of hydroprocessing involves the catalytic isomerisation and cracking of the straight chain alkanes, at 300-400 °C, the severity of which is dictated by the desired fuel products. This second step result is a mixture of straight chain, branched chain, and cyclic paraffinic hydrocarbons at similar or lower average carbon number than the original straight chains. The change in the molecular structure of the hydrocarbons allows aligning the properties to the specification of marketed fuels for the local climatic conditions. The various desired hydrocarbons product fractions, e.g. HVO diesel and/or HEFA kerosene, gasoline and naphtha fractions are then separated by distillation.

HVO diesel can in the EU, subject to meeting the GHG reduction threshold, be a biofuel or an advanced biofuel, eligible for double counting, depending on the feedstock used and both categories can be produced in the same plant, if capable of using waste and residues materials. However, HVO resulting from co-processing with fossil fuels is not accepted as a biofuel in all member states, e.g. Germany. In the USA, HVO is bio-based diesel if produced in a dedicated facility and an advanced biofuel if produced by co-processing, subject to eligible feedstocks being used and meeting the GHG reduction threshold.

Global production in 2017 was 6.5 billion liters (65 TWh or 5.6 Mtoe). There are some over 25 plants worldwide[26] including co-processing. The EU has 14 plants, including co-

[25] mainly produced via steam reforming of natural gas or refinery fuel gas

[26] SGAB Technology status and reliability of the value chains: 2018 Update. 28 December 2018. Ed. I Landälv, L Waldheim, K Maniatis. artfuelsforum.eu/news-articles/updated-sgab-report-technology-status-and-reliability-of-the-value-chains/

processing facilities, that in 2018 had 2 million liters production and 5 million liters capacity (some plants were being commissioned in 2018, and all co-processing capacity not being fully used). There are at least three dedicated plants in the USA and China and one plant in Singapore.

Biomethane from upgrading of anaerobic digestion biogas

Typical feedstocks for biogas production are agricultural substrates (e.g. corn or specifically grown energy crops), manure, wet waste fractions from the agriculture and food industry sector as well as sludges from e.g. water treatment works in both cities and industries. A special case is recovery of landfill gas from waste landfills to prevent release of the methane formed over decades into the atmosphere.

Pre-treatment of the material to be fed into the digester depends on the nature of the feedstock but may involve removal of non-digestable materials (plastics, metals, glass, grit), washing, milling, screening and pressing depending on the feedstock. All biomass fractions, with the exception of lignin, can be degraded by anaerobic microbes. For high fraction of or dedicated lignocellulosic feeds, e.g. agricultural residues, a pre-treatment[27] is in most cases used to make the cellulose and hemi-cellulose better available for the bacterial degradation. The pre-treated feedstock is fed to the digester, a sealed container, where it undergoes decomposition in the absence of oxygen over a period of several days. This process can take place at different operating temperatures, most commonly at 35-40°C (mesophilic) but also at higher temperatures, 55-60°C (thermophilic), thereby increasing the rate of digestion. Based on the constituents and consistency of the feedstock treated, an anaerobic digester can be designed as a 'wet', 'dry', 'liquid' or 'co-digestion' system while there are many types of reaction systems depending on the capacity and the nature of the feedstock. During the digestion, the bacterial population in the digester decomposes organic compounds in several steps (hydrolysis, acidogenesis, methanogenesis) to a mixture of almost equal parts of methane and CO_2 with some trace gases, mainly nitrogen and hydrogen sulphide, the "biogas", which is collected in storage tanks or inflatable domes.

For use as vehicle fuel or for grid injection, the CH_4 content of the biogas must be increased (> 97% CH_4) by removing most of the CO_2 from the biogas. Furthermore, the gas has to be dried and different trace gases (H_2S, siloxanes) removed. There is a variety of commercially

[27] This pre-treatment might be enzymatic, chemical or physical and for dedicated lignocellulosic feeds fairly comparable to the pre-treatment of lignocellulosic material for alcohol production.

available upgrading technologies (e.g. PSA or membrane separation, amine or pressurized water scrubbing).

The residues and waters after digestion contain dissolved organics and inorganics as well as non-digested solids. Depending on the feed, these residues can have a value as e.g. fertilizers or require other treatments prior to their disposal.

Upgraded biogas, i.e. biogas for transport, can in the EU, subject to meeting the GHG reduction threshold, be or not be, eligible for double counting, depending on the feedstock used and both categories can be produced in the same plant. In the USA, renewable natural gas is for most feedstocks counted as a cellulosic biofuel or otherwise as an advanced biofuel if produced in a waste digester, again subject to meeting the GHG reduction threshold.

There is a total of close to 50 million of micro-scale digesters operating around the globe, predominantly in China (84%) and India (10%) directly fuelling stoves and small furnaces[28]. In addition, there are an estimated 132 000 small, medium or large-scale digesters (i.e. an approximate range of 0.5 to 20 MW gas output), again predominantly in China (83%) but also in Europe (13%), USA, India and Canada, but there is a rapid growth in these numbers. The main application of the biogas is power and CHP using IC engines, 88 TWhe was generated in 2016 (indicating a global biogas production of the order of over 300 TWh).

In recent years the upgrading of biogas to biomethane for use as transport fuel or for grid injection has become a proven technology in larger scale installations (2-20 MW gas output). Globally some 700 plants upgrade biogas to biomethane (a few also producing liquefied bio-methane) predominantly in Europe, 77%, mainly in Germany but also in the UK, Sweden, France and the Netherlands, , USA (7%), China (4%), Canada (3%) and a few in Japan, South Korea, Brazil and India. The European production of biomethane amounted to 17 TWh[29] (1.5 Mtoe) while in the USA it is around 4 TWh[30]. So, in general, this technology is at TRL9, but when using agricultural wastes (straw) as the sole feed, there is one plant by Verbio in operation and another one in construction in Germany. Verbio also bought the

---

[28] Global Potential of Biogas. World Biogas Association, June 2019

[29] SGAB Technology status and reliability of the value chains: 2018 Update. 28 December 2018. Ed. I Landälv, L Waldheim, K Maniatis.

artfuelsforum.eu/news-articles/updated-sgab-report-technology-status-and-reliability-of-the-value-chains/

[30] www.anl.gov/es/reference/renewable-natural-gas-database

former Dupont cellulosic ethanol plant, see “Ethanol from lignocellulosic feedstocks”, and plans to convert it to bio-methane production in co-production with corn-based ethanol.

Emerging biofuel pathways

Ethanol from lignocellulosic feedstocks

The term “lignocellulosic” feedstock includes agricultural and wood residues, wood from forestry, Short Rotation Coppices (SRCs), and energy crops, such as some of the energy grasses and reeds as their main structural material are cellulose, hemicellulose and lignin. It also applies to waste fractions such as cellulosic fibers from cardboard and recycled paper.

Generally, unprocessed lignocellulosic biomass consists of 35–50% cellulose, 20–35% hemicellulose and 10–25% lignin. Woody biomass has in general higher lignin content than agricultural residues at the expense of the hemicellulose fraction while annual species (crops, grasses) have less lignin and are higher in hemicellulose. Cellulose is a crystalline polymer of glucose forming the fibers in the plant material. Cellulose fibrils are surrounded by first a matrix of hemicellulose and then lignin in the secondary plant cell walls. Hemicellulose is a more complex polymer of C5 and C6 sugars, often with a predominance of C5 sugars. Lignin is also a polymer based on phenolic building blocks that provides stiffness to the fibrils from external and “shields” these from biological and mechanical damage.

The first step in the processing of lignocellulosic feedstocks is a pre-treatment to fractionate the feedstock into its three main components. The most common method is the steam explosion with or without an acid catalyst but also acid and base treatment and organosolve processes have been or are in use. The nature of the pre-treatment has large impact on the accessibility of the still crystalline, de-lignified cellulose for saccharification while hemicellulose is mostly hydrolyzed to sugars and oligomers and dissolves at this stage. The lignin is not chemically altered and remain as a solid. The pre-treatment step also generates different undesired components acting as inhibitors for the enzymes and yeasts, respectively, used in the downstream process.

Additional water is added to the mixture of solids and liquids resulting from the pre-treatment to reduce the viscosity after which hydrolysis and saccharification of the cellulose and hemicelluloses oligomers take place. This step uses specifically developed enzyme cocktails, but also acid hydrolysis has been used. The enzyme treatment results in a viscous two-phase fluid. This fluid is either fermented in the same vessel (Simultaneous Saccharification and Fermentation (SSF)) or in a downstream fermenter (Separate Hydrolysis and Fermentation (SHF)). Lignin is separated before or after fermentation and usually dried to be used as a fuel for the process and/or for power generation. The cellulose- and hemicellulose-derived C6 sugars are fermented by yeast strains derived from traditional yeasts used for the production of wine, beer or bread, while for the fermentation of C5 sugars genetically modified yeasts have been developed in the recent years. After the fermentation has been finalized, the ethanol is recovered by distillation and dehydration as described for sugar and starch ethanol above in the section "Steel industry & chemical industry off-gases

There is a complex trade-off between the water addition, the viscosity, the enzyme consumption, the ethanol concentration achievable and the possible inhibition of the ethanol and the energy required for the downstream processing. At present, the technology can give up to 300 liters of ethanol per tonne of agricultural waste of which a significant part is derived from the C5 sugars, i.e. an efficiency to biofuels of the order of 35% (assuming 5 MWh/t dry substance).

Lignocellulosic ethanol is an advanced biofuel in the EU and a cellulose biofuel in the USA, however with the exception of the non-cellulosic portions of separated food waste and non-cellulosic components of annual cover crops where the ethanol is an advanced biofuel.

There are, and also have been, a number of industrial developments worldwide for lignocellulosic (aka second generation) ethanol, many of which have reached demonstrations at TRL6. However, only a few of these developments have reached industrial scale at TRL8. In the last decade, six plants at industrial scale (25 000 90 000 tonnes/year product capacity each or 13 000-45 000 toe/year (toe, tonnes of oil equivalents) have been built, one in the EU (Beta Renewables), two in Brazil (Raizen, Granbio) and three in USA (Abengoa Hugoton, Dupont and POET Liberty). However, the Abengoa and Dupont plants are closed, the POET plant is back to R&D work, and the Beta Renewables plant was closed but has been taken over by Versalis who has announced that operation will be resumed. The Beta Renewables and the Granbio plants are based on the same technology but different feedstocks, arundo donax and sugar cane bagasse, respectively.

Furthermore, there is one plant in construction in the EU by Clariant and others are being studied, and in India the government has instructed oil companies to invest in twelve plants, of which a few plants are already under construction and others are in different stages of planning. These projects are based on both Indian (Praj, IBC) and foreign technologies.

Gasification to synthesis gas and fuel production

Thermal gasification is very fuel-flexible; it can in principle use any reasonably dry combustible material as a feedstock. The feedstock potential for producing advanced biofuels lies in forest and forest industry residues, agricultural and agro-industrial residues as well as sorted municipal and industrial wastes (RDF[31], SRF[32], plastic wastes etc.).

Thermal gasification converts the combustible feedstock to a variety of products via conversion to a gaseous intermediate, the synthesis gas, which is a mixture of mainly carbon monoxide (CO) and hydrogen (H_2). The fuel pre-treatment requires drying of the feedstock to 10-20% moisture, if necessary, and milling/shredding and grading to particle size suitable for the type of gasifier used. In some cases, this may also involve some thermal treatment to facilitate milling or conversion to a bioliquid slurry to increase energy density and facilitate feeding. The pre-treated fuel is fed into the gasifier by mechanical devices in the case of solids or by pumping for liquids and slurries. In the gasifier, the fuel is converted to a raw product gas using steam and oxygen, or by steam combined with indirect heating, respectively. Operating conditions are, depending on the process and type of gasifier (fixed beds, directly heated fluidized beds, indirectly heated fluidized beds, entrained flow reactors) from 800 up to 1 500 °C and pressures from atmospheric up to 3 MPa. The cleaning of the raw gas constitutes of a series of process steps at temperatures starting from gasifier temperature and going down to ambient temperature, and with integrated heat recovery. These steps initially include removal of particulates, sulphur and other contaminants, as well as catalytic adjustment of the hydrogen/carbon monoxide ratio, and in most cases also CO_2 removal.

The technology for the use of the synthesis gas intermediate is well-established for fossil-derived synthesis gas and has immense industrial importance for producing hydrogen in refineries as well as many millions of tonnes of chemicals annually. Selective catalytic chemical reactions convert the synthesis gas to, by choice, methane, methanol, DME or Fischer-Tropsch hydrocarbons, respectively, at temperatures of 200 up to 400 °C. The synthesis gas can also be converted to ethanol by micro-organisms at ambient temperature. In addition, hydrogen as a product can be extracted directly from the gas.

Fischer-Tropsch hydrocarbon product is a mixture with a wide range of molecular weights from LPG over naphtha and distillates to waxes. The waxes are typically hydrotreated and then the combined liquid products are fractionated by distillation to gasoline, diesel and jet

[31] RDF: Refuse derived fuel, the fuel fraction remaining after recyclable material and non-combustible waste have been separated in a waste treatment facility however not associated with any specific quality measures.

[32] SRF: Solid recovered fuel, an RDF where certain quality parameters and procedures have been defined, for further information see standard EN 15357 and standard in development ISO/DIS 21637.

fuel. Methanol and DME can, if desired, be processed further to gasoline. The typical energy conversion efficiency (biofuel output energy/biomass feedstock energy as received) from feedstock to advanced biofuel products ranges from 40- 50% for drop-in hydrocarbon fuels and 60-70% for gases and methanol.

In the EU, biofuels derived via gasification are advanced biofuels as far as they are produced from biomass and biomass residues or the biogenic fraction of wastes, while in the latter case the fossil fraction is a recycled carbon fuel. In the USA, the fuels derived from biogenic materials and wastes are cellulosic biofuels, with the exception of the non-cellulosic portions of separated food waste and non-cellulosic components of annual cover crops where the fuel is an advanced biofuel. If the fossil part of wastes in a particular project is exempted as biomass, see above, it is also part of the advanced biofuel produced, but generally has no other benefits.

There are a number of TRL6+ pilot and demonstration plants in the EU and North America, and the technology is fairly widely used for other purposes than biofuels, such as fuel gas and power and heat. At present, only one advanced biofuel plant at industrial scale (TRL8) is in operation, the Enerkem plant in Edmonton, Canada, that produces methanol or ethanol from assorted wastes (RDF) at a nominal capacity of 24 000 toe/year. Up to 2018, also the GoBiGas plant in Gothenburg Sweden was in operation, producing biomethane from forest residue pellets up to a nominal capacity of 14,000 toe/year, but was closed for economic reasons (lower than expected energy prices).

There are also two plants in construction in the USA, Red Rock Biofuels and Fulcrum Sierra Biofuels that will both use the Fischer Tropsch process to produce hydrocarbons and mainly bio-jet, 45 000 toe/year from wood residues and 33 000 toe/year from RDF, respectively. Furthermore, there are two plants in planning using the Enerkem technology to produce methanol from RDF, in Rotterdam, the Netherlands, at annual capacities of 102 000 toe/year and Tarragona, Spain, at 123 000 toe/year, respectively. In California, Aemetis is planning a 23 000 toe/year ethanol plant using the InEnTec plasma gasification and the Lanzatech synthesis gas fermentation technologies, see section “Steel industry & chemical industry off-gases

Pyrolysis to bioliquid intermediates

Pyrolysis is the chemical decomposition of organic matter of biomass by heating in the absence of oxygen. The feedstock decomposes into organic vapours, steam, non-condensable gases and char. The technology can in principle use any dry combustible material as a feedstock. The feedstock potential for producing advanced biofuels lies in forest and forest industry residues, agricultural and agro-industrial residues as well as sorted municipal and industrial wastes (RDF, SRF, plastic wastes etc.). The latter fuels with a high fossil carbon content will be discussed in section "Waste plastics and the fossil fractions of wastes".

The pre-treatment of the biomass feedstock typically includes drying to less than 10% moisture and crushing/milling to particles of less than 5 mm. The highest yield of the desired liquid fraction, up to 65%wt on a dry feed basis, is obtained by thermal fast pyrolysis. Fast pyrolysis takes place in order of seconds at around 500 °C. The heating medium is typically circulating sand, but also catalysts have been used. On cooling, the organic vapours and the steam condense to a dark brown viscous liquid called fast pyrolysis oil (FPO) or sometimes bio-oil. The char and gas are used internally to provide the process heat required, and additionally also energy for export.

The word "oil" used in this context is misleading, the energy content is only half of that of fuel oil, it contains ash solids, the oxygen content is almost as high as for biomass (35-40%), it is acidic and non-miscible with either conventional oil or with water. Nevertheless, this liquid is transportable, storable and can without upgrading to some extent be used as a fuel oil substitute. By using a catalyst during pyrolysis or in the vapour phase, the oxygen content and acidity of the oil can be reduced, at the expense of a lower mass and energy yield. There is also a development of a pressurised pyrolysis in a hydrogen atmosphere, whereby the bioliquid generated has a yet lower oxygen content and acidity and being more similar to hydrocarbon fuels. There are developments of the upgrading of pyrolysis oil, either in an integrated facility at the production site or by co-feeding with fossil feeds at low blend ratios (a few %) in existing refineries.

A concept for the pyrolysis technology is where the intermediate product, the pyrolysis oil, can be produced at smaller capacity in distributed plants and the upgrading of the oil to drop-in transport fuels is done in large plants fed by FPO from a number of such plants.

The main routes from FPO to a drop-in hydrocarbon biofuel is by fluid catalytic cracking (FCC) or by hydrodeoxygenation (HDO). In the case of the FCC route, oxygen is expelled from the FPO as CO and CO_2 and the H/C ratio adjusted by coke formation to result in a hydrocarbon mixture where gasoline is the main fraction. The HDO route is basically a treatment with hydrogen whereby oxygen is expelled as water, this process having similarities with the HVO process, see section "Hydrogenated triglycerides and lipids (HVO)", and the resulting hydrocarbon mixture predominantly gives a diesel product. In both cases, a lower yield of biofuel results from the mass loss, and also some energy loss in the case of FCC, whereas the HDO treatment has a high energy yield based on the input biomass energy, as energy from external hydrogen is consumed.

Another pathway combining these routes are an initial hydrotreatment to stabilize the FPO followed by FCC treatment. The benefit is that both acidity and oxygen is reduced, and the blend ratio for co-processing can be increased significantly.

In the EU, biofuel derived via pyrolysis are advanced biofuels. In the USA, the fuels derived from biogenic materials and wastes are cellulosic biofuels, with the exception of non-cellulosic components of annual cover crops, where the fuel is an advanced biofuel.

The pyrolysis technology to produce an intermediate biooil, is demonstrated at TRL 8 by a handful of Ensyn plants in North America over the last decade and more recently by BTG in the Netherlands and Valmet/Fortum in Finland at capacities ranging from 10 000 -50 000 tonnes biooil/year, or approximately 4 000- 20 000 toe/year. However, this far, the primary product is a replacement of fuel oil. Nevertheless, upgrading of such bioils to biofuels in integrated plants or by refinery co-processing at percentage blends have been and is tested at different scales, but mainly at TRL5-6 pilots. In 2018, Ensyn reported that they had a take-off agreement for biooil intermediate with Valero, but specific details were not given. In late 2019, the Pyrocell in Sweden announced the start of construction of a 25 000 tonnes/year biooil plant co-located at a sawmill. The plant will be based on the BTG technology and the bio-oil off-take is for co-processing by the Preem Lysekil refinery, Sweden.

Hydrothermal liquefaction (HTL) to bioliquid intermediates

The hydrothermal liquefaction (HTL) process can treat lignocellulosic or other biomasses as well as waste fractions. Lignocellulosic and other solid feeds must be pre-treated to allow the formation of a slurry at a reasonably high solid content by mechanical or thermomechanical pre-processing such as e.g. steam explosion. On the other hand, wet fuels like sludges, algae etc. can be processed without drying, which would be necessary for other thermal processing methods.

Hydrothermal liquefaction (HTL) is a thermochemical conversion process of biomass (lignocellulosic or other biomasses) into a liquid intermediate by processing in a hot, pressurized water environment, typically 250 °C to 420 °C (but can be higher) and in a pressure range is 4 MPa-30 MPa (i.e. both subcritical and supercritical conditions), for sufficient time (10-60 minutes) to break down biopolymeric structure to liquid and gaseous components. The operating conditions are quite challenging, the feed must be turned into a pumpable slurry, and this slurry and the liquids produced have an impact on the lifetime of pump, valves and construction materials, etc.

The HTL process usually produces four different product fractions, a gas phase, a solid residue, a liquid aqueous phase and a liquid oily phase, i.e., bio-crude. The produced bio-crude intermediate separates from water but still has 10-20% oxygen and still a relatively high acidity. The HTL bio-oil has several more or less direct utilization routes e.g. low-blends into bunker fuel, but it can also be upgraded as an integrated process step or by co-feeding in refinery units to produce drop-in biofuels. The upgrading technology for this type of oil is in principle similar to the upgrading of pyrolysis oil, see section “Pyrolysis to bioliquid intermediates”.

In the EU, biofuel derived via HTL processing of biomass residues and wastes are advanced biofuels. In the USA, the fuels derived from biogenic materials and wastes are cellulosic biofuels, with the exception of non-cellulosic components of annual cover crops where the fuel is an advanced biofuel.

Most of the research on HTL has been done in batch processes, but several technology developers (PNNL/Genifuel, KIT, Aalborg University and Steeper Energy, Licella) have developed continuous TRL 5 pilot systems. However, prototypes ranging from 4 000 up to 16 000 tonnes/year, say 3 000 to 12 000 toe/year are in construction for forest wastes (Canfor, Canada and Silva Green Fuels, Norway) and plastic wastes (ReNew ELP, UK) with the intention to have off-site upgrading of the oil intermediate in fossil refineries. Nevertheless, compared to pyrolysis technologies, the upgrading of the intermediate bioliquid has not been tried to the same extent as for pyrolysis oil, such that overall, the technology when producing biofuels is at TRL4-5.

Lignin to bioliquid intermediates

Lignin, one of the three main components of lignocellulose and also one of few aromatic compounds produced by plants, is a polymeric substance composed of phenolic monomers that can be used as an intermediate for the production of biofuels. Lignin from pulping processes is dissolved in the pulping (black or brown) liquor and currently used as a fuel in the recovery boiler, where pulping chemicals are recovered for re-use. Such liquors can be gasified by procedures discussed in section “Gasification to synthesis gas and fuel production” and the chemicals recovered. The pulping lignin can be withdrawn up to an estimated 10-20% of the total amount with limited impact on the pulping processes. Pulping lignin can be separated from the liquor by precipitation or by membrane filtration for further separate treatment. An added advantage is that removal of a part of the lignin can allow a higher pulp production as the capacity of the recovery boiler is often a process bottleneck.

Hydrolysis lignin from lignocellulosic ethanol production is also a by-product and is available as a solid after the pre-treatment or after fermentation, depending on the process configuration. Today, it is also mainly used as a fuel for the internal energy demands of the process, plus some export energy, but could possibly be better valorized as a biofuel.

The processing of the separated lignin is in the liquid phase such that precipitated lignin is dissolved. First, de-polymerization to phenolic mono- and oligomers is accomplished by chemical catalysis using bases or acids in combination with thermal or HTL processing and/or hydrogen treatment. The oligomeric and monomeric substances, depending of the level of depolymerisation and nature of the components, are then dissolved in a fossil or a triglyceride feed fraction or reacted via esterification with e.g. mixed fatty acids to allow mixing with a fossil fuel fraction. Finally, the lignin-derived feed is co-fed to a refinery and is hydro-treated to remove oxygen and to produce cyclical aromatic or aliphatic hydrocarbons, depending on the process severity. The upgrading technology for this type of oil is in principle similar to the upgrading of pyrolysis oil, see section "Pyrolysis to bioliquid intermediates".

In the EU, biofuel derived via HTL processing of biomass residues and wastes are advanced biofuels. In the USA, lignin is not a feedstock listed in any approved pathway at present.

In Sweden, there are a few developments (Renfuel, RISE, Inventia, SCA and Suncarbon) targeting lignin in or separated from black liquor, and a few pilot scale units at TRL5-6 are being implemented. This pathway still has to reach the demonstration phase, and only Renfuel has this far disclosed plans for building a plant in Sweden consuming 25 000-30 000 tonnes/year of lignin and the intermediate to be co-processed by refiner Preem.

There are activities for recovering lignin from cellulosic ethanol plants, but the main focus is on bio-based materials rather than on biofuels, even if there are some activities aiming at biofuels.

Sugars to biofuels

Isolated sugars, today from crop or starch sources but in the future possibly also from lignocellulosic sources, is the starting point for a number of pathways to biofuels. There are two types of processes, one involving engineered microorganisms and one via aqueous chemical reactions.

The fermentation route involves different developments. Engineered yeasts can be used to ferment sugar into a class of compounds called isoprenoids that have use for pharmaceuticals, nutraceuticals, flavours and fragrances and chemical intermediates, as well as fuels. One of these isoprenoids is a 15-carbon hydrocarbon, beta-farnesene. It has been hydrogenated to farnesane, a compound accepted for 10% blending in jet fuel as Synthesized Iso-Paraffinic fuel, (SIP) in the ASTM D7566 standard. Another development is to produce butanols from sugars. Some bacteria naturally produce butanol and yeast can be engineered to produce butanol instead of ethanol. This pathway can be used for producing both n-butanol and iso-butanol, the latter also having a high value as a chemical building block.

A third development is to use an engineered microorganism to produce iso-butene that can be the basis for chemicals but also oligomerized and hydrogenated to e.g. gasoline. Since iso-butene is a gas that separates from the broth, this facilitates the product separation and upgrading, as well as limiting any product inhibition issues.

The second route is by chemical reactions called aqueous phase reforming (APR) that utilize heterogeneous catalysts including zeolites, metals and noble metals at temperature and pressure (200 °C-250 °C, 3 MPa-5 MPa) to reduce the oxygen content of the carbohydrate feedstock. This involves hydrodeoxygenation reactions that consume hydrogen simultaneously produced *in-situ* from the carbohydrate feedstock. The product from the APR step is a mixture of chemical intermediates including alcohols, ketones, acids, furans and other oxygenated hydrocarbons as well as paraffins which can undergo further catalytic processing using zeolites to generate a mixture of non-oxygenated hydrocarbons.

Yet another chemical pathway is to convert the sugars into specific platform chemicals, such as Hydroxy-Methyl-Furfural (HMF), furfural or levulinic acid that can be further upgraded catalytically to fuel blending components or hydrocarbons. However, this pathway is preferably used at present to produce bio-based speciality chemicals rather than fuels.

This far, all developments at pilot scale have focused on cane sugar or crop starch, as sugar-containing products produced via enzymatic hydrolysis of lignocellulose contains more inhibitors and C5 sugars. However, at laboratory scale there are developments to develop the tolerance of the microorganisms to widen the feedstock basis.

The biological technology that has reached the farthest is the Amyris technology to produce farnesene from sugars, a plant in Brazil with a capacity of 40 tonnes/day (some 12 000 tonnes/year or approximately 12 000 toe/year) has been operated and part of the products converted to bio-jet. However, the plant was sold to DSM and the Amyris and DSM activities are now focusing on high-value chemical specialities rather than on fuel at present.

Other developers including Gevo and Butamax have used fermentation technologies to produce iso-butanol at 5 000 tonnes/year (4 000 toe/year), and at 20 tonnes/year (18 toe/year) capacity, respectively. Both companies have plans for scale up at ethanol plants in the USA. Global Bioenergies, a French company, has developed a fermentation technology for producing iso-butene from sugars, and operates a 100 tonnes/year (108 toe/year) demonstration facility in Germany. The company has announced plans for a first industrial prototype in France. REG Life Sciences was pursuing a technology using bacteria to produce fatty alcohols at pilot scale. The company was acquired from REG by Genomatica in 2019, which may shift the product focus away from fuels. Overall, this pathway can be said to be in the TRL 5-8 range.

Chemical conversion of sugars to hydrocarbons is pursued by e.g. Virent at up to TRL 5 pilot scale.

Non-lignocellulosic biomass

Photosynthetic algae (including macro- and micro-algae) and photosynthetic cyanobacteria have the potential to produce considerably greater amounts of biomass per hectare than most terrestrial crops and some species could even directly produce fuel (H_2, ethanol or alkanes). Aquatic biomass can be cultivated using industrial carbon dioxide as carbon source and wastewater as nutrient input (nitrogen and phosphorus), thereby not competing with food crops for land or other resources. However, due to the large volumes of water involved in the cultivation, nutrient balancing and recovery, as well as contaminant control are essential for economic and environmental feasibility.

Large scale cultivation of microalgae in onshore, outdoor open pond systems and raceways is well established but limited to a few algal species which can tolerate extreme environmental conditions such as high salinity (Dunaliella), high pH (Spirulina (Arthrospira)) or undergo extremely high specific growth rates (Chlorella). Closed cultivation systems for microalgae, usually onshore, utilize photobioreactors made of transparent tubes, plates, bags or domes, which permit culture of single species at higher productivity than in open systems. However, inhibition due to the oxygen formed is a scale-up issue and furthermore, the prevention of intrusion of other competing species is also a challenge. Macroalgae (seaweed) are usually cultivated in offshore farms but their productivity is much lower than that of microalgae and may also have a seasonal growth pattern.

The typical microalgae concentration in cultivation broths is as low as 0.1-1% of total dry suspended solids which requires an at least two-step recovery by thickening and dewatering to reach a concentrate of 15-25% dry matter. To avoid degradation, the concentrate must be dried. The harvesting and drying are very energy demanding and account for a large part of total energy consumption, and methods for using e.g. waste or solar heat are pursued.

Algae biomass composition consists of carbohydrates, proteins, lipids and other products such as pigments, vitamins, etc., for use in food, cosmetics and other niche markets. The lipids, up to 70% on a dry basis, have been the most interesting fraction for conversion into biofuels. However, the extraction of the lipids requires energy-consuming methods for breaking the cell walls. The lipids, once separated from the other components, can then be converted to FAME and HVO, see sections "Biodiesel from triglycerides and lipids (FAME)" and "Hydrogenated triglycerides and lipids (HVO)".

In some cases, in particular for macroalgae, the cell walls are composed of carbohydrates that can be hydrolysed and the sugars fermented to ethanol.

Also, HTL (see section "Hydrothermal liquefaction (HTL) to bioliquid intermediates") of aquatic biomass is being developed as this process can avoid the need for extensive dewatering and drying. The entire algae biomass may also be used without or with limited dewatering via anaerobic digestion to produce bio-methane, see section "Biomethane from upgrading of anaerobic digestion biogas". These two technologies are also considered for processing the algal biomass residues, once lipids and sugars have been recovered.

Algal-derived biofuels would be advanced biofuels in the EU, while there is no algal pathway under RFS2 that has been approved by the EPA. Nevertheless, at present algal conversion routes would have a problem of meeting the GHG reduction requirements, with the possible exception of HTL and biomethane pathways.

During the last decade, there has been a number of developments at TRL 5 pilot scale to cultivate algae for production of bio-methane, lipids for FAME and HVO, as well as sugars for ethanol, as described in the cited report[33]. However, the decrease in the energy prices in 2014 have for most developers meant that the interest has shifted from fuels to high-value chemical specialities, and the energy is more seen as a way of valorising biomass as biomethane.

Low-carbon transport fuels from fossil waste sources

Steel industry & chemical industry off-gases

The feedstock for these processes is a variety of industrial waste gases that are today flared or used for energy (power and/or heat) production in excess of what is used for the internal

[33] SGAB Technology status and reliability of the value chains: 2018 Update. 28 December 2018. Ed. I Landälv, L Waldheim, K Maniatis.

needs of the process from which they are emanating. Examples of such gases are coke oven gas (COG), blast furnace gas (BFG) and basic oxygen converter gas (BOF gas) in the steel industry, converter gas from production of alloying metals and refinery off-gases that are similar to BOF gas. While coke oven gas and refinery fuel gases are rich in methane and other hydrocarbons, the other gases are very rich in CO but have low hydrocarbon content.

Such gases can be used to produce FT hydrocarbons or methanol after generating a gas similar to synthesis gas, see section “Gasification to synthesis gas and fuel production”. Gases with high hydrocarbon content are treated by steam reforming or partial oxidation to generate synthesis gas. The catalytic conversion of CO rich gases requires that H_2 is available in the synthesis gas in the correct proportions, which can be accomplished by a water gas shift reaction step consuming CO to produce H_2. The gases are then cleaned to synthesis gas quality by similar processes and then converted to fuels by the same type of catalytic reactions as was described in the cited section. There is one example of methanol production from coke oven gas in China.

Another option is gas fermentation that can utilize gas streams with a wide range of CO and H_2 compositions directly to produce ethanol, as the acetogenic microbes used are also capable of an efficient biological water gas shift reaction. Furthermore, the gas purity requirements are less strict than for chemical catalysis. The ethanol produced is then separated by distillation and dehydration as described in section “Ethanol from sugar and starch crops”. A tail gas, including any hydrocarbons in the feed, unreacted CO and H_2 not converted as well as CO_2 leaves the process. Some of the energy in the feed gas is consumed to build microbial biomass in the system. The excess biomass can be used to produce biogas via anaerobic digestion. The biogas together with the tail gas can be used to cover process energy needs.

Lanzatech have developed technology at TRL7, approaching TRL8, for CO or synthesis gas fermentation which is being demonstrated at industrial scale, 45 000 tonnes ethanol/year (29 000 toe/year) in a steel mill in China using CO-rich BOF gas. A second plant is under construction in Belgium using a mixture of BOF and blast furnace gas at a capacity of 65 000 tonnes ethanol/year (42 000 toe/year), and there are also a number of other projects being pursued, e.g. with Aemetis, for ferroalloy off-gas in South Africa and for refinery gas in India.

Waste plastics and the fossil fractions of wastes

Waste plastics, non-biogenic fraction of RDF etc. can, either separated or together with biogenic fractions, be processed by thermal conversion and upgrading methods already described above such as gasification, pyrolysis and HTL, and thus being at the same TRL level. The Enerkem gasification developments were already described above in section "Gasification to synthesis gas and fuel production".

One specific type of processing which has recently received a lot of attentions is the processing of separated plastic waste streams via pyrolysis or HTL systems. The pyrolysis of waste plastics, mostly fractions or mixed fractions of polyethene, polypropene and polystyrene, is mostly performed by slow pyrolysis at 400 °C in kilns or other types of furnaces to render a mixed oil fraction, char and some gases, the latter used internally as a fuel. The oil fraction from pyrolysis or from HTL processing can then be fractionated by distillation to yield conventional hydrocarbon fuel fractions, in particular a diesel fraction. This is mostly done as an integrated part of the process due to legal requirements in the EU, but could also be done in a refinery. Any liquid residue is recycled or used for energy in the process.

There are a number of such developments in the USA and the EU at a scale of 10 000-40 000 tonnes/year. Some examples of developers with industrial scale plants in operation and/or construction are IGE Solutions (NL), JBI (USA), Klean Industries (JP), Nexus Fuels (CN), Plastic Energy (UK), Quantafuel (NO), Recycling Technologies (UK), ReNew ELP (UK), Remondis (DE), Renewology (USA), and VADXX (USA).

Low-carbon transport fuels from other forms of renewable energy

In the EU, this refers to fuels that are produced using energy from other renewable energy sources. In practice this means the use of renewable power from geothermal, solar or wind power, where a local excess production can result during shorter or longer periods, thereby giving access to such energy at low costs. There are also developments using e.g. concentrated solar power or geothermal energy as a source for direct heat for use in fuel production.

Hydrogen

Production of hydrogen from renewable power is produced by means electrolysis of water in electrochemical cells. Electrolyzers are composed of several cells arranged in "cell stack" modules that can then be multiplied to reach the desired output capacity. The hydrogen produced is then compressed or liquefied for storage.

Hydrogen production by means of alkaline electrolyzers has been around for more than a century and is a fully commercial technology. Another technology that has more recently been introduced is the so-called PEM (Proton Exchange Membrane), which is now competing head-to-head with the alkaline electrolyzers. Other types (MCEC and SOEC, molten carbonate and solide oxide electrolyzer cells, respectively) are still in development. Electrolyzers installations have typically been up to a few MW in capacity, set by the hydrogen user's requirements. However, with the increased use of wind and solar power generation and also demand for hydrogen, and in particular renewable energy (RE) hydrogen, installations are growing in capacity to 10-20 MW and installations of 100 MW are in planning and 1 000 MW installations are studied in the Netherlands

E.ON has a power-to-gas (PtG) pilot unit in Falkenhagen, Germany with an electrolyzer capacity of 2 MW, the output mainly being injected to the gas grid, but also used by local users. A second PtG pilot unit is in construction outside Hamburg to demonstrate a more compact and efficient electrolysis equipment.

In addition, hydrogen form renewable sources can also be added to other biofuel conversion pathways. One concept is a hybrid gasification-to-biofuel pathway. Hydrogen addition results in process savings and a more efficient use of the biomass resources as the yield of biogenic carbon to fuel increases up to twice the amount without hydrogen addition[34]. Renewable hydrogen can also be used in other pathways where hydrogen is used, e.g. HVO, the upgrading of pyrolysis, HTL and lignin intermediate oils, thereby eliminating the internal production of hydrogen in stand-alone biofuel plants or replace fossil hydrogen in refineries. Another possibility is to add hydrogen to anaerobic digesters, and thereby assisting in the methanogenesis step to produce additional biogas from the CO_2 present.

E-fuels (aka PtG or PtL)

Electrofuels (E-fuels), Power-to-Gas (PtG) and Power-to-Liquid (PtL) refers to technologies, which convert renewable electric energy to another energy carrier, like for example methane, methanol or synthetic hydrocarbon fuels via the Fischer Tropsch process.

In short, as a first stage, electricity is converted to hydrogen through electrolysis as described above. To produce a hydrocarbon or alcohol fuel, a carbon source is also required. This carbon source is typically CO_2, which is readily available from many sources e.g. biogenic CO_2 from bakeries, ethanol fermentation in breweries or ethanol fuel plants, as well as from biomethane upgrading or gasification plants, or fossil CO_2 from, e.g. coal power plant flue gases or industrial waste gas streams in e.g. refineries and chemical plants. This use of CO_2 is also often referred to as an example of Carbon Capture and Utilization (CCU).

[34] Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment, Hannula, Ilkka. Energy, Volume 104, Pages 199-212, 2016.

The production of fuels is essentially as described for gasification synthesis gas as described in section “Gasification to synthesis gas and fuel production”. In the case of production of biomethane or gas fermentation to ethanol, CO_2 and H_2 can be reacted directly. For other products such as methanol and FT hydrocarbons, a reverse water gas shift reaction is needed to convert CO_2 to CO, prior to the catalytic synthesis process where the products are formed.

The largest Power-to-Methanol facility is the CRI’s ‘George Olah’ Renewable Methanol Plant with a capacity of 4 000 tonnes per year.

In addition, there are a number of pilot initiatives to produce methane (Audi/Solar fuels (DE), BioCAT (DK), methanol (MefCO2 (DE), Thyssen Krupp (DE)) and FT liquids (Sunfire (DE)) based on hydrogen from electrolysis at a scale of 1-5 MW electrolyzer capacity.

In general, these technologies are at TRL5-6, with the exception of the CRI plant at TRL8.

Availability and costs of sustainable bioenergy feedstocks

The theoretical availability and cost modelling indicate that large volumes of sustainable feedstock could be made available for biofuels production, sufficient to meet likely future demand as indicated in low carbon scenarios. Most of the material necessary could be supplied from wastes and residues, and from sustainable forestry practices. Agriculture can also be an important source of raw materials, with feedstocks produced in ways which complement traditional agricultural production through co-cropping and through use of less productive land.

Estimates of the potential available biomass and other uses vary significantly in the literature. While the theoretical potential is high, the economic availability can vary greatly, depending on numerous factors including yield and regional parameters (e.g. location and size of crop/forest lands, local infrastructure, etc.). There is a wide range of biomass availability globally, from as low as 95 Exajoule (EJ)/year to as high as 350 EJ/year. National studies indicate that much of the raw material could be produced and delivered to users at costs of between 3 - 6 EUR/GJ. More information from real projects is needed to test the costs of procuring suitable feedstock in the real world.

The overall biomass cost is highly case dependent and successful management of biomass supply chains will be critical if future investments in biofuels are to be realized. Despite efforts to reduce the cost of biomass and associated logistics, it is anticipated that increasing competition for commercial quantities of biomass will result in an increase in the price of the biomass feedstock.

National and regional assessments are very helpful in providing insights into likely long-term availability and costs of feedstocks for bioenergy production, including for the production of emerging biofuels. However, in order to be useful for estimating long term global availability such assessments need to be done in a very transparent way, with clear classification of the various resources and of the assumptions made in defining how much material could in practice be available, and around the sustainability considerations applied.

A useful step in harmonizing such approaches would be the development of some best practice guidelines for such studies, including some standardization and rationalization of the classification of the various potential feedstocks, and of the sustainability constraints which are applied. Such measures could facilitate the development of more consistent resource estimates, which could be more easily compiled to give a global estimate, at least for key producer and user regions.

Potential feedstocks and costs

Food crops such as corn, sugarcane and wheat are the primary feedstocks for the world's transportation bioethanol while vegetable oils such as rapeseed and soybean are currently the primary source of feedstock for bio/renewable diesel [35]. However, food security concerns and sustainability issues such as indirect land use changes (ILUC) have influenced biofuel policies to encourage the production and use of low-carbon biofuels that will be produced from lignocellulosic sources such as agricultural and/or forest residues[36]. A recent example is the 2018 revisions made to European Union's Renewable Energy Directive (RED), referred to as REDII, to include solid biomass sustainability criteria and stricter biofuel sustainability criteria as well as caps and quotas for the use of biofuels made from certain feedstocks, see section "Overview of regulated fuel qualities". Consequently, availability of food crops for the production of established biofuels on top of the current production is not assessed further in this report. The focus of the feedstock availability and cost will be on biomass and lignocellulosic residues, which are shortly called "biomass" in the remainder of this section.

Many different biomass types may be considered as feedstocks for emerging biofuel pathways. These can either be wastes, residues and by-products from other biomass-based production processes or energy crops specifically produced with energy production in mind. The feedstocks produced from wastes and residues for conversion to biofuels may be considered in four separate categories. [37] These are:

- Wastes - materials which have no other useful purpose, and which otherwise have to be managed, usually incurring a cost.
- Processing residues and by products which arise part of an industrial process and are already available in quantity at a particular site (including for example sawdust to be used for pellet production).
- Locally collectable residues which are produced as part of a harvesting procedure,

[35] Araújo, K., Mahajan, D., Kerr, R., Silva, M., 2017. Global Biofuels at the Crossroads: An Overview of Technical, Policy, and Investment Complexities in the Sustainability of Biofuel Development. Agriculture, 7, 32; doi:10.3390/agriculture7040032

[36] Popp, J., Harangi-Rákos, M., Gabnai, Z., Balogh, P., Antal, G., Bai, A., 2016. Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications. Molecules, 21, 285; doi:10.3390/molecules21030285.

[37] International Energy Agency (IEA), Paris, Technology Roadmap - Bioenergy for Heat and Power, 2012.

but which are dispersed, and which must be collected and brought to a central point before they can be used, such as cereal straw, forestry residues.

- Internationally traded feedstocks, such as wood pellets, based on raw materials available at an industrial site, which are extensively processed to improve the energy density and then transported long distances to supply large scale conversion plants.

Municipal Wastes

Disposal of waste materials such as municipal solid wastes pose an increasing environmental problem, especially in major cities, and is a major priority in rapidly growing economies such as China and India. Finding disposal solutions such as landfill become increasingly difficult and costly as volumes grow. Landfill is increasingly seen as environmentally unsustainable due to impacts such as methane emissions and impacts on water-courses. Solutions to minimise the problem include reducing waste generation, reusing and recycling materials and making use of some fractions of the waste as a feedstock, including for energy production through combustion and CHP production. The wastes are also being increasingly considered as a potential feedstock for biofuels production. The material in its raw form is very heterogeneous and significant pre-processing is needed to separate recyclable material (often required to reach recycling targets and related legislation and to produce a refuse-derived fuel which has a more closely defined specification, before it can be used as a feedstock.

Using wastes such as the biogenic fraction of MSW as fuel or feedstock provides an alternative disposal or environmental treatment option that avoids disposal costs at a landfill. This environmental credit is often necessary to make energy projects economically viable, because the difficult characteristics of the feedstocks require specific technologies with high capital and operating costs, while the resulting fuel products are sold at general market prices.

The credit available for removing materials from the waste stream depends on the environmental legislation in place. For example, the EU has an objective to move away from landfilling as part of its waste management directive, and has set targets for countries to reduce the wastes sent to landfill. This has stimulated countries to act. For example, the UK has introduced a land-fill tax on materials sent for landfill, which has been increasing steadily and now amounts to £91.35 (around 107 EUR) per ton of waste. This acts as a strong incentive for other waste disposal methods which can offer a lower disposal cost. In other countries, landfilling of combustible or organic wastes is prohibited by law, and incineration is dis-incentivized by taxation, generating similar drivers. This means that waste can be available at a negative cost at the conversion plant in areas where waste management policies and regulation are pushing a move to alternative waste disposal methods.

Some waste materials can acquire a value once there is a profitable use for them. For example, Used Cooking Oil (UCO) and tallow have a traded market value when used for biodiesel or HVO production. If conversion capacity exceeds the local availability of material, then they acquire a scarcity value which can seriously affect the profitability of operation. Securing long term waste feedstock supply contracts therefore is often a prerequisite before such plants can be financed.

Processing residues

Many bio-based industrial processes lead to the collection and concentration of large volumes of residues at the point of production. For example: the timber processing produces large volumes of sawdust and other wood residues; pulp and paper production generates black liquor; the sugarcane industry produces large volumes of bagasse.

If there are no existing uses for these materials, or an excess once internal energy needs have been satisfied, they can be available at zero or low costs as the production and collection costs of such materials have already been occurred as part of the original process. However, such other economic uses are often possible and the materials acquire an “opportunity cost”. For example, saw mill residues can be converted into wood pellets. Bagasse is the main source of energy for power and heat in the sugar mill, and is increasingly used for high efficiency co-generation resulting in grid-export of power. However, due to the use of mechanical harvesting increasing amounts of cane trash become available as fuel replacement for bagasse. Costs for use at the site where they are to be used typically range from zero to 15 EUR/MWh.

For process residues, the size of bioenergy plant operation may be limited by the availability of the raw materials, although this can be supplemented by bringing in additional materials available nearby in some cases but increasing costs. (For example, bagasse in sugar mills is increasingly being complemented by cane trash residues that were otherwise left in the sugar fields).

Collectable residues

These are materials produced during harvesting operations in agriculture or forestry that can be collected and brought to a central point for conversion into energy. Given the cost of collecting, transporting and eventually storing of the biomass, the costs of the delivered feedstock are increased since the collecting and transporting costs must be met by the user, with typical costs of 4-8 EUR/GJ (15-30 EUR/MWh). Increasing the catchment area pushes up the transport costs (and related CO_2 emissions) and will thus limit the economic scale of operation of such plants, with a catchment area usually limited to around 50 km radius.

Internationally traded fuels

Finally, there is the prospect of pre-treating biomass to produce solid, liquid and gaseous feedstocks with high energy density, suitable for international long-distance shipping for use in large scale conversion plants. For example, wood pellets produced from sawmill residues, are currently produced in several regions including Russia, British Columbia and the Southern United States, and brought in bulk sea carriers to Europe for large scale power generation. Given the attractive incentives in several European countries, many European based utilities are actively developing supply chains all around the world. Currently such trade is motivated by incentives provided in European markets. Such fuels are compatible with the large scales of operation which provide for more efficient power generation. Larger plants will also be preferred for biofuels production in order to gain the economies of scale associated with larger conversion plants. Costs for such fuels may reach 30-45 EUR/MWh.

In the long run it is likely to be more economic to site conversion plants close to where large quantities of low-cost feedstocks are available and to transport the finished fuel products, which have higher energy densities and are easier to handle.

Energy crops

While crops such as sugar, corn or palm, which can be used for food or animal feed production as well as a feedstock for biofuels production, it is also possible to grow crops specifically for energy purposes. Examples are the production of miscanthus, short rotation forestry (including poplar and willow) and crops such as jatropha (which contains an oil). In these cases, all the production, harvesting, and pre-treatment costs must be met by the off-taker. Care must also be taken to avoid displacing food production, and to minimise any negative direct or indirect land-use emissions (although moving from annual food crops to perennial energy crops may help improve soil carbon content).

To avoid competition with food production and to minimise associated land-use change emissions, energy crops may be produced as part of a rotation scheme, thereby not affecting the food and feed production of the same land. For example, trials show that carinata can be used as a "catch crop" produced between crops and improving soil carbon levels.[38] Alternatively crops can be produced on marginal land no longer in active use by farmers, and can help to restore the quality of such abandoned land.

Price versus costs

The costs of some of these resources may be low, and early users of the materials as feedstocks may benefit from this in terms of the prices they pay to producers. However, once a market for the material starts to develop, and especially if there is potential for competition between users for material, then the materials may acquire a higher value. For example, in Europe a number of plants were built designed to use post-consumer waste wood (from demolition sites etc.) to produce electricity. The financial investment case was based on the assumption that the developers would receive a gate fee for the materials which would otherwise have been sent to landfill. However, as capacity outstripped local supply, the wastes acquired a scarcity value and now commands a positive price, undermining the profitability of the plants that had been built.

Developers tend to try and avoid such issues through careful siting of plants so that there is no competition for local resources, and by a long-term contracting strategy that locks in supply for an extended period. Companies also seek vertical integration of their supply chain, so as to be in control of more elements of the supply chain. For example, the bio-power group Drax in the UK have invested in wood pellet mills in the south of USA; Neste and other HVO companies have acquired UCO collection entities; UPM are developing energy crop supply chains in South America.

Future Feedstock Cost

It is apparent that potential biomass supply costs will be influenced by many factors such as feedstock production costs, cost of harvesting and collection equipment, pre-processing operations (e.g. grinding and drying), storage regime, transportation distances and modes, etc. As summarized in Figure 2, the supply costs of biomass are a function of the total annual global biomass supply, with projected amounts available in 2030. The supply potential of each biomass component is summarized into two components: (i) the domestic supply cost (in USD/GJ) and the domestic supply potential (in EJ/ year) (fully coloured columns in the figure); and (ii) the related supply cost and the exportable volume (surplus)

---

[38] UPM Carinata farms absorb carbon dioxide from the atmosphere, July 2019. https://www.upm.com/news-and-stories/articles/2019/07/carinata-farms-absorb-carbon-dioxide-from-the-atmosphere/

(hatched columns in the figure) if a region has export potential[39].

Domestic biomass resources can be classified into three supply cost groups: (i) < USD 5 per GJ (4.5 EUR/GJ)[40] (low); (ii) USD 5-8 per GJ (4.5-7.3 EUR/GJ) (medium); and (iii) > USD 8 per GJ (7.3 EUR/GJ) (high). The low-cost group generally consists of processing residues and wastes (e.g., bagasse, corn cobs, rice husk, wood processing residue, animal waste). Feedstock costs can be zero for wastes which would otherwise have disposal costs or that are produced onsite at an industrial installation (e.g. black liquor at pulp and paper mills or bagasse at sugar mills). The medium-cost group consists of harvesting residues (e.g., cereal straw, corn stalk or other crop residues collected from the field) and the high-cost group consists mainly of energy crops and fuel wood. Although residues can be supplied at a relatively low cost, if supply chains are well established, utilization is typically restricted to short distances since transportation/collection costs are usually significant.

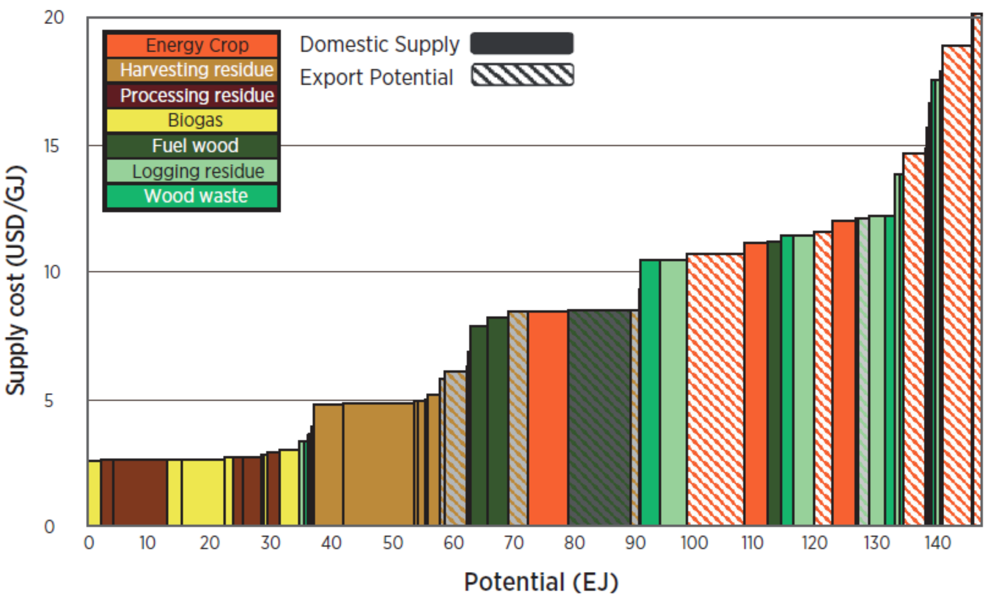


Figure 2: Projected annual global supply for primary biomass in 2030[35]

[39] The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

[40] 1 USD= 0.9 Euro

It has been estimated that the average, global cost of biomass is about USD 8.3 per GJ (7.5 EUR/GJ) (IRENA, 2014) with the cost of domestic biomass ranging from as low as USD 3 per GJ (2.7 EUR/GJ) in Africa (agricultural processing residues) to as high at USD 17 per GJ (15.5 EUR/GJ) for energy crops in more developed parts of the world. The amount of exportable biomass available in regions with surplus biomass is estimated to be about 26% of the total global supply potential. However, the costs associated with transporting this biomass to different world regions are estimated to add an average of USD 3 per GJ (2.7 EUR/GJ) to domestic prices (from 0.5 via rail to USD 4 per GJ (3.6 EUR/GJ) via ship, depending on the distance and transport mode)[39]

Predicting ways to reduce biomass costs is challenging as numerous factors are involved including the robustness of the local supply chain, resource potential, land availability, competitive industrial uses, sustainability criteria, etc.[41]. Thus, the overall biomass cost is highly case dependent and successful management of biomass supply chains will be critical if future investments in bioenergy and biofuel are to be realized. However, as covered in more detail below, there has been considerable progress in several areas of biomass handling such as improved mechanization for harvesting, collection and transportation of biomass, efficient pretreatment of biomass and processing to energy dense products (e.g. pellets) and the efficient use of road, rail and marine transportation of biomass over short-to-long distances. Other examples include:

- The forest industry reducing grinding costs of processing forest residues by improving the efficiency and the fuel consumption of this operation. In some regions of Canada, a grinding cost of 20 $CAD/dry tonne (dt) has been achieved as compared to previous costs of $CAD25-30/dt (20-30% reduction in the cost of grinding forest residues at the roadside)[42,43]. Ongoing research is looking into further integrating forest biomass logistics systems with existing forest supply chains to further reduce biomass logistics cost.

---

41 IRENA, 2012. Renewable energy technologies: cost analysis series- Volume 1: Power Sector, Issue 1/5, biomass for power generation. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-BIOMASS.pdf

42 International Wood Markets Group Inc., 2014. Wood products business case options for the Fort Nelson area. Prepared for Northern Rockies Regional Municipality.

43 FPInnovations, 2017. Using FPInterface to estimate availability of forest-origin biomass in British Columbia: Mackenzie TSA.

- Development of "Best Management Practices for Integrated Harvest Operations in British Columbia" to reduce the logistics costs and improve the quality of collected forest residues[44]. For example, new truck configurations with higher Gross Vehicle Weight (GVW) were introduced to reduce transportation costs. Another example is improving the piling practices of forest residues at the roadside to reduce their ash and moisture content. Good piling practices have also been shown to reduce the operating costs of handling, grinding and loading of forest residues onto trucks.
- The development and commercialization of new forest and agricultural equipment by Original Equipment Manufacturers (OEMs) such as Tigercat 845D equipped with specialized biomass shear head, Tigercat 630D skidder with oversized grapple, Peterson Precision whole tree chipper, Vermeer ZR5 self-propelled baler and Krone pellet harvester have increased the operating capacities and reduce the logistics costs of forest and agricultural biomass.
- In 2010, the US Department of Energy, Bioenergy Technologies Office funded five projects known as high-tonnage feedstock logistics projects to support AGCO Corporation, FDC Enterprises, TennEra LLC, the State University of New York College of Environmental Science and Forestry and Auburn University to work in partnership with OEMs to develop commercial harvesting equipment for corn stover, switchgrass and woody biomass feedstocks. As of late 2014, all five US DOE BETO-funded high-tonnage feedstock logistics projects have been completed, demonstrating significant cost reductions ($US13/dt on average) for collecting, storing, and transporting biomass. Some of these technologies are already commercialized.

  Demonstrated cost reductions included[45]:
    - AGCO Corporation: 29% reduction ($US51.54/dt to as low as $US36.75/dt) for single-pass harvesting, high-density baling and modified truck trailers.

---

44 FPInnovations, 2018. Best Management Practices for Integrated Harvest Operations in British Columbia. http://blog.fpinnovations.ca/blog/2017/09/18/a-new-guide-for-integrated-harvest-operations-in-british-columbia/

45 US Department of Energy (US DOE), Bioenergy Technologies Office 2014 accomplishments and successes: Growing America's energy future. Retrieved from https://www.energy.gov/eere/bioenergy/bioenergy-technologies-office-2014-accomplishments-and-successes.

- FDC Enterprises: 25% reduction ($US50.78/dt to as low as $US37.89/dt) for self-propelled balers, high-density balers, self-propelled bale pickup trucks, and self-loading/unloading trailers
- TennEra LLC: 7% reduction ($US56.38/dt to $US52.34/dt) for field chopping, bulk handling, and storage.

- In the area of feedstock development, improved energy crops that exhibit more favorable chemical compositions and are easier to convert to targeted biofuels have been developed. Examples of transforming sugarcane and Miscanthus into better feedstocks for producing biodiesel and biojet fuels include "engineering" these plants to produce higher levels of oil (lipids) rather than sugar (carbohydrates). In February 2018, the US DOE awarded $10.6 million grant to the so-called ROGUE (Renewable Oil Generated with Ultra-productive Energycane) project, a collaboration by researchers from the University of Illinois, Brookhaven National Laboratory, University of Florida, and Mississippi State University.
- In the area of landscape design, techno-economic analysis carried out by Idaho National Laboratory (INL) demonstrated that, by using integrated landscape management (ILM) techniques, stakeholders could produce energy crops at costs 20% lower than previously obtained[46].
- Projected biomass feedstock costs in Europe (by 2020) suggest that reductions of 2% to 25% could be achieved for agricultural and forest biomass, with projections that energy crops will be 5-10% cheaper as result of harvesting and logistic improvements[47].

With increasing demand for biomass for bioenergy and biofuels applications, it is anticipated that operating costs will continue to fall in parallel with improved quality of biomass delivered to the gate of biorefineries. As previously discussed, transition strategies are already underway in the agricultural and forest equipment manufacturing industries, including both the modification of existing equipment and the development of new equipment that will harvest, collect, transport and process commercial qualities of biomass in a cost-efficient

46 Roni, M., Thompson, D., Hartley, D., Griffel, M., Hu, H., Nguyen, Q, N., Cai, H., 2018. Herbaceous Feedstock 2018 State of Technology Report. INL/EXT18-51654.

47 IRENA, 2012. Renewable energy technologies: cost analysis series- Volume 1: Power Sector, Issue 1/5, biomass for power generation. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-BIOMASS.pdf

and effective manner. Such transitions will be critical if the world is to meet target cost and quality specification identified by the biorefineries that will produce sustainable, low cost biofuels[48].

Despite efforts to reduce the cost of biomass and associated logistics, it is anticipated that increasing competition for commercial quantities of biomass will result in an increase in the price of the biomass feedstock. This has already been observed with the supply of used cooking oil (UCO) and tallow. Both feedstocks are the waste streams of industrial operations that used to be purchased by biofuel producers at zero/low cost. However, due to increased demand for biofuels such as biodiesel and renewable diesel, the price of these feedstocks has increased in recent years is some regions of the world. The cost and price of forest and agricultural residues has proven more variable with both positive (e.g. supply/logistic chain cost reductions) and negative factors (e.g. increased competition for residues) influencing these values[49].

Summary – costs

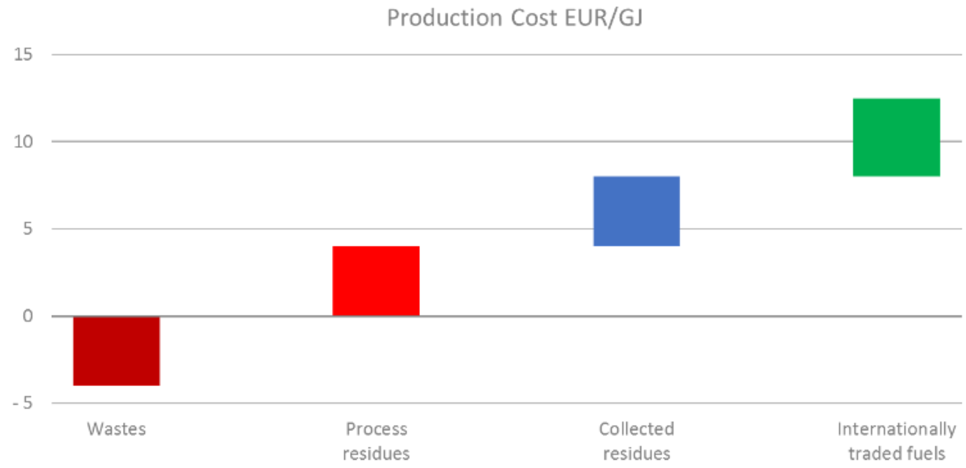


Figure 3: Typical cost ranges for biomass feedstocks

---

48 Mann, M., Biddy, M., Augustine, C., Nguyen, Hu, H., Ebadian, M., Webb, E., 2019. Evaluation of agricultural equipment manufacturing for a bio-based economy. Technical Report NREL/TP-6A20-71570.

49 E4tech, 2017. Ramp up of lignocellulosic ethanol in Europe to 2030. http://www.e4tech.com/wp-content/uploads/2017/10/E4tech_ICLE_Final_Report_Dec17.pdf.

With increasing demand for biomass for bioenergy and biofuels applications, it is anticipated that operating costs will continue to fall in parallel with improved quality of biomass delivered to the gate of biorefineries. However, increasing competition for commercial quantities of biomass will likely result in an increase in the price of the biomass feedstock, a trend that has been observed for forest biomass for the production of wood pellets and used cooking oils and animal fats for the production of biodiesel and renewable diesel.

Feedstock availability

Global estimates

There have been many studies which have attempted to quantify the potential supply of biomass feedstocks for bioenergy use. The range of estimates varies by several orders of magnitude depending on the assumptions made. Key issues include the proportions of various wastes and residues that could be used economically while complying with sustainability requirements, how much land might be used to produce energy crops, given uncertainties around future food demand, regional parameters (e.g. location and size of crop/forest lands, local infrastructure, etc.), crop rotations, slope and soil type, length of the harvest window, collection rates, the presence of a local processor or aggregator, and competing uses (e.g. animal feed and bedding)[50];[51].

As summarized in Figure 4, there is a wide range of biomass availability globally, from as low as 95 Exajoule (EJ)/year to as high as 350 EJ/year. This wide range in estimating the potential availability of biomass is largely due to differences in the assumptions. The different assumptions include land availability, global food consumption, yields and sustainability considerations[52]. However, estimates of biomass availability have come closer in reports published since 2010, primarily because more recent studies take into account sustainability issues and resource limitations, as well as improved quality of data regarding land

50 IEA Bioenergy Task 43, 2017. Mobilization agricultural residues for bioenergy and higher value bio-products: resources, barriers and sustainability. https://www.ieabioenergy.com/wp-content/uploads/2018/01/TR2017-01-F.pdf

51 E4tech, 2017. Ramp up of lignocellulosic ethanol in Europe to 2030. http://www.e4tech.com/wp-content/uploads/2017/10/E4tech_ICLE_Final_Report_Dec17.pdf.

52 The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

availability and yields.

IRENA (2014)[53] estimated that total available global biomass supply will be in the range of 97-147 EJ/year by 2030 (in primary energy terms). About 38-45% of this total supply is estimated to be available from agricultural residues and food waste (37-65 EJ/year) with the remaining amount (60-82 EJ/year) shared between energy crops (33-39 EJ/year) and forest biomass (27-43 EJ/year) (Figure 5). Although agricultural residues and wastes have the greatest global potential, forest biomass is also important. Energy crops could account for 26-34% of the total supply potential, eventually becoming the dominant source of biomass for future biofuel projects[54].

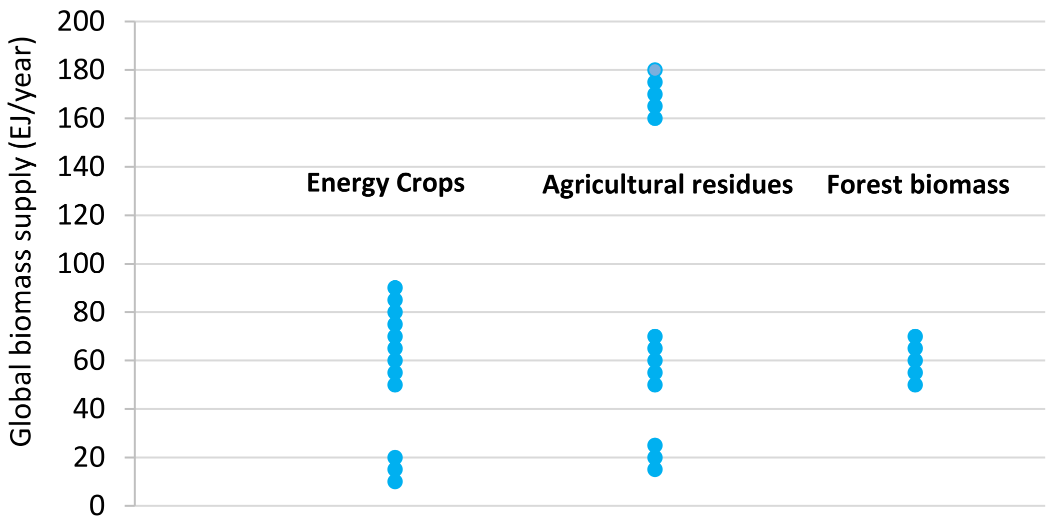


Figure 4: Summary of global biomass energy supply potential estimates in 2030 [55,56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,72]

---

53 IRENA, 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

54 The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

55 IRENA, 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

56 Fischer, G., and Scharttenholzer, L., 2001. Global bioenergy potentials through 2050. Biomass and Bioenergy 20, 151-159.
57 Berndes, G., Hoogwijk, M., van den Broek, R., 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy, 25, 1-28.
5858 Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G. Gielen, D., Turkenburg, W., 2003. Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy 25, 119-133.
59 Smeets, E.M.W., Faaij, A.P.C., Lewandowski, I.M., Turkenburg, W.C., 2007. A bottom-up assessment and review of global bio-energy potentials to 2050.Progress in Energy and Combustion Science 33, pp.56-106.
60 Smeets, E.M.W., Faaij, A.P.C., Lewandowski, I.M., Turkenburg, W.C., 2007. A bottom-up assessment and review of global bio-energy potentials to 2050.Progress in Energy and Combustion Science 33, pp.56-106.
61 Field, C.B., Campbell, J.E. and Lobell, D.B., 2008. Biomass energy: the scale of the potential resource. Trends in Ecology and Evolution 23 (2), 65-72.
62 Hoogwijk, M. and Graus, W., 2008. Global potential of renewable energy sources: A literature assessment. Background report. Ecofys, Utrecht.
63 Dornburg, V., et al., 2008. Biomass assessment: Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy. Netherlands Environmental Assessment Agency, 500102012, de Bilt.
64 Dornburg, V., et al., 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy & Environmental Science 3, 258-267.
65 WBGU, 2008. World in transition. Future bioenergy and sustainable land use. Summary for policymakers, October 2008. German Advisory Council on Global Change, Berlin.
66 Erb, K-H., Krausmann, F., Lauk, C., Plutzar, C., 2009. Eating the planet: Feeding and fuelling the world sustainably, fairly ad humanely – a scoping study. Social Ecology working paper 116, November 2009. Social Ecology Vienna, Vienna.
67 Hakala, K., Kontturi, M., and Pahkala, K., 2009. Field biomass as global energy source. Agricultural and Food Science 18, 347-365.
68 Gregg, J.S., and Smith, S.J., 2010. Global and regional potential for bioenergy from agricultural and forestry residue biomass. Mitigation, Adaptation Strategies Global Change 15, 241-262.
69 Haberl, H., Beringer, T., Bhattacharya, S.C., Erb, K-H, Hoogwijk, M., 2010. The global technical potential of bio-energy in 2050 considering sustainability constraints. Current Opinion in Environmental Sustainability 2, 394-403.
70 Haberl, H., et al., 2011. Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. Biomass and Bioenergy, 35, 4753-4769.
71 Beringer, T., Lucht, W., Schaphoff, S., 2011. Bioenergy production potential of global biomass plantations

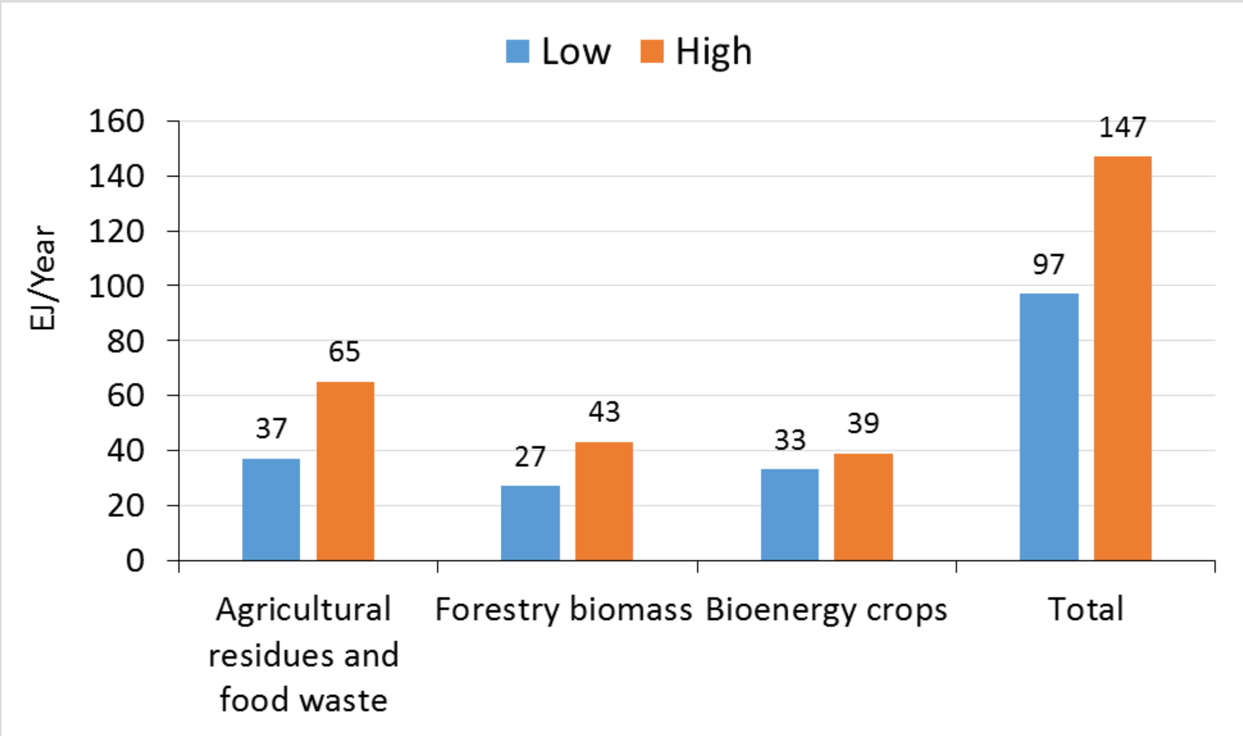


Figure 5: Potential global biomass supply in 2030 (Adapted from IRENA, 2014[73])

When the bioenergy supply potential of six regions of the world are compared (Figure 6), the largest potential supply is in Asia (43 EJ/year) and Europe, including Russia (36 EJ/year). North and Latin America together account for another 45-55 EJ/year of the total supply. Agricultural residues in Asia (6-16 EJ/year), energy crops in Latin America (~16 EJ/year) and fuel wood in Europe (0.3-13 EJ/year) and North America (~3 EJ/year) account for a large share of the total global biomass supply. Energy crops in North America (~7 EJ/year), Africa (5-7 EJ/year) and Europe (~7 EJ/year), as well as processing residues (4-10 EJ/year) and waste (~8 EJ/year) in Asia are also important (IRENA, 2014).

---

under environmental and agricultural constraints. Global Change Biology Bioenergy, 1-14.

72 Lauri, P., Havlík, P., Kindermann, G., Forsell, N., Böttcher, H., Obersteiner, M., 2014. Wood biomass energy potential in 2050. Energy Policy 66, 19-31.

73 The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

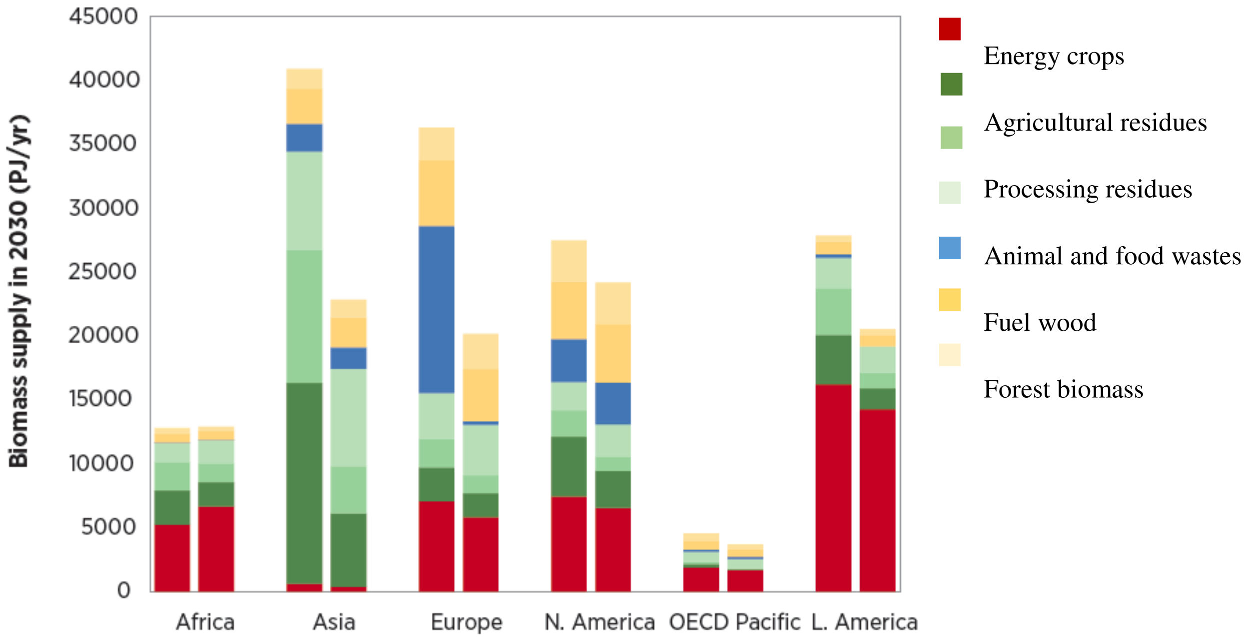


Figure 6: Breakdown of biomass supply ranges by regions (Europe includes Russia), 2030[74]. Two columns for each region represent the high and low supply potentials.

It is apparent (Figure 7) that various factors will influence the biomass supply potential estimates. For example, biomass derived from energy crops will require considerable investments in infrastructure (production and logistics) and will have to compete with land required to meet growing food and energy demand[74]. Latin America enjoys an advantage in this area because of its current land availability, but North America is more challenged because of anticipated domestic food and energy demand for any "surplus" land. It has been reported that African regions have the largest volume of potentially suitable land to produce energy crops. However, ongoing problems such as underdeveloped agricultural land, low productivity, difficult transportation logistics, etc., will first have to be resolved[74].

Fuel wood production using surplus forest areas will require the development of a robust supply chain with the establishment of potential dedicated biomass plantations requiring relatively long lead times, such as seven years for fast growing species such as eucalyptus[69]. Considering the very uneven land distribution among countries, full deployment of surplus land will only be achieved through expansion of international biomass (e.g. wood

[74] The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

pellet) and agricultural commodities trade. However, even if there is to be an increase in trade and the overall biomass market, various policy measures will be required such as stable financial support measures for early stage of development, long-term policy targets to ensure sustainable market opportunities, awareness-raising, pilot activities and the demonstration and introduction of sustainability criteria, quality standards, technical support, etc. [74].

It has been suggested that the amount of agricultural residues that might be available will be directly related to the volume of food/feed available as residues are typically generated in proportion to the amount of food/feed consumed[74]. The increase in food consumption has been calculated to range between 0.8 and 2.4% per year based on Food and Agriculture Organization (FAO) estimates[75]. If the world is to increase the harvesting of agriculture residues, conventional farming systems will need to be modified to handle, efficiently and sustainably, both the primary commodities and the residues. These types of integrated systems will also require an assessment from various perspectives, particularly the agronomic one, to ensure soil fertility while extracting a portion of the potential bioenergy feedstock. This type of 'integrated-approach" is already being pioneered in the US (corn-and-corn stover) and Brazil (sugar-and-sugar cane bagasse)[76].

For all biomass types, large-scale mechanized logistics systems will be critical since competitive feedstock costs will be a key factor for any potential energy applications.

75 Food and Agriculture Organization, 2014. FAOSTAT- the Statistics Division of the FAO. FAO, Rome. http://faostat.fao.org/.

76 The International Renewable Energy Agency (IRENA), 2014. Global bioenergy supply and demand projections. A working paper for REmap 2030. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

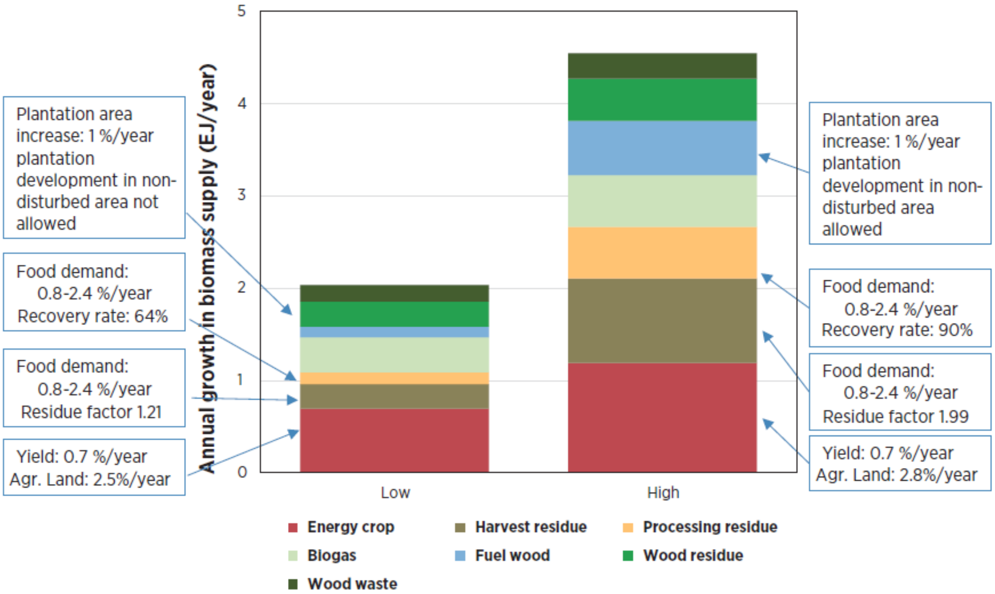


Figure 7: Factors that will contribute to the annual growth in the world's potential biomass supply by 2030 [71]

In a recent work, a review of the literature carried out as part of the work for the IEA Bioenergy Roadmap estimated the potential long-term availability of biomass sources (to 2060), based on analysis of a wide range of studies at global level.[77] The high-level results are summarized in Table 1.

The conclusions that can be drawn from this analysis are that:

- While the costs of feedstocks based on MSW are lower than those of other raw materials, global supplies are relatively limited and could not provide a substantial proportion of likely future biofuels needs. In many places waste incineration with energy recovery as power and also heat may be preferred to using the material as a feedstock for biofuel production.
- Much larger supplies of wastes and residues from forestry and agriculture are likely to be available which could provide the bulk of the raw materials needed for emerging biofuels production.
- There is considerable scope for raw material supply from agriculture, with an emphasis on crops that can be co-produced with food crops or using contaminated or

[77] International Energy Agency (IEA), Technology Roadmap: Delivering Sustainable Bioenergy, 2017 https://webstore.iea.org/technology-roadmap-delivering-sustainable-bioenergy

abandoned land so as to avoid issues related to direct and indirect land-use change emissions.

Table 1: Summary of sustainable biomass resources [78]

Source	Sustainability conditions	**Resources (EJ)** 2060
Municipal wastes	Taking account of the waste management hierarchy, which favors waste prevention and minimization and recycling, and evolution of waste management systems in economies as they develop.	10-15
Agricultural wastes, residues and processing residues from wood and agro-industry	Respecting the need to reserve some of the available resource for animal feed and to leave sufficient residues in the field for soil protection, and consistent with other uses.	46-95
Wood harvesting residues co-products	Used within the context of a sustainable forestry plan, which takes carbon aspects fully into account, along with measures to maintain other forest characteristics including biodiversity.	15-30
Agriculture	Produced on land in ways which do not threaten food availability and whose use leads to low land use change emissions, and subject to a positive assessment on other sustainability indicators such as biodiversity and water availability and quality.	60-100

There is still a need for more work to improve the knowledge of the likely availability of suitable feedstocks for biofuels production and of their costs. Given the complex local considerations that influence likely availability and costs, such assessments are best carried out at national and regional level. Some examples of the results of such analysis are provided below.

Information at national and regional levels

There have been a number of detailed studies on the availability and costs of the resources that could be used as bioenergy feedstocks of the costs that can inform estimates of the likely global situation. Some of these are summarized below.

[7878] 1EJ is equivalent to the energy contained in around 60 million tonnes of dry biomass feedstock.

Biomass availability and costs in USA

In the US, the national availability and cost of biomass have been assessed by US Department of Energy (US DOE) in three studies known as Billion Ton Studies .[79] According to these studies, combined forestry resources, agricultural resources, wastes, and currently used biomass total 1.2 billion tonnes under the base-case scenario (which assumes a 1% annual increase in yield for agricultural and woody energy crop resources) and 1.5 billion tonnes under a high-yield scenario (which assumes 3% annual increase in yield). Resources available in the near term include agricultural residues, wastes, and forest resources. Energy crops shown are scarce in the near term, but are the greatest source of potential biomass in the future, contributing 411 million tonnes and 736 million tonnes in 2040 under the base-case and high-yield scenarios, respectively. This analysis indicates that most of the US resource could be available "at the farm gate" or on the edge of a forest at a cost below 3 Eur/GJ, and delivered to users at costs between 3.3 and 5.6 EUR/GJ.

EU – S2Biom Study

The S2Biom project supports the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, and roadmaps, informed by a computerized and easy to use toolset with updated harmonized datasets at local, regional, national and pan European level for EU28, western Balkans, Turkey and Ukraine.[80] The study includes an estimate of the potential for biomass supply that could be made available while respecting strict sustainability criteria by 2030.

---

[79] Perlack, R. D., & Stokes, B. J. (2011). *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* Oak Ridge National Laboratory. U.S. Department of Energy. Retrieved from https://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf

Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J., & Erbach, D. C. (2005). *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-ton Annual Supply.* United States Department of Agriculture (USDA) and the United States Department of Energy (DOE). Oak Ridge, Tennessee: Oak Ridge National Laboratory. Retrieved from https://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf

US Department of Energy. (2016). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy.* US Department of Energy. Retrieved from https://www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf

[80] FNR - Agency for renewable Resources. (2016, November). *Welcome to the S2Biom project website*. Retrieved from S2Biom: www.s2biom.eu.

Different types of agricultural residues that are currently underutilized could provide between 186 and 252 Million tonnes in the 2030-time frame with the lower estimates put strong restrictions on collection of agricultural residues for reasons related to protection of soil fertility, etc. Additional resources could be made available from sustainable forestry which could provide between 615 million and 728 million tonnes by 2030. Wastes, including organic fractions of MSW could provide some 110-150 million tonnes per year in EU by 2030 (between 1.0 and 1.5 EJ).

A fourth major source of biomass relates to dedicated production of industrial crops on land which is unused– either because of its poor quality or because it is agricultural land which has been abandoned as a result of overexploitation, pollution, climate change and/or exodus from rural areas. Estimates for the EU in 2030 are in the range of 84 million tonnes to 180 million tonnes of biomass while the respective figures for Western Balkans, Moldova and Ukraine add another 54-62 Million tonnes.

The overall figures for all four categories are in the range of 1.0-1.4 billion tonnes of biomass which could technically be available within Europe by 2030 under sustainable practices. The study estimates the costs of the material at between 3 and 5 EUR/GJ at the roadside, similar to the cost estimates in the US studies discussed above.

Amounts of feedstock in Brazil

Brazilian mills crushed 620 million tonnes of sugarcane during the 2018/2019 season. The South-South-eastern region of the country were responsible for 70% of the crushed amount, while the Centre-Western region accounted for another 22%[81] (CONAB, 2019). The processing of sugarcane stalks yields large amounts of bagasse (around 180 million tonnes in 2018/2019, 50% moisture content), which are largely employed in integrated Cogeneration of Heat and Power (CHP) units for the generation of both thermal and electrical energy to supply internal process requirements. Sugarcane mills are able to export part of the produced electrical energy to the national grid or sell a small portion of surplus bagasse to the market. Besides sugarcane bagasse, sugarcane straw is also an abundant lignocellulosic material available for the bioenergy sector. Estimates point to an availability of some 43 million tonnes of sugarcane straw in Brazil (dry basis), considering a maximum recovery of 50% of the straw in the field – the recovery rate should be limited to allow a minimum amount of straw to remain in the field to protect the soil.

[81] (CONAB, 2019).

Brazil has more than 7.5 million hectares of planted eucalyptus area. In 2017, 68 million m^3 of eucalyptus were destined to the paper and pulp industry, 39 million m^3 being used for energy purposes, and another 26 million m^3 employed for other purposes.[82] The estimated price of this resource is in the range of 2.7 -3.7 EUR/GJ.

Conclusions

The theoretical availability and cost modelling indicate that large volumes of feedstock could be made available for biofuels production, sufficient to meet likely future demand as indicated in low carbon scenarios. Most of the material necessary could be supplied from wastes and residues, and from sustainable forestry practices. Agriculture can also be an important source of raw materials, with feedstocks produced in ways which complement traditional agricultural production through co-cropping and through use of less productive land.

Estimates of the potential available biomass and other uses vary significantly in the literature. While the theoretical potential is high, the economic availability can vary greatly, depending on numerous factors including yield and regional parameters (e.g. location and size of crop/forest lands, local infrastructure, etc.). There is a wide range of biomass availability globally, from as low as 95 EJ/year to as high as 350 EJ/year.

National studies indicate that much of the raw material could be produced and delivered to users at costs of between 3 - 6 EUR/GJ. More information from real projects is needed to test the costs of procuring suitable feedstock in the real world.

National and regional assessments are very helpful in providing insights into likely long-term availability and costs of feedstocks for bioenergy production, including for the production of emerging biofuels. However, in order to be useful for estimating long term global availability such assessments need to be done in a very transparent way, with clear classification of the various resources and of the assumptions made in defining how much material could in practice be available, and around the sustainability considerations applied.

A useful step in harmonizing such approaches would be the development of some best

---

[82] Temer, M., Filho, S. J., Cruz, M., Filho, R. D., de Freitas, J. V., de Mesquita Junior, H. N., . . . de Oliveira, R. M. (2017). *Boletim Snif 2017.* Serviço Florestal Brasileiro. 70818-900 - Brasília - DF, SCEN, Trecho 2, Bloco H: MINISTÉRIO DO MEIO AMBIENTE,. Retrieved from http://www.florestal.gov.br/documentos/publicacoes/3230-boletim-snif-2017-ed1-final/file

practice guidelines for such studies, including some standardization and rationalization of the classification of the various potential feedstocks, and of the sustainability constraints which are applied. Such measures could facilitate the development of more consistent resource estimates, which could be more easily compiled to give a global estimate, at least for key producer and user regions.

GHG emissions of emerging biofuels pathways

Current legislation in the USA and the European Union require advanced biofuels to show at least 50% / 65% reduction in GHG emissions respectively, as compared to their fossil fuel equivalents. The carbon intensity of a fuel is measured in gCO_2e/MJ using Life Cycle Assessment (LCA) and represents the GHG emissions emitted across the full life cycle of a product system, from feedstock acquisition to production, use, and final disposition. Carbon intensity of gasoline and diesel is about 95 gCO_{2e}/MJ.

Emerging biofuels, termed advanced by either USA or EU legislation, do not automatically have lower carbon intensity values than those of established biofuels. However, among the various pathways that have been certified under California Low Carbon Fuel Standard (LCFS) program, the average carbon intensity values of advanced biofuels are typically, sometimes significantly, lower than those of established biofuels. The current average CI values of biofuels (both established and emerging pathways) provided to California range from 15 to 65 gCO_{2e}/MJ, and can also be negative when obtaining credits for avoided GHG emissions from waste disposal or if combined with CCS.

The location/region where the biofuel production facility is located will be a key component of the final carbon intensity of the fuel. This is due to factors such as access to low carbon intensity energy sources for heat and power, the potential to co-locate with other biofuel plants or oil refineries to develop efficient biofuel production and supply chains, the type of biofuels and co-products produced, the type of feedstock and associated logistics, land type used for crop/biomass cultivation and agronomic practices, the local regulations on the use of feedstock, and carbon accounting mechanisms for biomass.

As LCFS-type policies become more common in increasing numbers of jurisdictions, the carbon intensity of current and emerging biofuels is expected to decrease.

Current GHG emissions of Renewable Transport Fuels

As discussed earlier, policies are increasingly incorporating sustainability criteria into biofuel policy development. Life Cycle Assessment (LCA) of GHG emissions is currently the predominant method used to assess the sustainability of many renewable fuel pathways, including biofuel blending mandates. To become eligible, companies typically have to “petition” to be a supplier of a fuel via an approved fuel pathway. A fuel pathway is usually a combination of three components that include feedstock, production process, and fuel type, and an assessment of the fuels lifecycle GHG emissions will determine which fuel pathways can qualify.

The EU's RED II provides default GHG emission values and calculation rules for liquid biofuels in Annex V and for solid and gaseous biomass for power and heat production in Annex VI. The current default values will be revised and updated when technological developments make it necessary. Producers have the option to either use default GHG intensity values provided in RED II or to calculate actual values for their respective production pathways[83] with the REDII GHG savings thresholds for renewable fuels summarized in Table 2.

Table 2: Greenhouse gas emissions savings thresholds in RED II [84]

Plant operation start date	Transport biofuels	Renewable transport fuels of non-biological origin	Electricity, heating and cooling
Before October 2015	50%	-	-
After October 2015	60%	-	-
After January 2021	65%	70%	70%
After January 2026	65%	70%	80%

The US EPA's RFS program covers the four categories of renewable fuels mandated under this program and their minimum GHG reduction requirement is summarized in Table 3. A list of approved pathways for renewable fuels and completed pathway assessments under the US EPA's RFS program can also be found at https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

83 Lonza, L. and O'Connell, A., 2018. Biofuels Production and Consumption in the European Union (EU): Status, Advances and Challenges. IEA Bioenergy Task 39 Newsletter, December 2018. http://task39.sites.olt.ubc.ca/files/2018/12/IEA-Bioenergy-Task-39-Newsletter-Issue-50-Final-Draft-1.pdf

84 Lonza, L. and O'Connell, A., 2018. Biofuels Production and Consumption in the European Union (EU): Status, Advances and Challenges. IEA Bioenergy Task 39 Newsletter, December 2018. http://task39.sites.olt.ubc.ca/files/2018/12/IEA-Bioenergy-Task-39-Newsletter-Issue-50-Final-Draft-1.pdf

Table 3: Renewable fuel categories under the RFS program[85,86] (US EPA, 2017a; Gottumukkala and Hayes, 2018)

Category	**Code**	**Minimum GHG emissions reduction requirment[1]**	**Description**
Cellulosic Biofuel	D3	60%	Renewable fuels made from cellulose, renewable gasoline, biogas-derived CNG and LNG
Cellulosic Diesel	D7	60%	Cellulosic diesel, jet fuel and heating oil
Advanced Biofuels	D5	50%	Renewable fuels other than ethanol derived from corn starch (sugar cane ethanol), biogas from other waste digesters, etc.
Biomass-Derived Diesel	D4	50%	Renewable fuels that meet the definition of either biodiesel or non-ester renewable diesel.
Renewable Fuel	D6	20%	Renewable fuels produced from corn starch or any other qualifying renewable biomass

[1] compared to the petroleum baseline

In contrast to biofuels blending mandates, LCFS policies do not have minimum GHG emission reduction requirements for specific fuel categories. LCFS policies are fuel-agnostic, with credits or deficits generated based on the carbon intensity (CI) of the particular fuel. The carbon intensity of a fuel is estimated in gCO_2e/MJ using LCA and represents the GHG emissions emitted across the full life cycle of fuel from feedstock acquisition to production, use, and final disposition. Under LCFS policies, fuels that can be produced at a lower carbon intensity compared to petroleum-based gasoline and diesel generate higher carbon credits. This typically translates into higher market values for these fuels.

As summarized in Figure 8, the California LCFS program has described the carbon intensity range of the major fuel pathways that have been certified in 2019. Each marker represents

---

85 US EPA, 2017a. Overview for Renewable Fuel Standard. Retrieved from https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard

86 Gottumukkala, L.D., and Hayes, D., 2018. Introduction to RINs. Retrieved from https://www.celignis.com/RINs-credits.php

the carbon intensity of an individual certified fuel pathway with the length of each bar indicating the range that might be achieved by that particular pathway. The wide range of carbon intensities is due to several reasons such as the life cycle emissions methodology of the LCFS, variations in feedstock types, origin of feedstock, raw material production processing efficiencies and transportation distances and modes (e.g. rail vs. truck). All of these factors contribute to the carbon intensity of an individual producer's fuel pathway. For example, as indicated in Figure 9, the carbon intensity of ethanol could be as low as 7.18 gCO2e/MJ. For this pathway, ethanol is produced from California Energy Beets using biogas derived from anaerobic digestion of green wastes and manure, with credit for avoided waste management and co-products (compost and animal feed) contributing to the low carbon intensity.

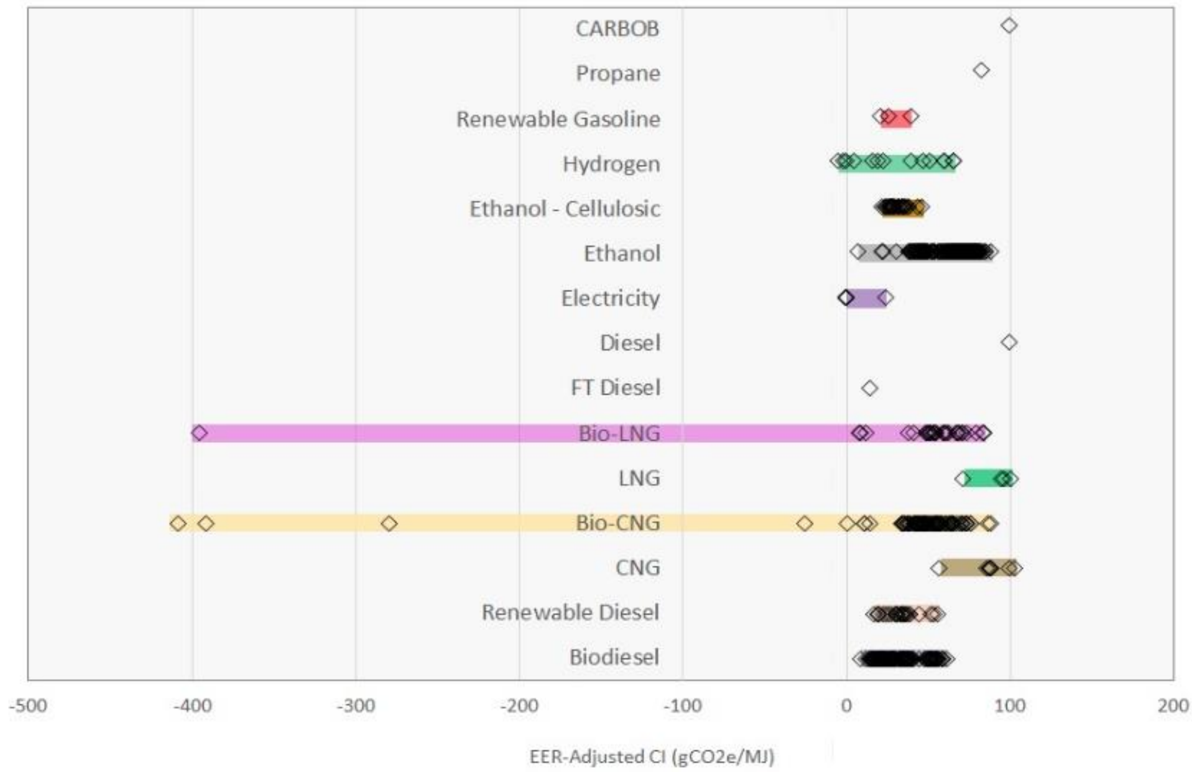


Figure 8: The carbon intensity values of current fuel pathways certified under the California LCFS program Renewable Diesel is HVO/HEFA biofuels.

CARBOB shows the carbon intensity of conventional crude oil based on the average crude oil supplied to California refineries and average California refinery efficiencies. Renewable gasoline is produced from co-processing of biocrude and crude oil in an oil refinery. Hydrogen pathways include compressed and liquid H_2 from central reforming of natural gas and on-site reforming with renewable feedstocks. It is noted that the alternative fuel's carbon intensity value is divided by its Energy Economy Ratio (EER) in order to obtain the EER-adjusted CI value, representing the emissions that occur from the use of alternative fuel per MJ of conventional fuel displaced[87].

It is worth noting that emerging biofuels, such as cellulosic ethanol and drop-in hydrocarbons (e.g. renewable diesel, gasoline and Fischer-Tropsch Diesel), do not necessarily have lower carbon intensity values than those of established biofuels (Figure 9). However, among the various pathways that have been certified under California LCFS program, the average carbon intensity values of advanced and drop-in hydrocarbons are typically, sometimes significantly, lower than those of established biofuels. The lower carbon intensity of cellulosic ethanol compared to corn ethanol is mostly due to the allocation of emissions associated with crop production, such as CO_2 from nitrogen fertilizer production and N_2O from nitrogen fertilizer application, to the primary grain product. While there are diesel-related emissions associated with crop residue collection and transportation, these are typically small compared to the fertilizer (production and use) associated emissions allocated to grain. However, there are exceptions, such as when an unsustainable volume of residue is removed and additional fertilizer must be added to compensate for lost nutrients (Personal communications with (S&T) Squared Consultants Inc., 2018).

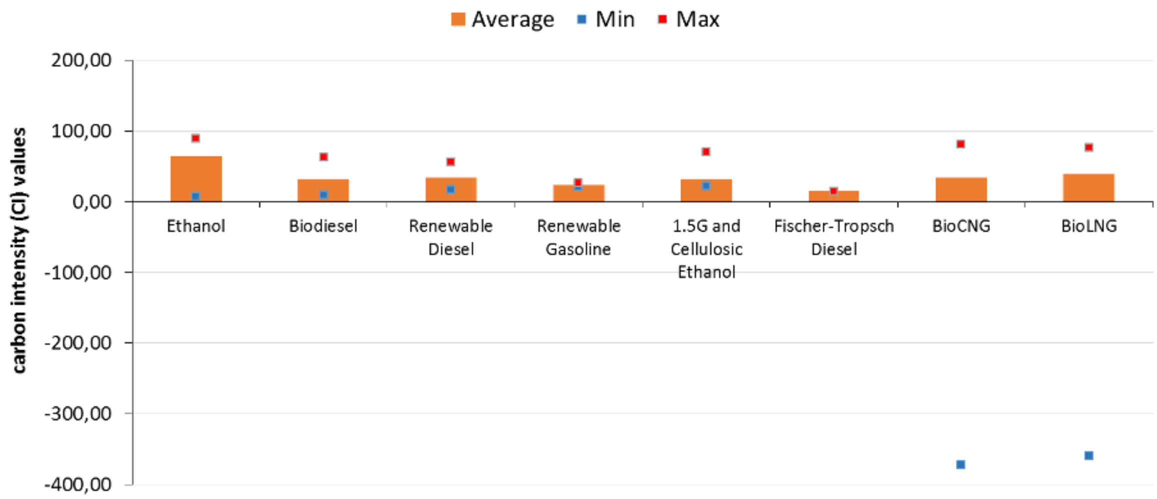


Figure 9: Minimum, average, and maximum carbon intensity (CI) values of some of the fuel pathways certified under California LCFS program in 2019

87 California Air Resources Board, 2019b. LCFS Pathway Certified Carbon Intensities. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

When the LCA values for the various oleochemical and lignocellulosic pathways to established and emerging drop-in hydrocarbons are summarized (Figure 10), a wide range is apparent. This large variation, as demonstrated by algae derived HEFA, is due to a range of issues such as a lack of maturity of the technology, differences in feedstock type, LCA system boundaries, LCA model assumptions and data inventory and types of final products/co-products.

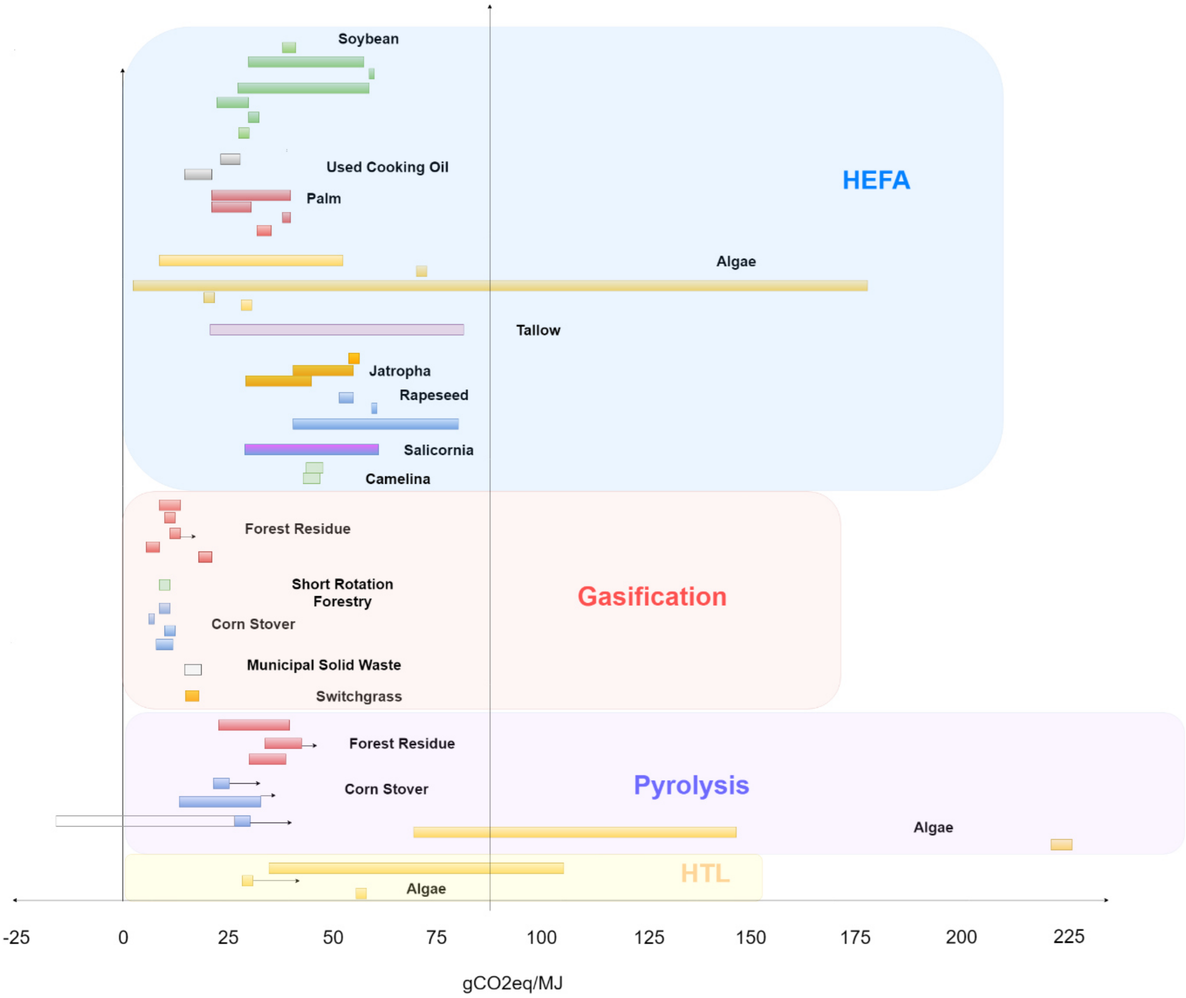


Figure 10: Summary of LCA values derived from oleochemical and lignocellulosic pathways to produce conventional and advanced drop-in hydrocarbons from various feedstock types[88]

88 Beavers, A.R., 2018. The potential of the aviation sector to reduce greenhouse gas emissions by using biojet fuels. Master Thesis, The University of British Columbia.

Future GHG emissions of Advanced Renewable Transport Fuels

As LCFS type policies become more common in increasing numbers of jurisdictions, the carbon intensity of current and emerging biofuels is expected to decrease. Some of the approaches used to decrease the GHG emissions of biofuels include:

- Development of “bolt-on” technologies which enable existing corn-ethanol dry mills in the US to convert corn kernel fiber coproduct into cellulosic ethanol[89,90].
- Reusing or selling the carbon dioxide (CO_2) produced by ethanol fermentation instead of treating the CO_2 co-product stream as a waste[91].
- Transitioning away from using fossil fuel-based energy sources such as coal and natural gas to using heat and/or electricity from renewable sources such as hydroelectricity, biogas/renewable natural gas or agricultural and forest biomass in the biofuels production processes
- For existing renewable diesel (HVO) facilities, using a green source of hydrogen can reduce the carbon intensity of the resulting biofuels. For hydrogen-related emissions, renewable diesel facilities vary in the efficiency of hydrogen recovery from off-gasses and re-use in the hydrotreating unit. Currently, existing renewable diesel facilities use hydrogen derived from methane-steam reforming. In general, hydrogen production and utilization contributes 10-15 g CO_2e/MJ to the carbon intensity of the final fuel (Personal communications with (S&T) Squared Consultants Inc., 2018). Thus, use of renewable natural gas (RNG) or low carbon intensity electricity for hydrogen production will consequently lower the carbon intensity of renewable diesel.
- One of the primary sources of GHG emissions of biofuels is those associated with

---

89 California Air Resources Board, 2017. California LCFS Tier 2 Fuel Pathway Application: Corn Kernel Fiber Cellulosic Ethanol Pathway for Mid America Agri Products/Wheatland, LLC Using Natural Gas and Electricity as Process Energy. GREET modeling technical support document. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/t2n-1263_report.pdf.

90 California Air Resources Board, 2018. Lifecycle Emissions of POET Biorefining – Emmetsburg Corn Kernel Fiber Cellulosic Ethanol with CA-GREET2.0 https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/t2n-1266_report.pdf.

91 State CO2-EOR Deployment Work Group, 2017. Capturing and Utilizing CO2 from Ethanol: Adding Economic Value and Jobs to Rural Economies and Communities While Reducing Emissions. http://www.kgs.ku.edu/PRS/ICKan/2018/March/WhitePaper_EthanolCO2Capture_Dec2017_Final2.pdf

the upstream feedstock-related emissions[92]. As discussed earlier, the biomass industry is making considerable progress in reducing the cost of biomass production and logistics. These include cheaper crop establishment, harvesting, collection and transportation by increasing the efficiency of logistics operations which result in a reduction in energy consumption and the associated GHG emissions.

- For fuel pathways that use Municipal Solid Waste (MSW) as feedstock, the carbon intensity is impacted by the ratio of biological-to-non-biological content in the waste and the ability of the biofuel plant to claim methane avoidance credits. As the proportion of non-biological content in waste increases, so does the carbon intensity of the fuel. Methane avoidance credits are only possible if the baseline is landfilling and there is no requirement for methane capture and use/destruction. This could result in significant avoided landfill emission credit up to 300 g CO2e/MJ (Personal communications with (S&T) Squared Consultants Inc., 2018). The actual amount of the emission credit depends on the local and municipal bylaws for methane capture and use/destruction and the LCA method used in the LCFS to calculate the carbon intensity value. Many landfills incorporate landfill gas collection systems and larger landfills typically use this gas for electricity generation, while smaller landfills more commonly employ gas flaring. In the case of the alternative being waste-to-energy installations, the GHG credit of the electricity produced is a strong function of the carbon intensity replaced grid power, the greener the grid the better becomes the fuel alternative. Considering that the greening of the grid is going fast in e.g. many EU member states, this will favor the fuel use of MSW over waste-to-energy.
- Forest residues that are currently burnt at the roadside of forest stands after logging operations can be used for the production of biocrude, resulting in very low carbon intensity values by avoiding emissions from slash pile burning. However, the actual carbon intensity value depends on the treatment of forest feedstocks under carbon accounting schemes, meaning that whether the forest biomass is considered as a byproduct. For example, under current accounting approaches in Canada, harvest residues are considered to be a by-product of the primary timber harvest. Avoiding forest residues burning can more than offset emissions associated with collection, preprocessing, and transportation, thereby resulting in a carbon negative feedstock. Carbon accounting treatment of crop residues, including an assumed soil organic

92 O'Connell, A., Kousoulidou, M., Lonza, L., Weindorf, W., 2019. Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. Renewable and Sustainable Energy Reviews, 101, 504-515.

carbon baseline, can also have a significant impact on final fuel carbon intensity (Personal communications with (S&T) Squared Consultants Inc., 2018).

It should be noted that the location/region where the biofuel production facility is located will be a key component of the final carbon intensity of the fuel. This is due to factors such as access to low carbon intensity energy sources for heat and power, the potential to co-locate with other biofuel plants or oil refineries to develop efficient biofuel production and supply chains, the type of biofuels and co-products produced, the type of feedstock and associated logistics, land type used for crop/biomass cultivation and agronomic practices, the local regulations on the use of feedstock, and carbon accounting mechanisms for biomass.

In summary, considerable progress has been made in both the production and use of established and emerging biofuels. However, as well as on-going technical progress lowering the cost and carbon intensity of the various biofuels, innovative policies will always be required to bridge the price gap that can be anticipated as the world continues to wean itself of non-sustainable fossil fuels.

Role of policy on production and use of emerging biofuels

Policies have been and will continue to be essential if we are to foster the growth of emerging biofuels used to decarbonize transport, particularly long-distance transport. Policies used include blending mandates, excise tax reductions or exemptions, renewable or low carbon fuel standards, as well as a variety of fiscal incentives and public financing mechanisms. The countries that have achieved the most success in growing the production and use of biofuels have used a mixture of market-pull and technology-push policies.

To date, most of the policies used to promote transport decarbonization have focused on increasing the use of biofuels in cars and trucks, at a national level. Other key transport sectors such as aviation and shipping have drawn considerably less policy attention despite being significant energy consumers and carbon/GHG emitters.

While the production and use of transport biofuels has more than doubled over the last decade, progress in expanding biofuels production remains well below the levels required to decarbonize transport significantly. Several factors continue to impact the effectiveness of biofuels policies such as relatively low petroleum and fossil fuel prices, uncertainty about future policy and funding programs to support conventional and emerging biofuels, the inconsistent regulation of global trade of biofuels and continuing concerns related to food security, land use change and overall sustainability.

Current biofuel production volumes

Biofuels policies have and continue to support the growth of biofuels production and use. The policies that have been successfully used to promote biofuels include blending mandates, excise taxes exemptions/reduction and renewable or low carbon fuel standard (LCFS), fiscal incentives and public financing. These policies are applied at different stages of the biofuel production and consumption chain and have helped enhance global biofuels production from over 37 million tonnes oil equivalent (Mtoe) in 2007 (~64 billion liters) to over 84 Mtoe in 2017 (~145 billion liters)[93]. Although the reported increase of 3.5% from 2016 to

---

93 BP, 2018. BP Statistical Review of World Energy. 67th Edition. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

2017 was well below the annual growth rate of 11.4% achieved over the past decade, this was the most growth observed over a three-year period (Figure 11). Highest annual growth rate was observed in the Asia-Pacific region, where it grew at an annual rate of 20.1% from 2006-2016 with a further 6% increase occurring from 2016 to 2017. The Americas and Europe continue to show the largest increase in biofuels production. In 2017, North America, South and Central America and Europe had global biofuel production shares of 45.5%, 26.9% and 16.8%, respectively[88].

The main biofuels produced were ethanol, biodiesel (fatty acid methyl ester or FAME fuels), biofuels produced by treating animal and vegetable oils and fats with hydrogen (known as hydrotreated vegetable oil (HVO) or hydrotreated esters and fatty acids (HEFA) biofuels). There was a concomitant increase in the contribution from biomethane in countries such as the US, Sweden and Germany. As estimated, 65% of biofuel production (in energy terms) was ethanol, 29% was FAME biodiesel and 6% was HVO/HEFA. The use of biomethane as a transport fuel, while growing rapidly, contributed less than 1% of the biofuel total[94].

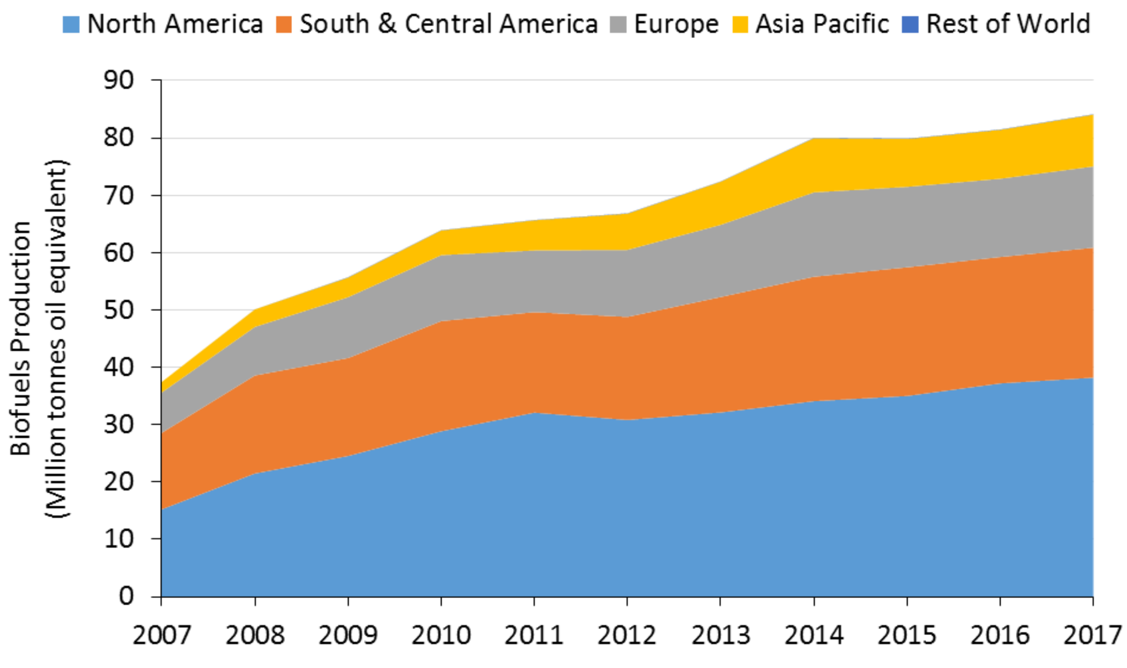


Figure 11: World biofuels production from 2007 to 2017. Biofuels production increased at an annual growth rate of 11.4%, from over 37 Mtoe in 2007 to over 84 Mtoe in 2017 (Adapted from BP, 2018)

94 REN21, 2018. Renewables 2018 global status report. http://www.ren21.net/gsr-2018/

Although established biofuels (i.e., sugar/starch-based ethanol and FAME biodiesel) comprised more than 93% of global biofuels market share in 2017, worldwide efforts continue to assess the potential production and use of drop-in hydrocarbons and emerging biofuels. This is largely a response to the growth in policies requiring improved sustainability attributes for the biofuels, especially lower life cycle net carbon emissions (lower carbon intensity) and less potential to exacerbate undesirable land use change. For example, fuels produced from agricultural, forestry, industrial or municipal wastes should typically show improved LCA values as compared to current biofuels such a corn-derived-ethanol. In 2017, the growth of biofuels was led by HVO/HEFA fuels, followed by ethanol from cellulosic materials such as corn fiber, and by fuels from thermochemical gasification- or pyrolysis-based processes[95]. Over 3.1 Mtoe (4.4 billion liters) per year of HVO/HEFA biofuels are now being produced globally[89] (REN21, 2018). Waste and residue feedstocks now account for a significant share of HVO/HEFA biofuels production, supporting deeper decarbonization from these fuels (REN21, 2018). Demand for HVO/HEFA biofuels is expected to continue to grow because of their "drop-in" properties and low carbon intensities, particularly when produced from "waste" oleochemical feedstocks such as tallow, used cooking and tall oils. Although these fuels are primarily produced in Europe, Singapore and the US, production is expected to grow as new facilities come on line and new investments are made to increase existing or build new plant capacities[96].

The majority of HVO/HEFA biofuels are sold as renewable diesel, with a relatively small portion of the oleochemical feedstock going to aviation biofuels ("biojet") with most of this fraction produced at AltAir's facility in California[97]. Due to the higher production cost of HVO as compared to FAME biodiesel, these fuels are mainly sold in markets such as California and British Columbia where Low Carbon Fuel Standard policies incentivize biofuels based

---

95 IEA Bioenergy Task 39, 2019. Implementation Agendas - 2018 Update: A review of key biofuel producing countries. http://task39.sites.olt.ubc.ca/files/2020/02/IEA-Bioenergy-Task-39-Implementation-Agendas-Final-Draft-Feb-4-2020.pdf

96 IEA Bioenergy Task 39, 2019. Implementation Agendas - 2018 Update: A review of key biofuel producing countries. http://task39.sites.olt.ubc.ca/files/2020/02/IEA-Bioenergy-Task-39-Implementation-Agendas-Final-Draft-Feb-4-2020.pdf

97 van Dyk, S., Su, J., McMillan, J.D., Saddler, J., 2019. Potential synergies of drop-in biofuel production with further co-processing at oil refineries. Biofuels, Bioprod. Bioref., 13:760–775, DOI: 10.1002/bbb.1974.

on their carbon intensity, or where other supporting policies based on GHG emission reductions such as in Germany and Sweden are in play (IEA Bioenergy Task 39, 2019). While not yet commercialized, other routes to drop-in hydrocarbons that can leverage a portion of the substantial existing petrochemical/refining infrastructure are also under development. These include the development of non-renewable + renewable feedstock co-processing approaches to help lower the carbon intensity of drop-in fuels that can be used in existing vehicle engines (van Dyk et al., 2019).

The production of biofuels from cellulosic feedstocks, including cellulosic ethanol has, so far, only been demonstrated at a relatively small scale due to the slower than forecast progress in scale up and commercial deployment. Most cellulosic ethanol is now being produced in the US primarily due to supporting policies. The 2019 volume requirements identified in the US Renewable Fuel Standard (RFS2) for each of, advanced biofuels, cellulosic biofuels and biomass-based biodiesel are 418, 4.92 and 2,100 million gallons, respectively[98]. In addition to blending mandates for established biofuels, some EU member states, including Austria, Denmark, Netherlands and Italy, have developed or are developing blending mandates for advanced biofuels. As of 2021, these targets are supposed to become mandatory across the EU, based on the new provisions of RED II (IEA Bioenergy Task 39, 2019). The UK's recently implemented Renewable Transport Fuel Obligations Order (RTFO II) identifies specific target for Development Fuels using incentives for certain types of biofuels, including aviation and high blends, to try to facilitate their production and use.

Although only 38 million liters of US RFS2 eligible cellulosic ethanol was produced in 2018, the amount of so-called "generation one-point-five (1.5 Gen)" ethanol produced from corn kernel fiber in conventional corn ethanol plants is expanding. In 2017, five corn ethanol plants, with a combined capacity of nearly 2 billion liters (500 million gallons), were approved by the US Environmental Protection Agency (EPA) to generate Renewable Identification Numbers (RINs[99]) credits under RFS2 program[100]. A number of pilot, demonstration and pre-

98 US Environmental Protection Agency (US EPA), 2018. Renewable fuel standard program: standards for 2019 and biomass based diesel volume for 2020. https://www.govinfo.gov/content/pkg/FR-2018-12-11/pdf/2018-26566.pdf

99 "Renewable Identification Numbers" (RINs) are saleable regulatory credits that represent a quantity of qualifying renewable fuel. To qualify as a renewable fuel under the US RFS program, a fuel should be produced from an approved feedstock through an approved pathway.

100 REN21, 2018. Renewables 2018 global status report. http://www.ren21.net/gsr-2018/

commercial emerging biofuels plants in other countries such as Canada, Brazil, Austria, China, India and Italy are also producing or have produced biofuels from biomass feedstocks ranging from agricultural and forest residues and the cellulosic portion of municipal waste streams. A list of current facilities that produce emerging biofuels at pilot and demonstration scales can be found at the IEA Bioenergy Task 39's large-scale demonstration plants website: https://demoplants.best-research.eu. Details on demonstration facilities for various pathways are provided in the sections "Emerging biofuel pathways", "Low-carbon transport fuels from fossil waste sources", and "Low-carbon transport fuels from other forms of renewable energy" of this report.

Policies to increase biofuels production

Despite considerable progress being made in the technical aspects of emerging biofuels production, it is widely recognized that the right policies will be needed to help expand commercialization. For example, the Brazilian initiated *Biofuture Platform*, a 20-member country collaboration, has highlighted the importance of the right policies enhancing low-carbon biofuel production and use. EU policy support for emerging biofuels and the increasing number of quota policies announced by member states is also anticipated to catalyze commercial development. In other parts of the world, India plans to build twelve cellulosic biofuel plants, several of which are in development, while China has indicated its intent to develop cellulosic ethanol[101].

Biofuel policies can be divided into technology-push and market-pull policies (Figure 12). Typically, technology-push policies help drive early stage technology development such as research, demonstration and commercialization of biofuels. These types of policies can be used to help reduce the cost of research and development, drive new ideas and take early stage technologies through the valley of death that exists between initial development and commercialization[102]. Other types of "financial investment" polices that have encouraged expanded biofuels production and use include:

- Grants used to encourage conversion technology development, increase technology

101 BioFuture Platform, 2018. Creating the Biofuture: A report on the state of the low carbon bioeconomy. http://biofutureplatform.org/wp-content/uploads/2018/11/Biofuture-Platform-Report-2018.pdf

102 Jordaana, S.M., Romo-Rabagob, E., McLearyb , R., Reidyb , L., Nazaric , J., Herremansb, I.M., 2017. The role of energy technology innovation in reducing greenhouse gas emissions: A case study of Canada. Renewable and Sustainable Energy Reviews, 78, 1397–1409.

readiness levels and de-risk the technology and associated supply chains. Related programs have been used to de-risk early market development and to support technologies with long-term market potential but high initial investment risk

- Loan guarantees to “buy-down” the risk of financing larger, first-of-a-kind commercial facilities
- Corporate tax breaks to newly built biofuels production facilities
- Guaranteed return on renewable energy assets
- Compensation for depreciation of acquired renewable energy assets

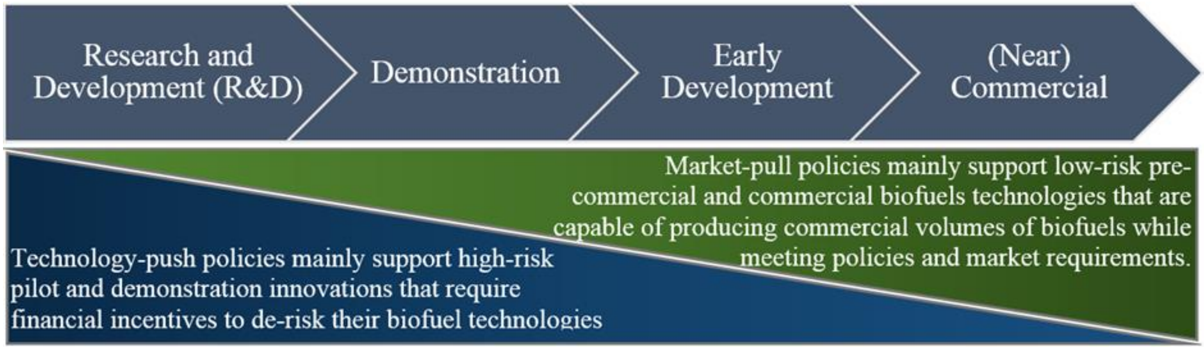


Figure 12: Technology-push and market-pull biofuel policies. Countries that use a mixture of market-pull and technology-push policy instruments have been most successful at increasing biofuels production and use and also at developing and deploying less mature emerging biofuels production technologies.

Market-pull policies, such as biofuels blending mandates and fuel/CO_2 excise reduction /exemptions have proven effective in supporting technologies that are relatively mature, helping create a demand for biofuels, as demonstrated by the established ethanol or biodiesel markets[103]. However, these types of policies can sometimes be limited in their effectiveness as some of these early-stage technologies can prove challenging to commercialize, struggling to compete against fossil fuels and established biofuels. Market-pull policies such as California’s LCFS, the EU’s REDII, Brazil’s RenovaBio and Canada’s Clean Fuel Standard (CFS) are examples of policies that hope to “pull” emerging biofuels into the market by providing financial incentives to produce biofuels with the lowest carbon intensity.

It is likely that effective technology-push and demand-pull policies will both be needed to increase the rate of introduction and diffusion of emerging biofuel technologies. Although

---

[103] Costantini, V., Crespi, F., Martini, C., Pennacchio, L., 2015. Demand-pull and technology-push public support for eco-innovation: The case of the biofuels sector. Research Policy, 44, 577-595.

technology-push policies have been shown to generate innovation in emerging biofuels, the growth in demand induced by market-pull policies such as LCFS tends to increase public and private investment in more mature technologies. The volume of low carbon fuels consumed in California increased from 2011 to 2017, from 1 152 million gasoline gallon equivalent (GGE) in 2011 to 1 930 GGE in 2017, (a 60% increase) (Figure 13)[104].

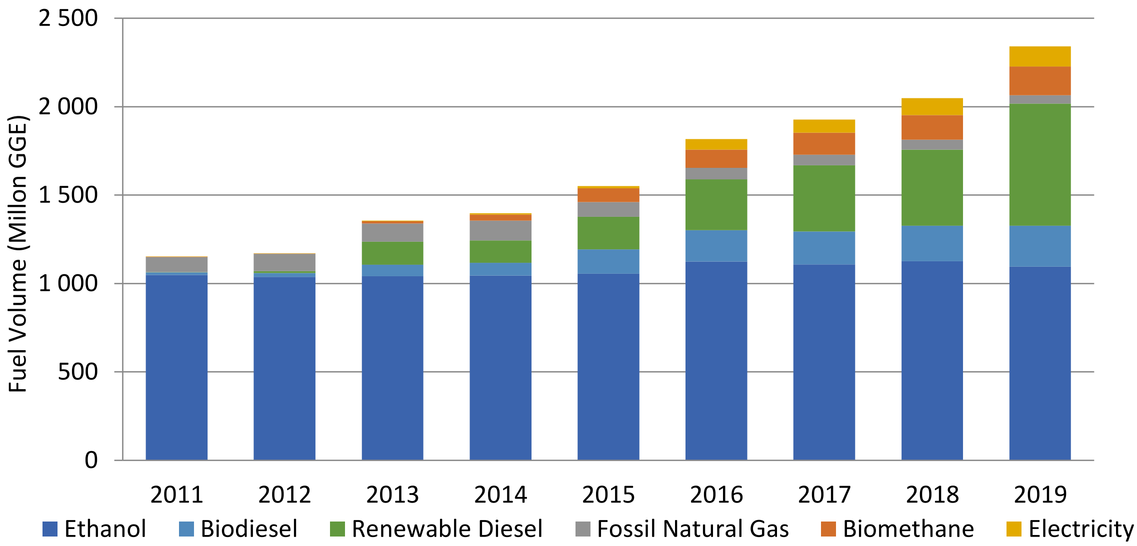


Figure 13: Alternative low-carbon fuel volumes used in California [105]

The influence of policies such as the LCFS can be seen in Figure 14 where the market value of cellulosic ethanol in California increased from 3.74 in 2016 to 4.33 $/gallon in 2018, with about 60% of the market value proving to be policy driven (RINs and LCFS premium). This makes emerging biofuels with low carbon intensities cost-competitive with fossil fuels in the California market. Thus, it is apparent that market-pull instruments will be critical for the short-and-mid-term economic viability of the low carbon emerging biofuels. In addition, technology-push instruments such as R&D and grant instruments dedicated to emerging biofuels will be required to drive early stage technologies towards demonstration and commercialization.

---

[104] California Air Resources Board, 2019. Data dashboard. Retrieved from https://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

[105] California Air Resources Board, 2019. Data dashboard. Retrieved from https://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm

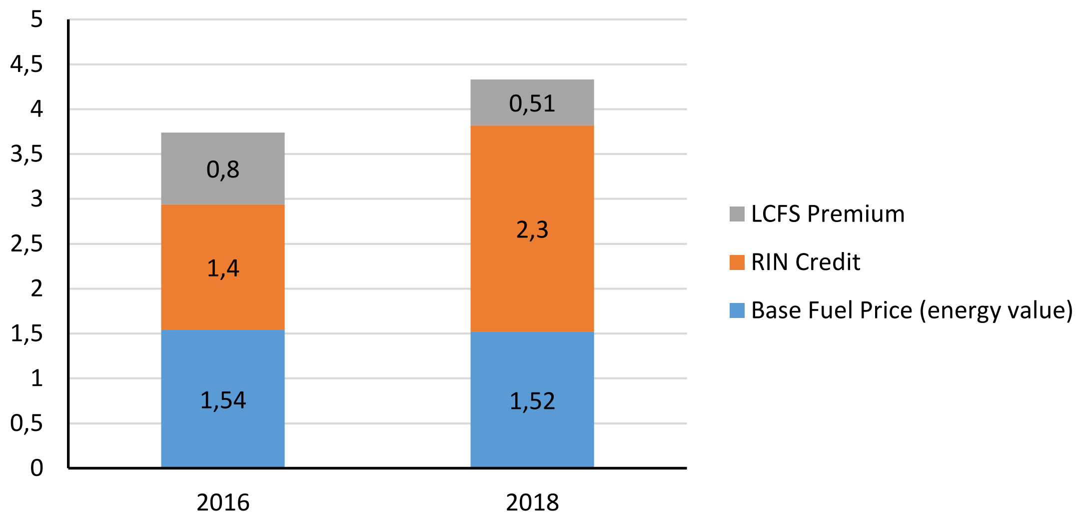


Figure 14: The market value of cellulosic ethanol in California in 2016 and 2018[106]

Another example of the importance of policies is the package of clean energy and emissions reduction goals passed by the European Commission under RED II. This includes a scaling down of established biofuels and an increasing role for emerging biofuels and other low-carbon alternatives, such as renewable electricity, to decarbonize transport. In Brazil, the RenovaBio program will introduce LCFS criteria to vehicular fuels, reinforcing the need for sustainability in biofuels production, consequently encouraging the production and use of low-carbon emerging biofuels[107].

Those policies have, so far, been primarily focused on road transport, especially at the national level. Other transport sectors, such as rail, aviation and shipping, have, until recently, received comparably less policy attention despite being large energy consumers and GHG emitters. However, transport policies and industry efforts are increasingly focused on decarbonizing long-haul transport sectors (i.e., road, rail, aviation and shipping), where electrification is much more challenging. The aviation has adopted a number of targets, including a 50% reduction in net aviation CO_2 emissions by 2050 (compared to 2005

106 BiofuelDigest, 2018. The Digest's 2018 Visual Guide to the economics, politics of renewable fuels. Retrieved from http://www.biofuelsdigest.com/bdigest/2018/03/15/the-digests-2018-visual-guide-to-the-economics-politics-of-renewable-fuels/

107 IEA Bioenergy Task 39, 2019. Implementation Agendas - 2018 Update: A review of key biofuel producing countries. http://task39.sites.olt.ubc.ca/files/2020/02/IEA-Bioenergy-Task-39-Implementation-Agendas-Final-Draft-Feb-4-2020.pdf

levels)[108] despite there being few direct support policies that target the use of renewable fuels in the aviation sector. Although Indonesia introduced a 2% renewable jet fuel mandate in 2017, set to increase to 5% by 2025[109], this has yet to be enforced. The EU's new REDII allows aviation and marine biofuels to "double-count" (using a multiplier of 1.2) in their possible contribution towards the region's renewable transport target[110].

Shipping is another long-distance transport sector that is under increasing pressure to reduce its carbon and sulfur emissions. Shipping mainly uses "heavy" fossil fuels that contain sulphur and heavy metals and, in parallel with aviation, will likely prove to be one of the hardest transport sectors to decarbonize. Apart from technological challenges, the type of biofuels that will be used in shipping faces numerous barriers, such as the large price gap between renewable and conventional fuels and very limited regulations, particularly regarding the GHG emissions attributes of maritime fuels. International shipping is regulated by the International Maritime Organisation (IMO). Since the Paris agreement (which did not include international shipping), the IMO has developed reduction strategies for GHG emissions and other air pollutants. In 2016, the IMO agreed to a 0.5% cap on sulphur in its fuels by 2020[111]. In 2018, the IMO reached an agreement on an "initial strategy" to reduce CO_2 emissions from shipping. The initial strategy identifies measures that could indirectly support the GHG reduction efforts. One of these measures concerns the use of zero-carbon or fossil-free fuels for the shipping sector and the development of robust lifecycle GHG/carbon intensity guidelines for alternative fuels[112].

---

108 International Air Transport Association (IATA), 2017. Climate Change: three target and four pillars. https://www.iata.org/policy/environment/Pages/climate-change.aspx.

109 Widiyanto, S., 2017. Indonesian aviation biofuels and renewable energy initiatives. ICAO seminar on alternative fuels. https://www.icao.int/Meetings/altfuels17/Documents/4%20-Indonesia%20Initiative_Ministries.pdf

110 International Council on Clean Transportation (ICCT), 2018. Advanced Biofuel policies in select EU members states: 2018 Update. https://theicct.org/sites/default/files/publications/Advanced_biofuel_policy_eu_update_20181130.pdf

111 International Maritime Organisation (IMO), 2016. The 2020 global sulphur limit. http://www.imo.org/en/MediaCentre/HotTopics/GHG/Documents/2020%20sulphur%20limit%20FAQ%202019.pdf

112 The Maritime Executive, 2018. IMO Agrees to CO2 Emissions Target. https://www.maritime-executive.com/article/imo-agrees-to-co2-emissions-target

Summary of the role of biofuels policies

In summary, policies have been and will continue to be essential if we are to foster the growth of emerging biofuels used to decarbonize transport, particularly long-distance transport. Various types of policies have and will continue to be successfully used, including blending mandates, excise tax reductions or exemptions, renewable or low carbon fuel standard, as well as a variety of fiscal incentives and public financing mechanisms. These policies have and will be applied at different stages of the biofuel supply chains (production and consumption). To date, most of the policies used to promote transport decarbonization have focused on increasing the use of biofuels in cars and trucks, at a national level. Other key transport sectors such as aviation, shipping and rail have drawn considerably less policy attention despite being significant energy consumers and carbon/GHG emitters.

The countries that have achieved the most success in growing the production and use of biofuels have used a mixture of market-pull and technology-push policies. It is apparent that a balanced distribution of policy efforts between demand-pull and technology-push has been most successful in fostering the development and deployment of biofuels technologies and the growth of biofuels markets.

While the production and use of transport biofuels has more than doubled over the last decade, progress in expanding biofuels production remains well below the levels required to decarbonize transport significantly. Policies are essential but have not been sufficient to drive the level of development that is needed. It is apparent that several factors continue to impact the effectiveness of biofuels policies such as relatively low petroleum and fossil fuel prices, uncertainty about future policy and funding programs to support established and emerging biofuels, the inconsistent regulation of global trade of biofuels and continuing concerns related to food security, land use change and overall sustainability.

Sustainability requirements are increasingly being incorporated into biofuels policies such as LCFS-type policies that incentivize reductions in the carbon intensity and assure sustainability. These types of policies should lead to more stable and increased markets, promoting the greater production and use of emerging biofuels, particularly in sectors such as aviation and marine, where appropriate biofuels can be readily integrated and used.

The likely costs of emerging biofuels production and the scope for cost reduction

The costs of producing emerging biofuels have been assessed in a recent IEA Bioenergy study. The costs are currently significantly higher than the current costs of fossil fuel equivalents.

There is significant potential for reducing the costs of the assessed range of advanced biofuels. In order to achieve these, projects must first demonstrate in practice that the current production objectives in terms of reliable production at high availability and efficiency can be achieved consistently. The reductions will only then be achieved if there are opportunities to build a significant number of further generations of plants which will allow experience to accumulate and provide the basis for learning, and for growing confidence in the technologies.

Large scale deployment will depend on continuing policy support. First, industry will need support during the demonstration and risky and costly early commercialisation of the technologies, so as to bridge the "valley of death". And then, continuing strong support will be needed to offset the differences between biofuels and fossil fuel prices, and to incentivise low carbon transport fuels.

While the costs of the advanced biofuels and other fuels discussed above are an important factor, a broader range of issues also need to be considered when comparing these options and also when looking at other low-carbon options. These include the extent to which they can directly replace fossil fuels, the costs of any modifications or of distribution costs associated with fuels, the likely availability of feedstocks and the life-cycle GHG emissions associated with particular routes. The overall consideration of the future for the advanced biofuels need to be seen in the context of these other factors, and based on an analysis of full system costs, feedstock availability and life-cycle GHG emissions.

Background

Bioenergy already plays an important role in the global energy economy and is a critical element in future low carbon scenarios, where it can especially play an important role in reducing Green House Gas (GHG) emissions from the transport sector. Current biofuels production is principally made up of ethanol and biodiesel (sometimes referred to as "conventional biofuels"). Future biofuel deployment will also require a range of bio-based transport fuels which are suitable for long-haul transport applications including aviation. A number of appropriate technologies to produce such fuels are being developed and commercialized, but so far, their production is only at a limited scale, although the production of HVO has been growing rapidly and this growth is expected to continue with a production capacity anticipated to grow from the current level of 5.5 billion liters/year to 13 billion liters by 2024.[113]

In order to establish the current production costs of these fuels and the scope for these costs to be reduced, a study has recently been completed as a project under the IEA Bioenergy TCP.[114] The principal results are summarized here.

This project used as its starting point a study on the costs of advanced biofuels carried out within the program of work of the Sub-Group on Advanced Biofuels (SGAB) (under the European Commission's Sustainable Transport Forum (STF)) and published in 2017. The report on this study reviewed data available on the current costs of producing a range of advanced biofuels, based on extensive contact with industry and other players active in the field. The aims of this project were to:

- Update and extend the SGAB study to provide estimates of the current costs of producing a selection of relevant novel advanced biofuels;
- Identify the scope for cost reduction for these advanced biofuels;
- Develop a model for likely cost reduction progress as deployment grows;
- Compare these costs and cost trajectories with likely trends in fossil fuel prices, and those of established biofuels.

The project made direct contact with over 90 companies involved in developing a range of advanced biofuel technologies and used information they provided along with published studies to assess current costs of production and the scope for cost reduction.

Current Production Costs

The study considered cost data on the following technologies, either using updated information available from the companies contacted or from the literature, or else the data provided in the SGAB report when this was found to be representative.

---

[113] IEA Renewables 2019

[114] IEA Bioenergy, Task 43, Advanced Biofuels – Potential for Cost Reduction, ,

https://www.ieabioenergy.com/publications/new-publication-advanced-biofuels-potential-for-cost-reduction/

Cost analysis confined to those technologies where estimates could be based at least in substantial pilot plant work or on demonstration or commercial scale plant. The following technologies were included:

- Production of hydrotreated vegetable oil (HVO) and methane produced by anaerobic digestion (two options which are already widely deployed)
- Production of ethanol from cellulosic feedstocks by fermentation (including the production of ethanol form corn fiber, integrated into a “conventional” corn ethanol plant
- Methane and methanol, produced by thermal gasification and synthesis, produced from both biomass and waste-based feedstocks
- Fischer-Tropsch (FT) Liquids produced from biomass and waste feedstocks
- Fuels produced by pyrolysis followed by upgrading either in stand-alone plant or by co-processing with fossil fuels in an oil refinery. No significant cost difference was found between these two options.

Information gathered from industry and other sources was consolidated to provide a range of cost estimates for each of the technology routes for which information was available. The costs were broken down to show the contribution of capital, feedstock and operating costs. The costs were normalized by assuming a standard financing rate with the capital charges calculated using a finance cost of 10% and a project lifetime of 15 years. It was assumed that plants could be operated for 8 000 hours per year. The costs were also scaled so as to consider a large-scale plant size with a product output equivalent to 200MW.

Table 4 and Figure 15 summarize the results.

Table 4: Summary of current production cost ranges.

		Costs, EUR/GJ			
Process		**Capital**	**Feedstock Costs**	**Operating Costs**	**Total**
Cellulosic ethanol	Low	11.7	9.2	7.8	28.6
	High	16.7	13.9	13.3	43.9
Cellulosic ethanol "1.5 Gen"	Low	9.2	0.0	5.0	14.2
	High	10.6	0.0	5.8	16.4
Methanol and methane- biomass	Low	9.2	4.2	3.9	17.2
	High	13.6	9.2	8.3	31.1
Methanol and methane - wastes	Low	11.9	-6.9	8.3	13.3
	High	16.4	0.0	8.3	24.7
FT Liquids – Biomass	Low	11.9	5.0	3.9	20.8
	High	20.6	13.9	5.6	40.0
FT Liquids – Wastes	Low	13.3	-6.9	8.3	14.7
	High	20.6	0.0	8.3	28.9
Bio-oil plus co- processing	Low	11.1	9.4	1.4	21.9
	High	18.3	18.9	1.4	38.6
Bio-oil stand alone	Low	10.6	4.2	8.1	22.8
	High	10.6	8.3	16.4	35.3
HVO	Low	0.8	11.1	2.2	14.2
	High	4.2	16.7	4.4	25.3
AD – Biomethane	Low	6.9	-3.6	7.8	11.1
	High	9.2	13.9	10.6	33.3

Note: "Cellulosic ethanol", 1.5 Generation most frequently refers to the production of cellulosic (such as corn fiber) ethanol integrated into a corn-based ethanol plant.

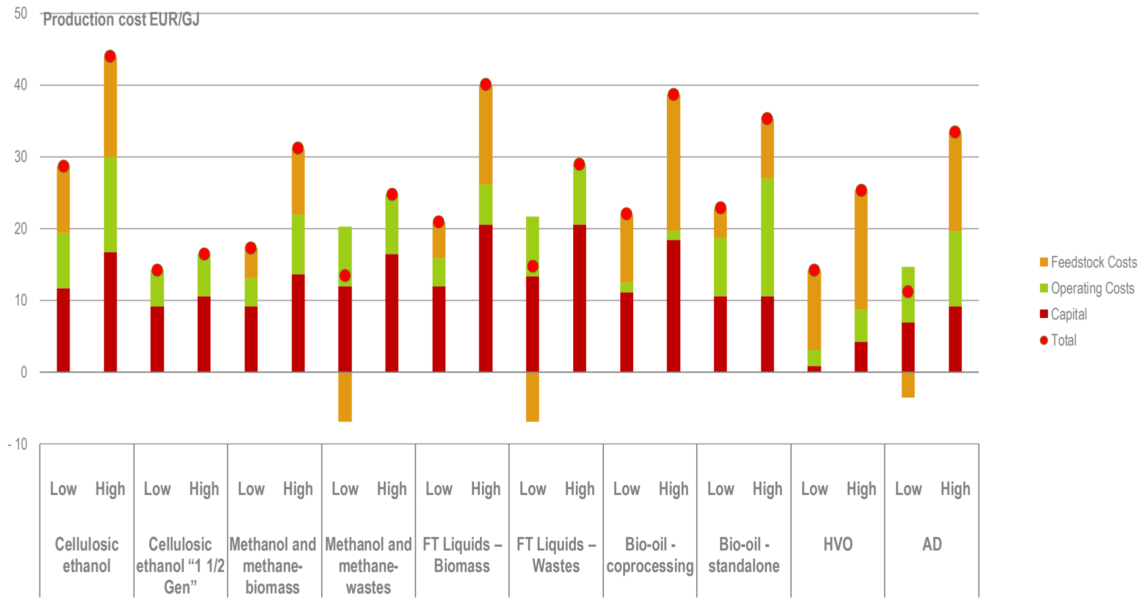


Figure 15: Summary of current cost ranges

The study largely confirmed the estimates of the current costs of producing advanced biofuels contained in the earlier SGAB cost analysis report. Costs are in the range of 15 EUR/MWh to 44 EUR/GJ for production based on biomass feedstocks and 9 EUR/GJ to 26 EUR/GJ for waste-based production, illustrating the cost advantages of using such feedstocks. The low cost of producing "1.5 generation ethanol" – ethanol produced form cellulosic corn fiber in conjunction with conventional corn ethanol - illustrates the benefits of integrating "advanced" and conventional biofuels production.

These costs of advanced biofuels can be compared with those of conventional biofuels such as starch/sugar-based ethanol and FAME-type biodiesel. US prices for both these fuels are reported by Iowa State University's CARD program. The price of US ethanol is strongly linked to corn prices, but over the last five years has been between 1.2 USD/gallon and 1.6 USD/gallon. This is equivalent to 13-15 EUR/GJ. Prices in Rotterdam and Brazil are between 450-700 USD/m^3 and 300-600 USD/m^3 respectively (18-29 EUR/GJ and 12-24 EUR/GJ. According to the CARD program data, US biodiesel prices, strongly linked to soya bean prices, have been between 2.8 USD/gallon and 3.5 USD/gallon, equivalent to 19-24 EUR/GJ. European biodiesel prices have been in the range of 19-28 EUR/GJ.

For comparison, the prices of the fossil fuel equivalents lie within a range of 8-14 Euro/GJ.

Potential for cost reduction

Many of the advanced biofuels technologies discussed here are still at relatively early stages of deployment and commercialization, with only a handful of plants operating successfully at large commercial scale. There is therefore considerable scope for reducing costs. In the report this is considered in two stages.

Where technologies are at an early stage of deployment, with only a few commercial plants built and operating, there is significant potential for cost reduction as a few successor plants are built, taking advantage of the experience gained in the first plants. The potential for such reductions has been identified in discussion with project developers and are associated with improvements due to continuing project optimization, improvement through on-going R&D and in some cases by moving to larger scale plants to further benefit from scaling factors. In addition as the technologies become better established, the technical risks will be seen as less significant by project developers and financiers, and so capital for plants may become available on more favorable terms, i.e. it should be possible to finance plants at lower finance rates, as confidence in the technologies grow. Taken together these reductions are referred to here as “medium term cost reductions” and could be realized within a 10-15-year time period if the necessary plants were built.

In addition there is further potential for “long-term cost reduction”, due to continuing learning effects, such as have been experienced across a wide range of technologies and which are often described using learning curves. A massive scale of deployment of these technologies would be needed to reach the levels of contribution to global energy needs indicated in low carbon scenarios such as the IEA 2DS scenario. Under these conditions significant experiential learning could be expected. However, the extent of further cost reductions is more difficult to estimate with any precision as they will depend on a wide range of factors. In particular such reductions will depend heavily on the rate of deployment of the various technologies. If attained, they would most likely be realized on a timescale beyond 15 years.

Medium term cost reduction

There is significant potential for cost reduction by process improvements through R&D and through experience being gained in the current generation of demonstration and early commercial plants. The industry players suggested that there was significant scope for cost reductions to the capital and operating costs as a number of additional commercial plants are built. For cellulosic ethanol processes it was considered that capital costs could be reduced by between 25 and 50%, and operating costs by some 10-20%. For the range of thermal processes, the reduction potential was judged to be lower, since these tend to be based on unit operations which are well established in petrochemical and other applications. Nonetheless it is anticipated that capital and operating costs could be reduced by between 10 and 20% in the medium term.

Industry felt that the scope for feedstock cost reduction was more limited. While improved efficiencies in supply chains might be possible in some cases, these might be offset by the need to move to more expensive feedstocks, and by the fact that increased demand could push up feedstock prices.

Further costs reductions could be achieved in the medium term if, once the technologies are better established and thus perceived as less risky, finance could be made available on more favorable terms. In modelling this impact it is assumed that finance can be made available at a lower rate (8 instead of 10%) and over a longer period (20 rather than 15 years). This has the impact of reducing the capital element in the final production cost by some 22%)

Table 5 and Figure 16 show the impact of such reductions on the costs of the range of advanced biofuels studied.

Table 5: Potential costs of biofuels production after reductions in EUR/GJ

		Cellulosic ethanol	Methanol/ /Methane Biomass	Methanol/ /Methane Waste	FT Liquids - Biomass	FT Liquids Waste	Bio-oil	HVO	AD Methane
Current costs	Lo	28,6	15,3	10,6	24,2	11,7	23,1	14,2	11,1
	Hi	43,9	31,4	21,9	36,7	25,6	40,0	25,3	33,3
With process improvements	Lo	24,2	10,8	7,8	21,4	8,9	21,9	14,2	11,1
	Hi	33,9	28,3	19,7	31,4	23,1	37,8	25,3	33,3
Lower cost of capital	Lo	22,2	9,7	6,1	19,7	6,9	19,4	13,9	9,4
	Hi	31,1	27,2	17,8	30,6	19,4	33,9	24,4	31,4

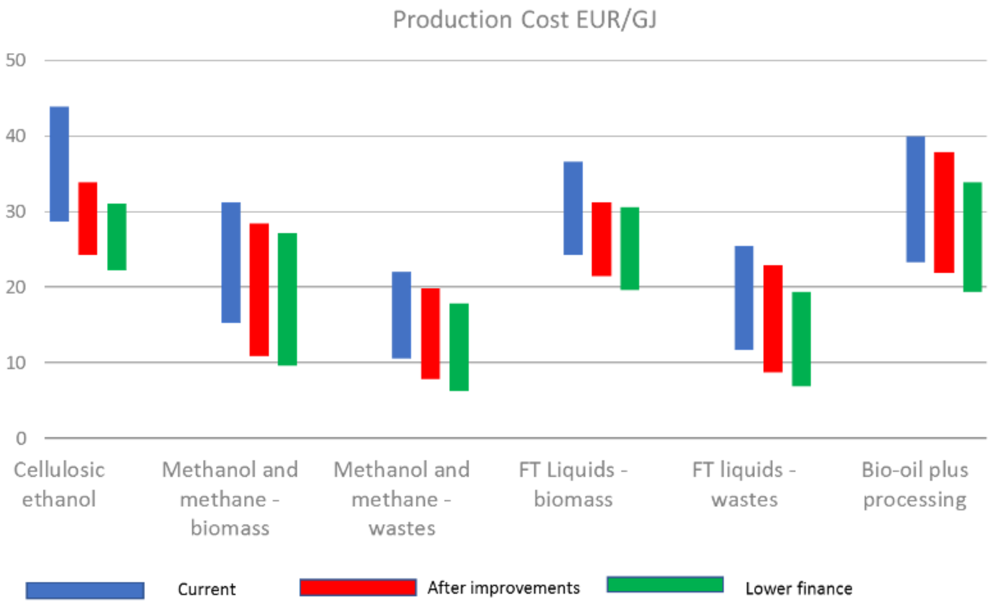


Figure 16: Potential costs of biofuels production after reductions

This indicates that these "medium term" reductions could lead to overall production costs reduction by between 10-27%. In addition, if increased experience makes it possible to finance plants on more favorable terms this will further reduce costs by some 5-16%. Taken together these measures can reduce the production cost ranges from between 17 EUR/GJ to 44 EUR/GJ to between 12 EUR/MWh and 33 EUR/GJ for production based on biomass feedstocks, and from between 13-29 EUR/GJ to between 8 and 22 EUR/GJ for production from waste feedstocks.

Long-term cost reduction

Achievement of the level of production of advanced biofuels envisaged within long term low carbon scenarios will require extensive deployment of the technologies. For example, producing the 25 EJ of advanced biofuels envisaged within the IEA's 2DS Scenario would require around 4 300 plants each producing the equivalent of 200 MW.[115] Such large-scale

---

[115] A biofuels plant with an output of 100 MW operating for 8000 h/year would produce fuel with an energy content of 800 GWh, or 2.88 PJ. This is equivalent to:

108 thousand tonnes of ethanol (137 million litres or 36 million US Gallons)

144 thousand tonnes of methanol (183 million litres or 48 million US Gallons)

65.5 thousand tonnes of HVO (84 million litres or 22 million US Gallons) deployment will allow significant further opportunities for reduction in capital and operating costs through experiential learning, as plant capital and operating costs fall in line with a learning curve, in which costs fall by a fixed proportion for each doubling of cumulative production capacity. Such cost reductions have been seen across a wide range of technologies, including for conventional ethanol production where costs have fallen by some 20% for each doubling of cumulative capacity.

Such effects are likely to be seen also for advanced biofuel production, but such reduction is likely to apply to the capital and operating elements of costs rather than to the feedstock elements. However, given the range of complicating factors it is difficult to estimate the scope for such reductions with any precision as this will depend on the learning rate achieved which may well differ between the technology options. To illustrate the potential impacts of such reductions, Figure 17 illustrates the impact of a range of different learning rates, assuming that feedstock costs remain constant.

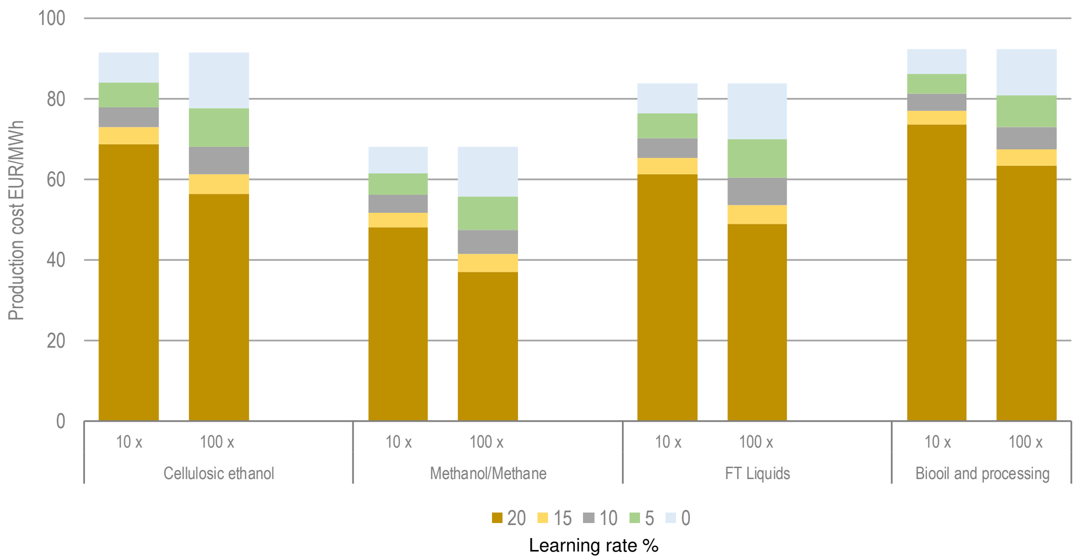


Figure 17: Examples of impact of learning in costs with increasing learning rates

As the figures show, depending on levels of deployment increase and of the learning rate achieved, experiential learning could have significant impacts on future costs, nearly 50% in the most extreme case shown.

---

66 thousand tonnes of gasoline (90 million litres or 24 milion gallons)

Importance of feedstock costs

Overall production costs are very sensitive to the feedstock costs and to the efficiency with which the energy in the feedstock is converted into the final product, as indicated by

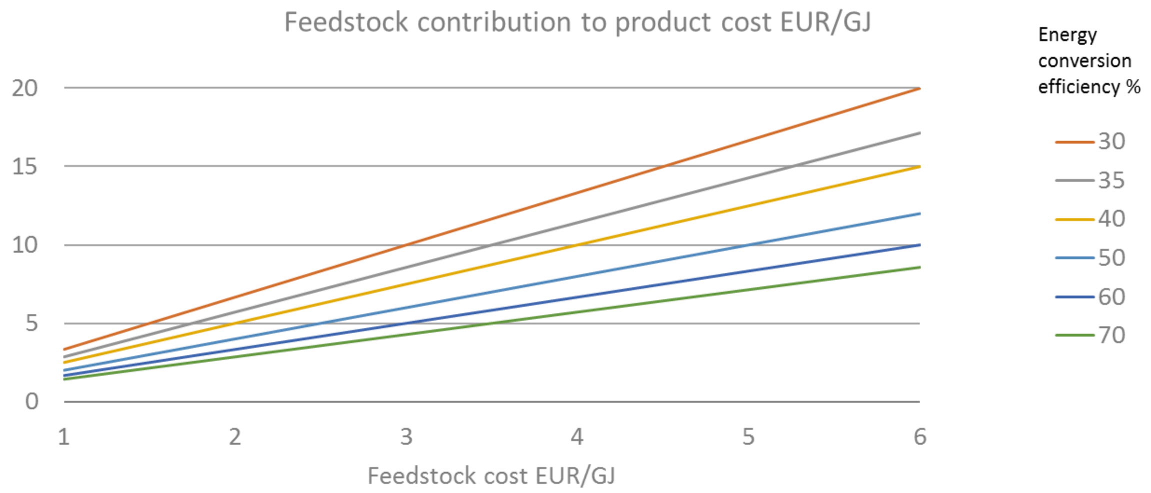


Figure 18.

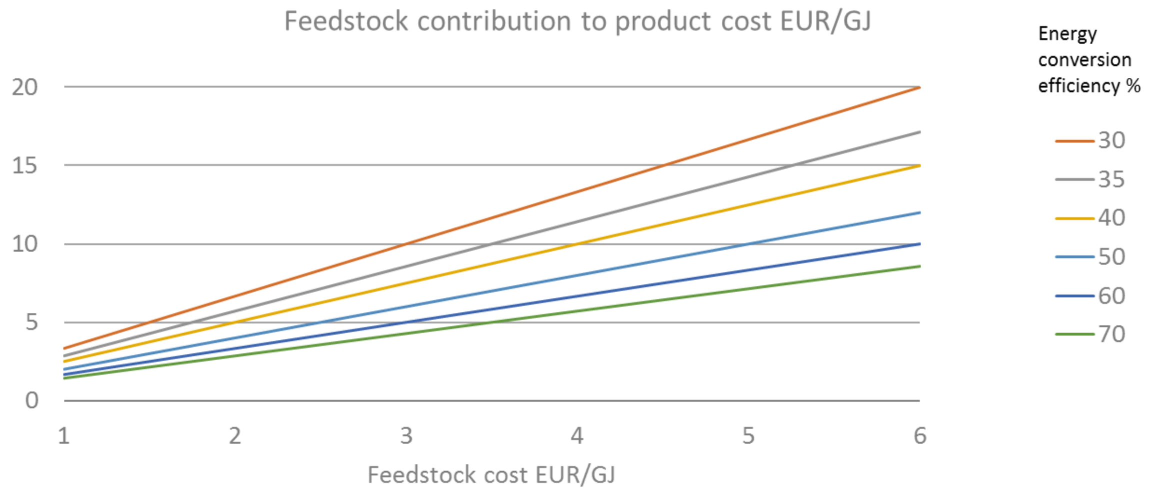


Figure 18: Cost of feedstock in the overall cost of production

In the analysis of cost reduction potentials, it was assumed that feedstock costs remain constant. Under these assumptions, as capital and operating costs fall, the feedstock costs assume a greater importance in the overall cost structure.

It is difficult to predict feedstock cost and price trends particularly in situations where demand is significantly scaled up. While global and regional studies indicate that significant quantities of wastes residues and energy crops could be available at roadside costs below 20 EUR/tonne (see section “Availability and costs of sustainable bioenergy feedstocks”), more detailed studies are needed to confirm that feedstocks could practically be delivered at these costs taking all the logistical and market factors into account.

Benchmarking costs

The estimates of the current costs of production of the range of advanced biofuels have to be benchmarked against the current prices of the fossil fuels that they aim to replace. Analysis of recent oil price trends suggests that the costs of competing fossil fuels have been within the range of 8-14 EUR/GJ (allowing for the differences between the prices of finished petrochemical products and crude oil prices). This implies a significant cost gap of between 3.3 EUR/GJ and 7.8EUR/GJ) between these prices and the estimates of the current costs of advanced biofuels. If the medium-term cost reductions discussed above can be achieved the gap will be narrowed but will still be significant (except for some waste-based projects). The cost reduction potential report estimates that the likely cost gap is equivalent to some 49-525 EUR/tonne of carbon dioxide equivalent (EUR/tCO_2e) compared to today’s costs and 0–365 EUR/tCO_2e when cost reduction potential is factored in compared to recent fossil fuel price ranges

In the longer term, the effective cost of using fossil fuels may rise through a combination of higher prices and more extensive carbon pricing, or other incentives may be available for low carbon transport fuels. If there is an extensive increase in the production capacity of advanced biofuels, then there is the prospect of the technologies being competitive in the context of anticipated fossil and carbon prices.

Conclusions

There is likely to be significant potential for reducing the costs of the assessed range of advanced biofuels. In order to achieve these, projects must first demonstrate in practice that the current production objectives in terms of reliable production at high availability and efficiency can be achieved consistently. The reductions will only then be achieved if there are opportunities to build a significant number of further generations of plants which will allow experience to accumulate and provide the basis for learning, and for growing confidence in the technologies.

Large scale deployment will depend on continuing policy support. First industry will need support during the demonstration and risky and costly early commercializationof the technologies, so as to bridge the “valley of death”. And then, continuing strong support will be needed to offset the differences between biofuels and fossil fuel prices, and to incentivize low carbon transport fuels.

While the costs of the advanced biofuels and other fuels discussed above are an important factor, a broader range of issues also need to be considered when comparing these options and also when looking at other low-carbon options. These include the extent to which they can directly replace fossil fuels, the costs of any modifications or of distribution costs associated with fuels, the likely availability of feedstocks and the life-cycle GHG emissions associated with particular routes. The overall consideration of the future for the advanced biofuels need to be seen in the context of these other factors, and based on an analysis of full system costs, feedstock availability and life-cycle GHG emissions.

There are some examples of policy and regulatory portfolios which have been introduced and which are successfully leading to some early deployment and use of advanced biofuels. The success of such policies should be monitored so that policy best practice can be applied more widely. Some policy best practice examples are provided in Part 4 of our report (How to reach widespread deployment of advanced renewable transport fuels).

Compatibility of fuels with existing engines

The compatibility of fuels with fuel infrastructure and vehicles includes the aspects material compatibility, tolerance, vehicle compatibility and vehicle compliance, i.e. fulfilment of all regulatory requirements concerning pollutant emissions and safe vehicle use. Biofuels can be used in low blends, as drop-in fuels with up to 100% substitution, or as special fuels in dedicated or adapted engines.

The easiest way to introduce biocomponents is to operate within the framework of existing standards for gasoline and diesel fuel. Typically, standards allow blending of ethanol and FAME biodiesel corresponding up to an energy share 10-15%. Some activities to introduce intermediate ethanol blends (E20, E25) are under way in Europe and are common practice in Brazil. However, for higher substitution and more substantial decarbonization of transport, complementary actions are needed.

Drop-in type fuels are fully fungible with conventional hydrocarbon fuels and compatible with existing vehicles and fuel infrastructure; no infrastructure or vehicle modifications are needed. Paraffinic renewable diesel fuel, whether from hydrotreatment of oils and fats (HVO) or Fischer Tropsch synthesis, can completely substitute fossil diesel and for most performance criteria is superior to regular diesel.

B100 is not a real drop-in type fuel, as it requires some changes in calibration, engine hardware and maintenance schedules. Notwithstanding, some heavy-duty vehicle manufacturers allow the use of B100 fuel in present-day sophisticated vehicles.

In the case of gasoline, there are no superior renewable hydrocarbon drop-in components, as bio-gasoline hydrocarbon compounds tend to have low octane numbers. New blending components, such as pure hydrocarbons, higher alcohols or ethers, could alleviate the challenges.

Finally, special fuels can be used as such or as high blends in dedicated or adapted engines. Such fuels are, e.g., gaseous fuels (methane, LPG), dimethyl ether (DME) and high concentration alcohol fuels (E85, ED95). These fuels have a merit in chemically simple structure, and in most cases, also inherently clean burning. However, the market introduction of such fuels has to go hand in hand with building up the refueling infrastructure and the vehicle fleet, requiring huge joint efforts.

The world population of natural gas vehicles exceeds 20 million units. Cleaned biogas, biomethane, is a drop-in substitute for natural gas. Ethanol flex-fuel vehicles (FFV) are still offered for the markets in North and South America, but have in practice vanished from the

European market. FFVs are a cost-effective way of enabling the use of high concentration ethanol.

Regardless of the method to introduce biofuels, whether low-level blending, drop-in fuels or special fuels for dedicated vehicles, fuel quality, vehicle/fuel compatibility and vehicle compliance have to be maintained. Prerequisites are standards defining and securing fuel properties and vehicles adapted to and certified for the fuels they are using. The fuel is simply not a parameter that can be decoupled from the rest of the system, which comprises of engine, lubricant, exhaust after-treatment system, refueling infrastructure and regulation regarding safety and emissions.

Introduction

For more than 100 years, internal combustion engines have mainly been operated on hydrocarbon fuels. Over the years, engines and fuels have been developed and improved in parallel. A modern road vehicle is a quite complicated and sophisticated piece of machinery. To sustain performance and low exhaust emissions, fuel properties have to be kept within certain boundaries. Some fuel parameters, such as octane number of gasoline and cetane number of diesel fuel, are directly related to engine performance and integrity, whereas some other parameters, like sulphur and aromatic content, relate to exhaust emissions. Prerequisites for using effective exhaust after-treatment systems are fuels with zero lead and ultra-low levels of sulphur. A number of parameters are regulated to secure operation over time (e.g., oxidation stability, residues, ash, corrosion). Some parameters relate to cold weather operability (e.g., vapour pressure (gasoline) and cold-flow properties (diesel).

There are in principle three different ways to introduce biofuels for road vehicles:

- Low level blending of traditional biocomponents, e.g., ethanol, conventional biodiesel (fatty acid methyl ester FAME) within existing fuel standards
  - Simple solution, but limited impact, typically only 10 – 15% energy replacement
- Drop-in type components suitable for high level blending
  - Drop-in fuel means a fuel that is fully fungible with conventional hydrocarbon fuels and compatible with existing vehicles and fuel infrastructure
  - Simple solution, impact can be high, up to 100% replacement
  - Paraffinic renewable diesel (Hydrotreated Vegetable Oil HVO, Fischer-Tropsch diesel) is a kind of silver bullet for diesel
  - No really good biocomponent options available for high level blending in gasoline, bio-gasoline hydrocarbon (bio-naphtha) compounds tend to have

low octane

- Dedicated fuels for dedicated vehicles
    - Gaseous fuels, high concentration alcohol fuels
    - ”Chicken and egg” dilemma, what comes first, fuel infrastructure or vehicles?

The grouping above is suggestive, not absolute. Neat (100%) conventional FAME biodiesel can be used in only slightly modified diesel engines, and in the case of dedicated vehicles, biomethane (cleaned biogas) constitutes a drop-in alternative for natural gas.

Table 6 provides an overview of transport fuels and how they can be used in vehicles. Most of these fuels can be produced via a number of pathways, i.e. from a range of feedstocks and through various conversion technologies, see section “Technology pathways and status” for details.

Table 6: Application of transport fuels

Fuel	Application in road transport
Ethanol[116]	Gasoline blends (E5, E10, E85 in FFVs), stoichiometry and materials issues constitute blending walls in conventional vehicles Additive treated ED 95 for diesel-type engines (commercial), potentially also engines with assisted ignition (spark-plug, glow-plug, dual-fuel)
Methanol	Low-level blends with gasoline Heavy-duty engines as in the case of ethanol (additive treated fuel, engines with assisted ignition)
Various higher alcohols	E.g. butanol in gasoline blends
Ethers	E.g. MTBE (from methanol) and ETBE (from ethanol) in gasoline blends, preferred by the auto manufacturers over ethanol or methanol as such; blending wall stems from stoichiometry
FAME/Biodiesel	Diesel blends (B7, B10, B20, B30), neat B100 Neat B100 typically requires some vehicle modifications
Drop-in hydrocarbons	Gasoline-type components with limited octane for blending components Paraffinic HVO and Fischer-Tropsch diesel, drop-in, up to 100% substitution
Methane	Passenger cars (mostly bi-fuel methane/gasoline vehicles) Heavy duty vehicles with either mono-fuel or dual-fuel technology On-board storage either as compressed biogas (CBG) for LD vehicles or liquefied biogas (LBG) for HD vehicles
	Application in shipping
Biofuels	Various types of bioliquids, including some "biocrudes" less stringent fuel requirements than in the on-road sector
Methane	Mainly dual-fuel engines, fuel storage in liquid form, currently fossil natural gas, bio-methane could replace natural gas
	Application in aviation
Liquid renewable fuels	Current regulation allows up to 50 % renewable components, very stringent certification process, hydrotreatment (HEFA fuels), synthesis and e-fuels potential routes to aviation fuels

[116] Brazil: special case for ethanol, regular gasoline contains 27 % ethanol (E27), also hydrous ethanol (E100) on the market, special vehicles flex-fuel/bi-fuel vehicles combing gasoline/ethanol with methane available

In markets with stringent vehicle and emission regulations, vehicles and fuels have to be on pair, meaning that a vehicle should be approved and certified for the fuel it is operating on. Changing the fuel might have effects on the engine itself, the exhaust after-treatment system and even the lubricant. One can thus state, that the fuel is not a parameter that can be freely varied, it has to be a part of a balanced system (Figure 19).

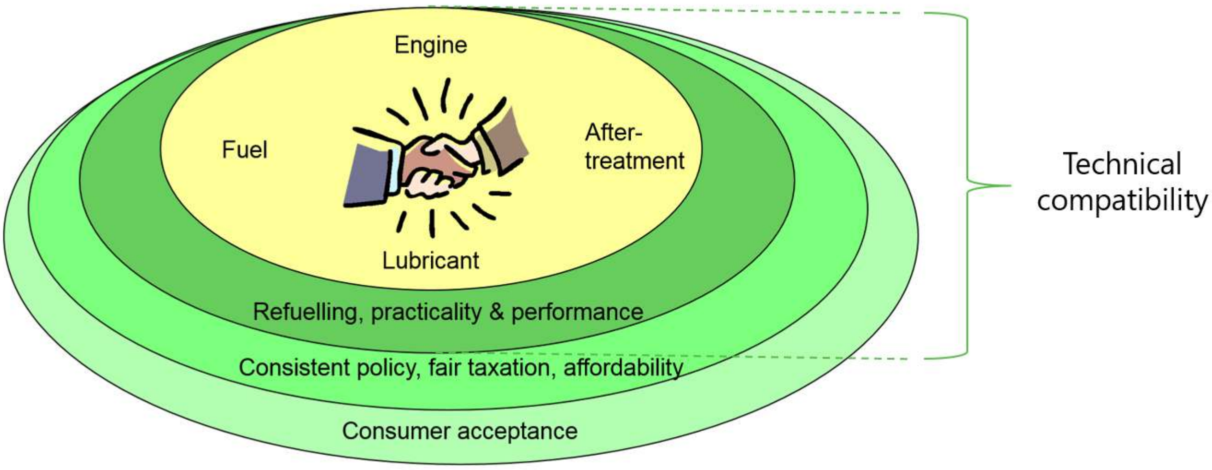


Figure 19: Prerequisites for technical compatibility, and in the end, consumer acceptance.

Reasons for limiting the concentrations of certain components

The term "blending wall" used in conjunction with low-level blending of biocomponents into commercial grade fuels means that for some technical reasons, there is a need to limit the concentration of a certain component. This is done to safeguard operability and to make sure that commercial grade gasoline and diesel are compatible with the vehicle fleet and the refueling infrastructure in place. The need for limits can arise from chemical as well as from physical properties of biocomponents.

In the case of Europe, the Fuel Quality Directive 2009/30/EC (FQD)[117], concerning the quality of gasoline, diesel and gas-oil, sets requirements for the parameters, which are most critical for engine performance and exhaust emissions. Some of the limits are directly linked to the use of biocomponents.

For gasoline, there are limits for maximum oxygen content and maximum concentration of individual oxygenates. The oxygen content of the fuel affects the stoichiometry of the air-fuel mixture. In older or less sophisticated engines without closed-loop air-fuel ratio control,

[117] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0030&from=EN

increasing oxygen content means leaning out of the mixture, which eventually can lead to, e.g., misfiring, overheating and engine malfunction. Modern gasoline cars with closed-loop lambda control can, to a certain degree, compensate for fuel oxygen.

There is also a need to limit the concentration of oxygenates from a materials compatibility point of view. Ethanol is corrosive, polar and conductive, and can attack metals and elastomers. Methanol is even more challenging than ethanol in this respect. Higher alcohols and ethers, on the other hand, are less prone to cause problems.

The limits on oxygenated compounds set by the FQD are:

- oxygen content maximum 3.7% m/m (corresponds to 10% v/v ethanol)
- ethanol content maximum 10% v/v (E10)
- methanol content maximum 3% v/v
- higher alcohols and ethers maximum 12…22% v/v, depending on the component

There is also a maximum limit on the vapor pressure of summer grade gasoline, 60 kPa. At low concentrations, ethanol tends to increase the vapor pressure of gasoline (azeotrope formation). Thus the volatility of the base gasoline might need adjusting when blending in ethanol. Excessive vapor pressure might lead to elevated evaporative emissions as well as to malfunctions due to vapor lock in the fuel system.

In the case of diesel fuel, the FQD limits the content of conventional FAME-type biodiesel to 7% v/v (B7), with some exceptions for fleet operations. There are several reasons for this (see also Worldwide Fuel Charter later in the text):

- some materials issues with elastomers
    - FAME is a strong solvent
- high end of distillation temperature for FAME
    - could lead to engine oil dilution
- limited oxidation stability
- limited cold flow properties
- certain impurities carried over from feedstock and process

The background information in the FQD states:

"In order to facilitate the effective marketing of biofuels, CEN (European Committee for Standardization) is encouraged to continue working rapidly on a standard allowing the blending of higher levels of biofuel components into diesel and, in particular, to develop a standard for 'B10'.

A limit for the fatty acid methyl ester (FAME) content of diesel is required for technical reasons. However, such a limit is not required for other biofuel components, such as pure diesel-like hydrocarbons made from biomass using the Fischer-Tropsch process or hydro-treated vegetable oil."

Definitions for compatibility

There are different levels of compatibility, starting from materials compatibility to the compliance of the vehicle and the fuel to be used. ACEA, the European Automobile Manufacturers' Association, has defined compatibility and compliance in the following way[118]:

- Material compatibility: the fact that the material withstands exposure to the fuel (type) without negative effects concerning the durability and performance of the exposed material if the fuel (type) would be used.
- Tolerance: compatibility based on lifetime running on the fuel (type) without compromising vehicle safety or performance issues when using the fuel (type).
- Vehicle compatibility: guarantee that the vehicle is declared to be tolerant for the use of the fuel (type) and fulfils vehicle manufacturer defined conditions in respect of customer expectations for day-to-day vehicle operation.
- Compliance of a vehicle: when using the fuel (type) the vehicle fulfils all regulatory requirements concerning pollutant emissions and safe vehicle use assessed on the basis of tests using regulated reference fuels for the fuel (type).

As stated in the last bullet, reference or certification fuels are needed for the emission certification of vehicles. These fuels can be special certification fuels (reflecting market quality) or fuels fulfilling a certain standard. On the international level, special certification fuels are defined by UNECE WP.29, Regulation 83[119]. Fuels included are E5, E10, E85, E75 ("winter quality E85"), B5, B7, and in addition, certain gaseous fuels.

For the U.S., the Environmental Protection Agency (EPA) defines emission certification fuels[120].

The European Union in principle falls back on UNECE. Specifications for certification fuels

---

[118] https://www.nen.nl/Evenementen/Presentaties/20190625-Presentaties-Future-fuels.htm?utm_medium=email (Andreas Kolbeck)

[119] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:42015X0703(01)&from=EN

[120] https://www.epa.gov/emission-standards-reference-guide/epa-emission-standards-light-duty-vehicles-and-trucks

are included in the emission regulations[121]. In some cases, a reference is made to European fuel standards (actual EN standards, draft standards or even so-called workshop agreements). The Euro VI regulation for heavy-duty engines requires heavy-duty engines to be certified on the fuel they will be running on[122]. Possible alternatives are, e.g., B7, B10, B20/B30, B100, 100% paraffinic diesel (XTL), gaseous fuels and also ED95 (additive-treated ethanol for diesel engines).

Legislation, standards and recommended practices

Fuel quality and fuel composition are regulated on various levels, both internationally and nationally.

The highest level, legally binding, is defined by laws, Directives (EU) and regulations. In the case of Europe, e.g., the Fuels Quality Directive 2009/30/EC and regulation concerning vehicle emissions are legally binding. Likewise, in the U.S., the US Codes of Federal Regulations are binding. As said, the FQD regulates the fuel parameters, which are most critical for engine performance and exhaust emissions.

The second level is standards. Standards are, in principle, voluntary agreements and not legally binding, representing industry practice. A standard is based on consensus among all interested parties[123]. There are international, regional and national fuel standards, e.g., ISO (International Organization for Standardization), CEN (European Committee for Standardization) and ASTM (American Society for Testing and Materials) standards. Some EN and ASTM standards are also recognised internationally (e.g., aviation fuels are certified by ASTM[124]). In some cases national legislation can refer to standards, thus making standards legally binding.

Standards are typically more comprehensive than the legally binding documents. The European FQD only lists 6 parameters for diesel fuel, whereas the European standard for diesel fuel, EN 590[125], all in all list 16 parameters to be controlled. The additional

---

121 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1151&from=EN

122 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32018R0932

123 https://www.nen.nl/Evenementen/Presentaties/20190625-Presentaties-Future-fuels.htm?utm_medium=email (Ortwin Costenoble: standards)

124 https://www.astm.org/cms/drupal-7.51/newsroom/astm-aviation-fuel-standard-now-specifies-bioderived-components

125 **EN 590:2013+A1:2017 (**WI=00019524) Automotive fuels - Diesel - Requirements and test methods

parameters relate to functionality and vehicle durability, e.g., lubricity, corrosion, ash, sediments, oxidation stability and cold operability.

For oxygen and ethanol content of gasoline and FAME content of diesel, the EN standards are in congruence with the FQD. The European standard for diesel fuel contains both a minimum and a maximum value for density (FQD only has a maximum density value). In EN 590, minimum density is 820 kg/m^3 for summer grade fuel and 800 kg/m^3 for winter grade fuel. Especially the minimum value of summer grade diesel, 820 kg/m^3, limits the share of paraffinic renewable diesel (HVO, BTL) that can be blended into commercial grade EN 590. Paraffinic diesel is typically lighter than regular diesel, with a density of some 780 kg/m^3.

Figure 20 presents an overview of the European fuel standards currently in place. Not all of these standards are necessarily for use as motor fuels or as such (e.g. EN 16900 specifies fast pyrolysis bio-oils for boiler use at industrial scale, EN 15376 ethanol used as a blending component).

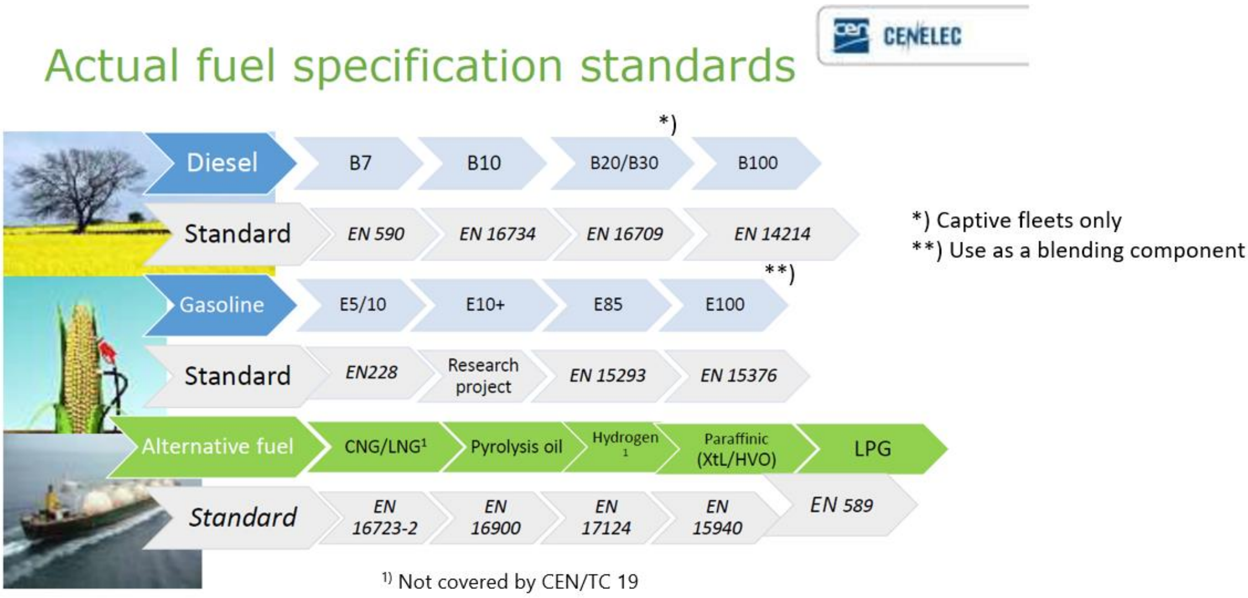


Figure 20: Current European fuel standards[7].

Conventional diesel (EN 590) may contain up to 7% v/v FAME. There are also standards for B10[126] (can be marketed to the general public), B20/B30[127] (for use in captive fleets only)

---

126 EN 16734:2016+A1:2018 (WI=00019543) Automotive fuels - Automotive B10 diesel fuel - Requirements and test methods

127 EN 16709:2015+A1:2018 (WI=00019549) Automotive fuels - High FAME diesel fuel (B20 and B30) -

and B100[128] (FAME as a blending component or for use in engines adapted to this fuel).

As of 2016, there is a standard for paraffinic diesel. EN 15940[129]. This standard covers diesel fuel from synthesis or hydrotreatment, which means BTL, GTL (gas-to-liquids) and HVO fuels. EN 15940 states:

“Paraffinic diesel fuel does not meet the current diesel fuel specification, EN 590. The main differences between paraffinic diesel fuel and automotive diesel fuel are in the areas of density, sulfur, aromatics and cetane. Its density can be outside the regular diesel specification, and the described class A type fuel has a higher cetane number. Paraffinic diesel fuel is not validated for all vehicles, consult vehicle manufacturer before use.

Paraffinic diesel is a high quality, clean burning fuel with virtually no sulfur and aromatics. Paraffinic diesel fuel can be used in diesel engines also to reduce regulated emissions.”

The standard for gasoline, EN 288[130], covers two gasoline grades, E5 (maximum 5% v/v ethanol and 1.85% m/m oxygen) applicable to all gasoline engines, and E10 (maximum 10% v/v ethanol and 3.7% m/m oxygen) for those vehicles which are E10 compatible.

There is also a standard for high concentration ethanol fuel, E85[131], to be used in flex-fuel vehicles. The standard for anhydrous ethanol E100[132] is applicable for ethanol used as a blending component.

As indicated in Figure 20, the European Commission has initiated a process to increase the allowable ethanol concentration of gasoline. As a part of this process, in 2015 - 2019, a research project “Engine tests with new types of biofuels and development of biofuel standards” was carried out by CEN with Netherlands’ Standardization Institute (NEN) as

---

Requirements and test methods

128 EN 14214:2012+A2:2019 (WI=00019562) Liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods

129 EN 15940:2016+A1:2018+AC:2019 (WI=00019563) Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods

130 EN 228:2012+A1:2017 (WI=00019523) Automotive fuels - Unleaded petrol - Requirements and test methods

131 EN 15293:2018 (WI=00019511) Automotive fuels - Automotive ethanol (E85) fuel - Requirements and test methods

132 EN 15376:2014 (WI=00019452) Automotive fuels - Ethanol as a blending component for petrol - Requirements and test methods

coordinator133. Regarding standardization, the main conclusions were:

- E20 should be feasible as a fuel in Europe, as most post-2011 vehicles in fact are compatible with E20
- tests methods for FAME should be improved to safeguard the robustness of FAME blended fuels
- The lower density limit of summer grade EN 590 diesel fuel could be lowered to 800 kg/m^3, to allow blending in of increased amounts of paraffinic components (meaning up to 50% paraffinic renewable diesel in EN 590)

The fuels in use vary by region and country. In the U.S., the fuel grades include E10, E15, E85, B5 and B20134. ASTM D4814 135 defines gasoline fuels with up to 15% ethanol. The use of E15 is approved for use in model year 2001 and newer light-duty conventional gas vehicles. ASTM D 6751136 specifies biodiesel (B100) for use as a blend component with middle distillate fuels, whereas ASTM D7467137 specifies the blended fuels (B6…B20).

In Brazil, all gasoline contains 27% ethanol (E27). In addition, neat ethanol (E100) is on the market. For diesel fuels, there is a blending mandate that will reach 15% FAME (B15) in 2023, and currently this value is 12%[138].

The third level is "Code of Practice" type documents and recommendations. This group includes documents such as:

- Worldwide Fuel Charter (WWFC)[139] of the auto and engine manufacturers
    - encompasses fuel quality recommendations by region and by degree of sophistication of emission regulations
- CEN guidelines for good housekeeping (diesel fuel[140], gasoline[141], prevention of

[133] https://www.nen.nl/Evenementen/Presentaties/20190625-Presentaties-Future-fuels.htm?utm_medium=email (Ortwin Costenoble: H2020 project)

[134] https://afdc.energy.gov/

[135] https://www.astm.org/Standards/D4814.htm

[136] https://www.astm.org/Standards/D6751.htm

[137] https://www.astm.org/Standards/D7467.htm

[138] https://www.iea-amf.org/app/webroot/files/file/Workshop_Transport_Decarbonisation/02%20Brazilian%20Perspective%20on%20Transport%20Decarbonisation%20-%20Miguel%20Oliveira.pdf (fuel specs mentioned orally)

[139] https://www.acea.be/uploads/publications/WWFC_19_gasoline_diesel.pdf

cross contamination[142])

- CONCAWE guidelines for handling and blending FAME[143]

The sixth and most recent edition of the Worldwide Fuel Charter was published in October 2019. It defines 5 categories or specifications for gasoline (2 - 6, category 1 is abolished as obsolete) as well as for diesel (1 - 5). Category 6 (for gasoline) and category 5 (diesel) are fuels fit for markets with the most stringent emission regulations. In fact, category 6 for gasoline is forward-looking, anticipating increased efficiency requirements and defining octane levels of 98 and 102 RON.

The Worldwide Fuel Charter is published by the members of the Worldwide Fuel Charter Committee as a service to legislators, fuel users, producers and other interested parties around the world to provide advice on sufficiency and fitness for purpose. The document states:

"The Charter and Guidelines have two purposes: to inform policymakers and other interested parties how fuel quality can significantly affect engine and vehicle operation, durability and emissions performance throughout the year; and to promote harmonized fuel quality worldwide in accordance with vehicle, engine and emission control system needs, for the benefit of consumers and the general environment. The Charters impose no obligation on any users or producers of fuel, and they do not prohibit use of any engine or vehicle technology or design, fuel, or fuel quality specification. They are not intended to, and do not, replace engine and vehicle manufacturers' fueling recommendations for their engine and vehicle products. Consumers are encouraged to check their vehicle owner manuals for specific guidance and to compare that guidance with fuel dispenser labels."

In addition to the five specifications for gasoline and five specifications for diesel, the WWFC presents plentiful of technical background information. The chapter on gasoline also discusses oxygenates. As for oxygen content and concentration of individual oxygenates, the WWFC falls back on the FQD and EN 228 (e.g., oxygen 3.7% m/m, ethanol 10% v/v, methanol 3% v/v). However, there is a provision for increased amounts of oxygenates:

---

140 https://infostore.saiglobal.com/en-us/Standards/CEN-TR-15367-1-2014-334308_SAIG_CEN_CEN_767928/

141 https://infostore.saiglobal.com/en-us/Standards/CEN-TR-15367-2-2007-334309_SAIG_CEN_CEN_767930/

142 https://infostore.saiglobal.com/en-us/Standards/CEN-TR-15367-3-2009-334310_SAIG_CEN_CEN_767932/

143 https://www.concawe.eu/publication/report-no-909/ https://www.concawe.eu/publication/report-no-308/

“To achieve 98 - 102 RON, the Charter provides flexibility for oxygen to reach up to 8% m/m (equivalent to about 20 - 22% v/v ethanol), but only for vehicles designed for such fuel and where dispensers are labelled to enable consumers to determine if their vehicles can use a particular gasoline-ethanol blend.”

For methanol, the WWFC states:

“The use of methanol is only acceptable if: (i) specified by applicable standards (e.g., maximum 3% v/v methanol in standard EN 228); (ii) consumed in vehicles compatible with its use; and (iii) stated in the owner's manual.”

The chapter on diesel includes a part discussing biofuels and alternative synthetic fuel components. Regarding conventional biodiesel, the WWFC presents a long list of possible problems:

- Biodiesel may be less stable than conventional diesel fuel, so precautions are needed to avoid problems linked to the presence of oxidation products in the fuel. Some fuel injection equipment data suggest such problems may be exacerbated when biodiesel is blended with ultra-low sulphur diesel fuels.
- Biodiesel requires special care at low temperatures to avoid an excessive rise in viscosity and loss of fluidity. Additives may be required to alleviate these problems.
- Being hygroscopic, biodiesel fuels require special handling to prevent high water content and the consequent risk of corrosion and microbial growth.
- Deposit formation in the fuel injection system may be higher with biodiesel blends than with conventional diesel fuel, so deposit control additive treatments are advised.
- At low ambient temperatures, FAME may produce precipitated solids above the cloud point, which can cause filterability problems.
- Biodiesel may negatively impact natural and nitrile rubber seals in fuel systems. Also, metals such as brass, bronze, copper, lead and zinc may oxidize from contact with biodiesel, thereby creating sediments. Transitioning from conventional diesel fuel to biodiesel blends may significantly increase tank sediments due to biodiesel’s higher polarity, and these sediments may plug fuel filters. Thus, fuel system parts must be specially chosen for their compatibility with biodiesel.
- Neat (100%) biodiesel fuel and high concentration biodiesel blends have demonstrated an increase in nitrogen oxide (NO_x) exhaust emission levels.
- Biodiesel fuel that comes into contact with the vehicle’s shell may be able to dissolve the paint coatings used to protect external surfaces.

Consequently, the WWFC is rather restrictive towards FAME. For categories 1 - 4, maximum

FAME content is 5% v/v. In category 5, no FAME is allowed (non-detectable). Throughout all five categories of diesel fuel, there are comments on “other biofuels” and “ethanol/methanol”:

- Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications
    - this is basically in congruence with the FQD (authors’ comment)
- Ethanol/methanol must be at or below detection limit of the test method used

Fuel quality marking for Europe

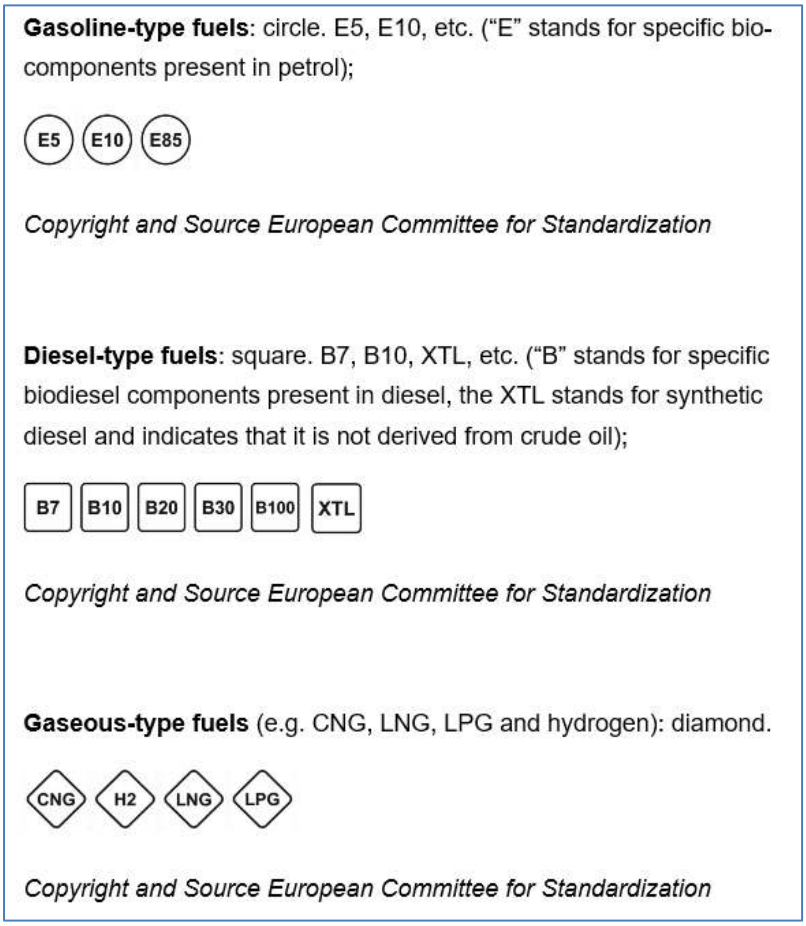
As of October 2018, in order to avoid confusion for consumers and businesses, a new compulsory fuel labelling system for Europe has been introduced. The system covers all 28 European Union member states, the EEA countries (Iceland, Lichtenstein and Norway), the former Yugoslav Republic of Macedonia, Serbia and Turkey. The system is based on a common and harmonized set of fuel labels for use on newly produced vehicles as well as at all filling stations dispensing gasoline, diesel, hydrogen, compressed natural gas, liquefied natural gas or liquefied petroleum gas fuels, as well as at vehicle dealerships[144].

These labels are placed on the nozzles of all filling pumps, on the pumps themselves and in the immediate proximity of the fuel filler flap/cap of newly produced passenger cars, mopeds, motorcycles, tricycles and quadricycles, light commercial vehicles, heavy-duty commercial vehicles and buses and coaches. They should also appear in the vehicle owner's manual, and they may appear in the electronic handbook available via a vehicle's infotainment center.

The system stems from Directive 2014/94/EU[145] on deployment of alternative fuel infrastructure. The system guarantees compatibility, but not necessarily bio content, even though the labels refer to biocomponent concentrations. Gasoline-type fuels are marked with a circle, diesel-type fuels with a square and gaseous fuels with a diamond (Figure 21).

[144] https://ec.europa.eu/commission/presscorner/detail/en/MEMO_18_6102

[145] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=en



Gasoline-type fuels: circle. E5, E10, etc. ("E" stands for specific bio-components present in petrol);

E5 E10 E85

Copyright and Source European Committee for Standardization

Diesel-type fuels: square. B7, B10, XTL, etc. ("B" stands for specific biodiesel components present in diesel, the XTL stands for synthetic diesel and indicates that it is not derived from crude oil);

B7 B10 B20 B30 B100 XTL

Copyright and Source European Committee for Standardization

Gaseous-type fuels (e.g. CNG, LNG, LPG and hydrogen): diamond.

CNG H2 LNG LPG

Copyright and Source European Committee for Standardization

Figure 21: The new fuel labelling system for Europe28.

Figure 22 (diesel truck fuel tank and fuel dispenser) shows actual photos of the markings. In this case, the truck is approved for B7, B10 and 100% paraffinic diesel fuel (XTL). The dispenser, on the other hand, provides two grades of gasoline (E5 and E10), and two grades of diesel (B7 corresponding to EN 590) and 100% renewable HVO diesel (XTL, corresponding to EN 15940)

Figure 22: Actual photos of fuel markings (truck fuel tank and fuel dispenser).

Examples of vehicle adaptation to special fuels

As stated earlier, it is possible to use special fuels, namely some high concentration liquid biofuels and gaseous fuels, in dedicated or adapted engines. In most cases, 100% paraffinic renewable diesel does not require any engine modifications, and even B100 requires only minor modifications to engine hardware and maintenance procedures.

It is, in principle, relatively simple to modify a gasoline car to run on **high concentration ethanol E85**. E85 consists of up to 85% v/v ethanol, the balance being hydrocarbons to facilitate cold starting. However, when an OEM vehicle manufacturer makes a so-called flex fuel vehicle (FFV), capable of running on any fuel from neat gasoline to E85, several considerations have to be made, e.g.;

- materials compatibility of the fuel system as well as of the base engine itself
- proper calibration of the fuel system including adaptation to the fuel in use
- securing adequate emission performance, including operation at low ambient temperatures
- coping with potential safety issues arising from, e.g., the evaporative behavior and conductivity of ethanol

Figure 23 shows features of flex fuel vehicles.

It is self-evident, that simple aftermarket conversions to E85, focusing merely on the recalibration of the fuel system, cannot deliver adequate performance and safety, and should therefore not be recommended. E.g. ACEA speaks strongly against aftermarket conversions[146].

FFVs have almost disappeared from the European market. There are at least two reasons for this. Firstly, the Euro 6 emission regulation requires emission certification with E85 also at -7 °C, which poses some calibration challenges. Secondly, there is no real incentive for the auto manufacturers to produce FFVs, contrary to zero carbon dioxide (CO_2) tailpipe electric vehicles. However, in the Americas, North and South, there is still an ample offering of FFVs.

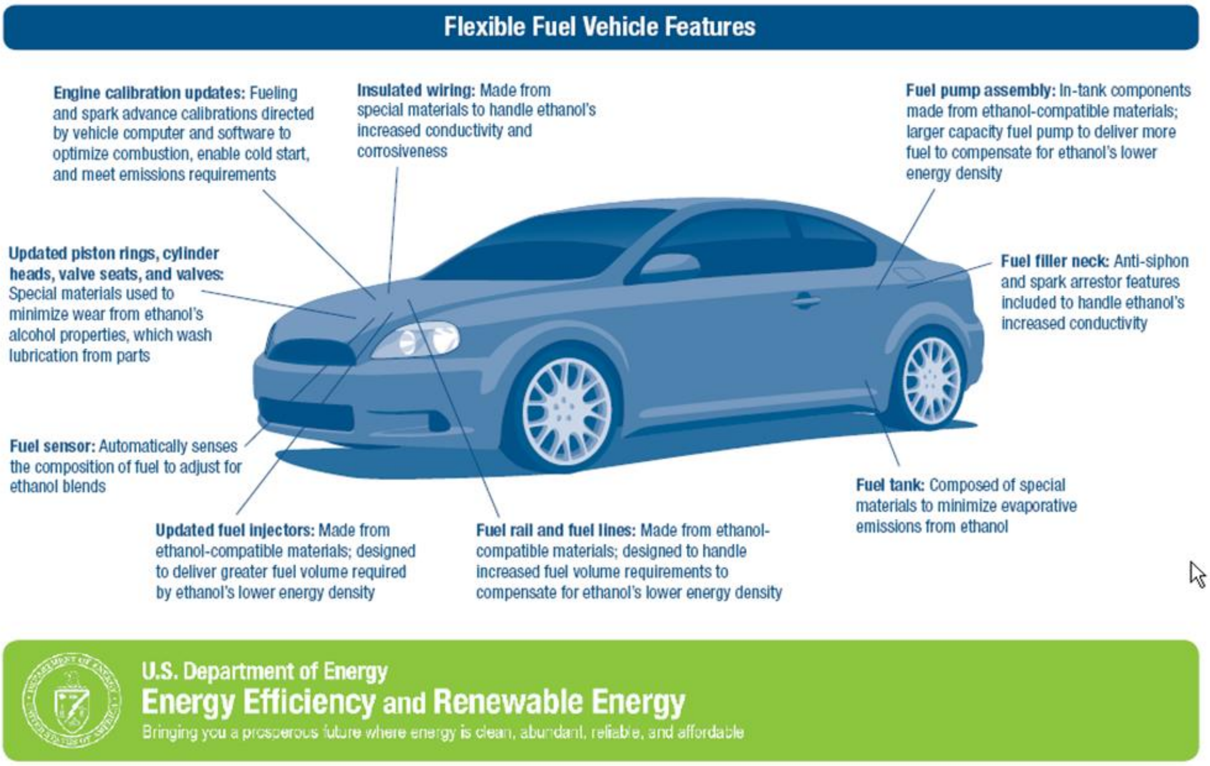


Figure 23: Flex fuel vehicle features[147].

There are a number of heavy-duty engines approved for B100 fuel. The Association Quality Management Biodiesel (AGQM) was founded in 1999 as an initiative for the quality assurance of leading biodiesel producers and traders. AGQM maintains a list of approvals

[146] https://www.acea.be/publications/article/position-paper-aftermarket-flexfuel-converters

[147] https://afdc.energy.gov/vehicles/flexible_fuel.html

for B20/B30 and B100 fuels[148]. Included on the list of manufacturers that allow the use of B100 in certain latest technology Euro VI engines are companies such as DAF, Daimler (Mercedes-Benz), MAN, Scania and Volvo. AGQM's web page also contains links to fuel related technical bulletins of the manufacturers. The bulletins typically contain some provisions and comments regarding the use of B100, e.g.:

- the fuel has to fulfil the EN 141214 standard
    - in some cases additional requirements on ash and phosphorus to safeguard particulate filters against blocking
    - reduced service intervals of particulate filters (ash removal)
- engines have to be ordered with special calibration and some special components for B100 operation
- increased urea consumption in the selective catalytic reduction (SCR) system due to higher engine-out NO_x emission
- reduced engine output and increased volumetric fuel consumption due to lower volumetric heat value in comparison with regular diesel
- reduced engine oil, oil filter and fuel filter exchange intervals for B100
- higher engine oil viscosity to compensate for engine oil fuel dilution

Effects of biofuels on tailpipe emissions

Currently, the main motivation for implementation of biofuels is reduction of CO_2 emissions. However, to some extent biofuels can also contribute to the reduction of harmful tailpipe emissions.

When estimating the impact of biofuels on air pollutant emissions from road vehicles, there are two determining factors to consider: first, the combination of the vehicle's engine and exhaust after-treatment technology; and second, the characteristics of the biofuel compared with the fossil fuel being replaced. Taken together, these two components provide an indication of the performance of biofuels relative to fossil fuels in terms of air pollutant emissions and impact on human health.

With sophisticated engines and after-treatment technology, the effect of a fuel's chemical and physical characteristics on tailpipe emissions is greatly reduced. For vehicles that comply with the latest emissions standards, most tailpipe air pollutant emissions reach very

---

[148] https://www.agqm-biodiesel.com/application/files/3415/2992/6037/WEB_EN_AGQM_0216_FREIGABEN.pdf

low levels regardless of the fuel used. For older vehicles, however, fuel type can significantly influence air pollutant emissions. Therefore, fuel selection is particularly relevant in many emerging economies and developing countries with large urban agglomerations and older vehicle fleets. Alternative fuels can help cleaning up ambient air, but they are not the primary tool to reduce emissions.

The fuel effects on tailpipe emissions can be summarized as follows:

- Oxygenated components (alcohols, ethers, esters) tend to decrease carbon monoxide, hydrocarbon and particulate emissions but increase emissions of nitrogen oxides
- Methane provides soot-free combustion independent of the sophistication of the engine
- Reducing aromatics (e.g., paraffinic renewable diesel) reduces particulate emissions and exhaust toxicity
- Chemically simple fuels (e.g., alcohols, methane, propane) tend to form less toxic emission components than complex fuels (gasoline, diesel), especially in engines optimized for these alternative fuels

Figure 24 (light-duty vehicles) and Figure 25 (heavy-duty vehicles) present simplified summaries of fuel effects on tailpipe emissions. The figures show that for present-time vehicles, the effects are slender.

Ethanol generally results in lower air pollutant emissions when blended with gasoline, with the level of emissions falling as the share of ethanol rises. This improvement is especially notable for particulate (PM) emissions, wherein lower emissions from high-ethanol blends are achieved with direct-injection spark-ignition engines. Ethanol also reduces tailpipe carbon oxide (CO) emissions; however, cold starting is more challenging with E85 than with gasoline, potentially raising volatile organic compound (VOC) emissions, and higher ethanol blends can increase acetaldehyde emissions compared with gasoline.

Biomethane delivers low CO, PM and VOC emissions when used in a spark-ignition gas engine. NO_x emissions vary significantly depending on engine and exhaust after-treatment technology; they are low for engines with a properly functioning three-way catalyst (TWC) and higher for less sophisticated lean-burn gas engines, for which there is some evidence of elevated formaldehyde emissions.

FAME biodiesel used at high blend levels decreases CO, VOC and PM emissions, potentially up to 50% in less sophisticated engines. However, at high blends FAME increases NO_x emissions compared with fossil diesel as a result of higher oxygen content and subsequently higher combustion temperatures.

HVO has high ignition quality and the paraffinic nature of the fuel improves combustion and thus reduces CO, hydrocarbon (HC) and PM emissions compared with regular diesel. Unlike FAME biodiesel, HVO also has potential to reduce NO_x emissions up to 10%. Of all fuels suitable for use in diesel vehicles, HVO delivers the lowest exhaust mutagenicity.

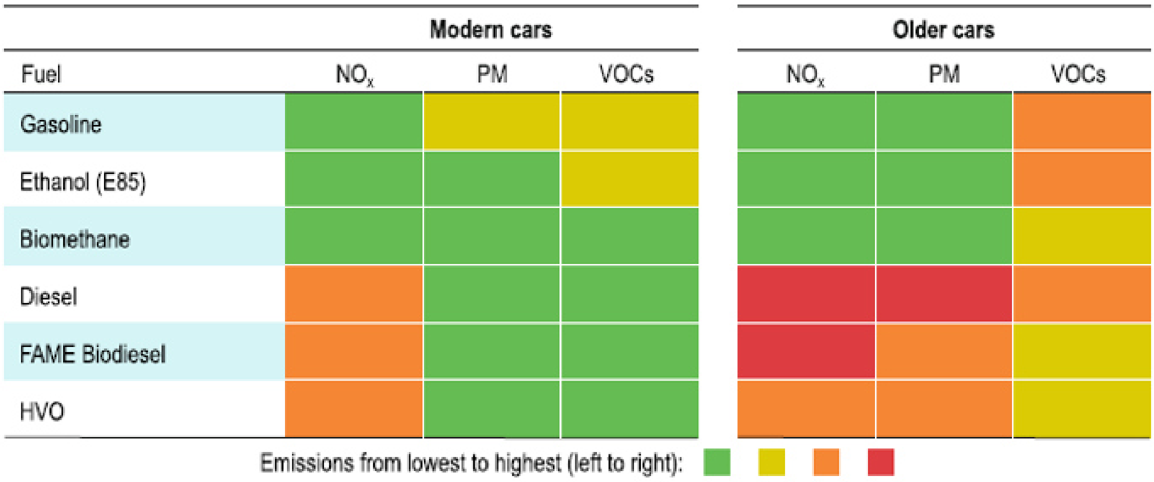


Figure 24: Fuel effects on tailpipe emissions of light-duty vehicles[149].

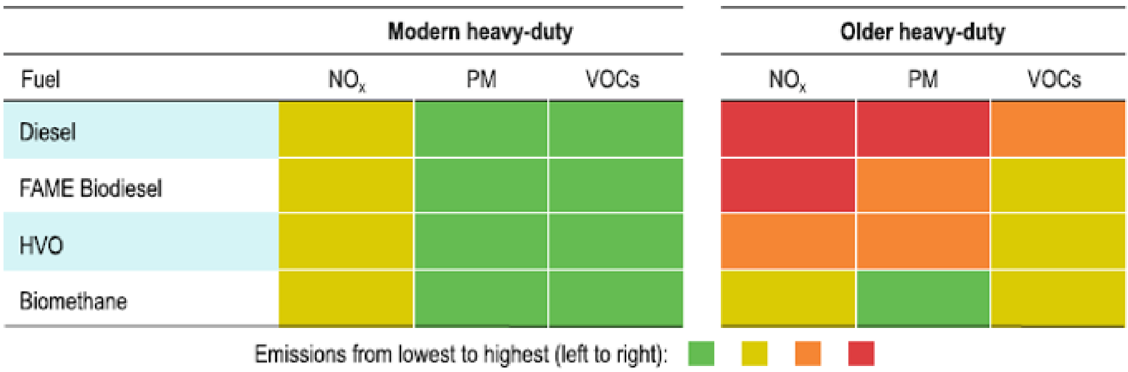


Figure 25: Fuel effects on tailpipe emissions of heavy-duty vehicles[33].

---

[149] https://www.iea-amf.org/app/webroot/files/file/other%20publications/Renewables%202018_biofuels%20and%20air%20quality.pdf

Additional information on fuel properties, performance and vehicle compatibility

The website of the IEA Technology Collaboration Programme on Advanced Motor Fuels (AMF, https://www.iea-amf.org/) contains a section named "Fuel Information" (https://www.iea-amf.org/content/fuel_information/fuel_info_home).

The "AMF Fuel Information System" focuses on the end-use aspects of advanced motor fuels. Performance of vehicles, effects on emissions and compatibility with infrastructure are included, whereas resources, production and GHG emissions are excluded. When the end-use aspects are evaluated, the complex field of engine/after-treatment options, uncertainties of measurement methods and incomparability of measurement campaigns have to be taken into account. In the system, priority is given to new studies; however, these represent only minor part of published studies.

The "AMF Fuel Information System" is based on information from AMF projects and other reliable sources. Links to relevant AMF work are provided in all sections. The objective of the "AMF Fuel Information System" is to provide easy access to all end-use related aspects of advanced motor fuels.

The fuels and fuel components covered are:

- Diesel and gasoline
- Bio/synthetic gasoline
- Bio/synthetic diesel (paraffins)
- Fatty Acid Esters (biodiesel)
- Oils and fats
- Oxygenates
- Ethanol
- Methanol
- Butanol
- Methane
- LPG
- DME

In addition, cross-cutting issues such as fuel comparisons and significance of emissions are covered.

The following is a sample of information contained in the system (case ethanol and paraffinic diesel):

Ethanol is the dominant biocomponent in the gasoline market. Edible ethanol is produced by fermentation of sugar-containing feedstock. Production of fuel ethanol from cellulosic feedstock is under commercialization phase. Industrial ethanol can be produced from petrochemical ethylene by the acid-catalyzed hydration, but this cannot be used to meet bioenergy obligations. Ethanol is a monomolecular compound with narrow boiling point, whereas gasoline consists of hundreds of different hydrocarbon molecules. Ethanol is aromatic-, olefin- and sulfur-free compound. Oxygen content of ethanol is 35%.

General:

- *Ethanol properties*
- *Special engines for alcohol use*

Ethanol for otto engines:

- *Ethanol as low concentration "E10" fuel to be used in conventional gasoline cars.*
- *Fuel ethers. Ethanol can be converted into e.g. ETBE, to be used in conventional gasoline cars.*
- *E85 fuel containing up to 85% ethanol in gasoline for special flexible-fuel vehicles (FFV).*

Ethanol for diesel engines:

- *Fatty Acid Ethanol Esters (FAEE)* Ethanol can be converted into FAEE for low level diesel blending.
- *Diesel engines for ethanol*. Ethanol utilization in compression-ignition requires special engines and/or changes in fuel, such as "*Etamax D concept*".

Note: Ethanol as blending component in diesel fuel is not recommended for safety reasons. However, IEA-AMF Annex 46 (Schramm, J. Ed. 2016) points out the reduced particle emissions with this concept. Ethanol blending in diesel is also part of IEA-AMF Annex 10.

Paraffins are favorable components for diesel fuel. Diesel fuel itself contains paraffins in addition to other hydrocarbon groups. However, diesel fuel contains also napthenics and aromatics, which are not so favorable for combustion. Paraffinic diesel fuel has normally very high cetane number, no sulfur, nitrogen, oxygen nor aromatics. Paraffins can be produced with various processes from fossil or renewable feedstocks. Synthetic fuels are produced by gasification and Fischer-Tropsch (FT) synthesis from natural gas (GTL) and coal (CTL). Biomass-based BTL fuel is not commercially available, yet. Hydrotreating of oils and fats is a commercial process for producing renewable paraffinic diesel, abbreviated HVO. Today more and more of HVO is produced from waste and residue fat fractions e.g. from animal fats and non-food grade vegetable oil fractions. Paraffinic components for diesel fuel are produced also from crude tall oil, a residue of pulp production.

Properties

- Legislation and standards
- Density and energy content
- Cold properties
- Cetane number
- Distillation
- Sulfur content and trace elements
- Stability and water
- Lubricity
- Measuring bio-content in fuel

Compatibility

- How much paraffins can be blended in diesel fuel?
- Blending HVO/XTL paraffins with FAME
- Compatibility with materials
- Storage and handling

Emissions

- Engine cleanliness and emission control devices
- Power output, fuel consumption, and CO_2
- Regulated emissions
- Unregulated emissions
- Optimizing engines for HVO
- Field trials
- Summary

Summary

The compatibility of fuels with fuel infrastructure and vehicles, both the legacy fleet and new vehicles, is a crucial issue. The full scale of compatibility means materials compatibility, tolerance and vehicle compatibility over the lifetime of the vehicle and also vehicle compliance. The latter means that when using the fuel (type) the vehicle fulfils all regulatory requirements concerning pollutant emissions and safe vehicle use assessed on the basis of tests using regulated reference fuels for the fuel (type). For compliance, reference fuels and fuel standards have to be in place.

The easiest way to introduce biocomponents is to operate within the framework of existing standards for gasoline and diesel fuel. However, when using traditional biocomponents such as ethanol and FAME biodiesel, there are technical limitations, so-called “blending walls”, on how much of these components can be added without compromising vehicle performance and durability. Typically, standards for regular gasoline and diesel only allow blending conventional biocomponents corresponding to an energy share 10 - 15%. Some activities to introduce intermediate ethanol blends (E20, E25) are under way. However, for higher substitution and more substantial decarbonization of transport, complementary actions are needed.

Drop-in type fuels, fully fungible with conventional hydrocarbon fuels and compatible with existing vehicles and fuel infrastructure, are one obvious solution. The degree of substitution can be as high as 100%. Implementation can be fast, as no infrastructure or vehicle modifications are needed. Paraffinic renewable diesel fuel, whether from hydrotreatment of oils and fats (HVO) or synthesis (BTL) is a kind of silver bullet for the diesel sector. For most performance criteria, paraffinic diesel is superior to regular diesel.

B100 is not a real drop-in type fuel, as it requires some changes in calibration, engine hardware and maintenance schedules. Notwithstanding, some heavy-duty vehicle manufacturers allow the use of B100 fuel in present-day sophisticated vehicles.

In the case of gasoline, there are in practice no superior renewable hydrocarbon drop-in components, as bio-gasoline hydrocarbon compounds tend to have low octane numbers. New blending components, either pure hydrocarbons, higher alcohols or ethers, could alleviate the challenges.

The remaining option is special fuels for dedicated or adapted engines. Included in this category are, e.g., gaseous fuels (methane, LPG), dimethyl ether (DME) and high concentration alcohol fuels (E85, ED95). These fuels have a merit in chemically simple structure, and in most cases, also inherently clean burning.

Dedicated vehicles and dedicated refueling infrastructure always pose the “chicken and egg dilemma”, that is, simultaneously and in a balanced way, to build up the refueling infrastructure and the vehicle fleet. The efforts to introduce a completely new fuel on the market are huge. DME has every now and then been forwarded as a promising alternative for diesel engines. The IEA AMF Technology Collaboration Programme has contributed to the development of an international ISO standard on DME for automotive applications[150]. In spite of the potential for high efficiency and low CO2 emissions on a well-to-wheel basis, clean combustion and the existence of an international standard, DME has so far only been used in some pilot projects.

The world population of natural gas vehicles exceeds 20 million units. Cleaned biogas, biomethane, is a drop-in substitute for natural gas. Flex-fuel vehicles are still offered for the markets in North and South America, but have in practice vanished from the European market. FFVs are a cost-effective way of enabling the use of high concentration ethanol.

Regardless of the method to introduce biofuels, whether low-level blending, drop-in fuels or special fuels for dedicated vehicles, fuel quality, vehicle/fuel compatibility and vehicle compliance have to be maintained. Prerequisites are standards defining and securing fuel properties and vehicles adapted to and certified for the fuels they are using. The fuel is simply not a parameter that can be decoupled from the rest of the system, which comprises

[150] https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_47.pdf

of engine, lubricant, exhaust after-treatment system, refueling infrastructure and regulation regarding safety and emissions.

Abbreviations

ACEA	European Automobile Manufacturer´s Association
AGQM	Association Quality Management Biodiesel
ALIISA	Model used by VTT to calculate the future composition of vehicle fleets in this study
AMF	Advanced Motor Fuels
APR	Aqueous phase reforming
ASTM	American Society for Testing and Materials
B5, B7,...	Diesel blends with x% FAME
BEV	Battery electric vehicle
BFG	Blast furnace gas
bio-LPG	Biobased liquefied petroleum gas
BOF gas	Basic oxygen converter gas
CBIO	Carbon Certificate, used in Brazilian regulation
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CEN	European Committee for Standardization
CFS	Clean Fuel Standard, Canadian regulation
CHP	Combined heat and power
CI	Carbon intensity, a measure of fossil GHG emissions over the life-cycle of a fuel
COG	Coke oven gas
CONCAWE	Environmental Science for European Refining
CTL	Coal to liquid
DDGS	Dry distillers grains and solids, by-product of ethanol production
DME	Di-methyl ether
E5, E10,...	Gasoline blends with x% ethanol
ED95	Fuel quality on the market in the Northern European countries, consisting of 95% ethanol and 5% additives for the use in CI engines
EER	Energy Economy Ratio, used in Californian regulation
ETBE	Ethyl tert-butyl ether, ethanol-containing gasoline additive
EUR	Euro
EV	Electric vehicle
FAEE	Fatty acid ethyl ester

FAME	Fatty acid methyl ester
FAO	Food and Agriculture Organization
FCC	Fluid catalytic cracking
FCEV	Fuel cell electric vehicle
FFA	Free fatty acids
FFV	Flex-fuel vehicle, capable of using either gasoline or high-blend ethanol (or pure hydrous ethanol in the case of Brazil)
FPO	Fast pyrolysis oil
FT	Fischer Tropsch
GGE	Gasoline-gallon-equivalent
GHG	greenhouse gases
GTL	Gas to liquids
GVW	Gross vehicle weight
HD	Heavy duty
HDO	Hydrodeoxygenation
HDT	Heavy duty truck
HDV	Heavy duty vehicles
HEFA	Hydrotreated esters and fatty acids
HEV	Hybrid electric vehicle
HTL	Hydrothermal liquefaction
HVO	Hydrotreated vegetable oils
IEA	International Energy Agency
ILUC	Indirect land-use change
IRENA	International Renewable Energy Agency
LBG	Liquefied biogas
LCA	Life-cycle assessment
LCFS	Low-carbon Fuel Standard, Californian regulation
LD	Light duty
LDT	Light duty truck
LDV	Light duty vehicles
LPG	Liquefied petroleum gas (auto gas)
MCEC	Molten carbonate electrolyzer cell
MDT	Medium duty truck

MSW	Municipal solid waste
MTBE	Methyl tert-butyl ether, methanol-containing gasoline additive
NEN	Netherland´s Standardization Institute
OEM	Original equipment manufacturer
PEM	Proton exchange membrane
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
RDF	Refuse derived fuel
RE	Renewable energy
RED	Renewable Energy Directive, EU regulation
RED-II	Recast of the Renewable Energy Directive, EU regulation
RenovaBio	Renova Bio, Brazilian regulation
RFS	Renewable Fuel Standard, US regulation
RIN	Renewable Identification Number, used in US regulation
RNG	Renewable natural gas
RON	Research Octane Number
RTFO	Renewable Transport Fuel Obligation, UK regulation
RVO	Renewable Volume Obligation, used in US regulation
SCR	Selective catalytic reduction, an exhaust after-treatment system
SGAB	Sub-Group on Advanced Biofuels
SHF	Separate hydrolysis and fermentation
SIP	Synthesized Iso-paraffinic fuel
SOEC	Solid oxide electrolyzer cell
SRC	Short rotation coppice
SRF	Solid recovered fuel
SSF	Simultaneous saccharification and fermentation
STF	Sustainable Transport Forum
TCP	Technology Collaboration Programme (of the IEA)
TRL	Technology Readiness Level
TTW CO_2 emissions	Tank-to-wheel CO_2 emissions, i.e. tailpipe emissions
TWC	Three-way catalyst
UCO	used cooking oil

USD	United States (of America) Dollar
VOC	Volatile organic compound
WTT CO_2 emissions	Well-to-tank CO_2 emissions, i.e. upstream emissions from fuel or electricity production
WTW CO_2 emissions	Well-to-wheel CO_2 emissions, i.e. WTT and TTW combined
WWFC	Worldwide Fuel Charter