IEA Bioenergy
Technology Collaboration Programme

Assessment of successes and lessons learned for biofuels deployment

Report Work package 2 | Meta-analysis of existing studies

IEA Bioenergy TCP
Intertask project of Task 39, Task 40, and Task 45

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Index

Executive summary

The report presents a meta-analysis on several studies dealing with "successes and lessons learned for biofuels deployment" for advanced as well as from conventional biofuels. Biofuels that were evaluated include: Ethanol (sugar cane 1G) in Brazil; Ethanol (sugar cane 2G) in Brazil; Ethanol (corn 1G) in Brazil; Ethanol (corn 1 G) in the USA; Ethanol (cellulosic, various sources, 2G) in Europe; Biodiesel (FAME) in Brazil; Hydrotreated Vegetable Oil (HVO) in Europe; Biomass to Liquid (BtL)/DME (dimethyl ether) in Sweden; and Biosynthetic Natural Gas (SNG) in Sweden. Relevant studies were screened, and indicators were established to compare different biofuels. Indicators included policies, feedstocks, products, technologies, economics, environmental issues, social aspects, scalability and ease of implementation and reproduction in different countries or regions. For this Work Package (WP), the success stories were limited to biofuels with a technology readiness level (TRL) of at least 7. The standards and indicators of such biofuels can help ascertain conditions to foster their expansion and implementation in other regions, define gaps, especially economic, and devise solutions for the expansion and deployment of new or less mature biofuels. The successful cases of several biofuels, as discussed in this report, indicate that it is possible to supply large amounts of biofuels to help replace fossil fuels and reduce their global warming potential. However, the expansion of biofuel production and the replication of successful country or regional models in other places is not without challenges. The dependency on crop feedstock availability and price fluctuations may limit biofuel production in some instances. Legal restriction to food crop feedstock is also a challenge for the expansion of production of successful conventional biofuels. Temporary feedstock cost and availability restrictions may also be challenges, as shown by changes and postponements of biofuel blending mandates in several countries, especially during the COVID-19 pandemic. Recent developments were described, and markets discussed. The WP2 report includes a comprehensive dataset derived from the analysis.

KEY MESSAGES

- There is significant literature and experience to allow for a comparison of different biofuels options.
- Data were compiled based on TRL, biofuels main use, main feedstocks, products, economics, public policies, environmental impact, employment, implementation potential, replication potential, scale-up potential, and impact on the Sustainable Development Goals (SDG) that can shed light on lessons learned across the production chain.
- Conventional biofuels such as ethanol (both sugar cane and corn) and biodiesel are being sustainably produced and commercialized in substantial quantities in several countries. They represent, so far, the most relevant biofuels to replace fossil fuels in the world.
- Yields, costs, and environmental indicators improved with time.
- Biofuel blending mandates and proper public policies were important to support implementation and technological improvements.
- Recent economic crises (COVID-19 pandemic, Russo-Ukrainian war) affected biofuel blending mandates and use in several countries.

- Advances in biofuel production and use over the past years will have to be restored after the current crisis period.

- Published indicators for 2G/advanced ethanol are seldom available, but evidence exists that technological bottlenecks are being overcome.

- BtL, Bio-SNG, HVO, and straw-derived 2G ethanol show suitable indicators of environmental impact, SDG, and feedstock diversity to be replicated in different regions but economics is still a challenge.

- Although feedstock issues exist on biofuels produced from food crops in some countries, lessons learned with these biofuels turned them into relevant benchmarks and set standards for their replication in other regions and for novel biofuels with low TRL.

- Most biofuels in the market today are conventional biofuels such as ethanol (from sugar cane or corn) and biodiesel (from soybean oil or palm oil). These biofuels have crops, often food crops, as their main feedstock. This also applies to HVO.

- Despite these biofuels being success stories, according to metrics of some regions in the world, their production or consumption should decrease or be discontinued in the future. Yet, at this point, other biofuels produced exclusively from crop residues and non-food crops seem not to be economically produced on a scale large enough to replace the current volume of conventional biofuels.

- In view of the need to sharply increase biofuel production to abate the climate crisis, restrictions on some biofuel feedstocks may have to be rethought, especially where they can be sustainably produced, until non-food biofuels become feasible.

Introduction

The project “Lessons Learned Biofuels” evaluated the technical, economic, societal, and political reasons underlying the past and ongoing booms and busts cycles of biofuel technologies development, demonstration, deployment, and replication in order to identify technology successes and the best policy framework conditions and measures for stimulating increased future markets for production and consumption of sustainable transport biofuels.

In the project scope, a review of national programs of leading biofuels producer countries was done to compare different producer countries framework conditions and policy approaches as well as levels and rate of biofuel production growth that these conditions have enabled. This assessment highlighted the most important factors that have been incorporated and identified the balance between market-related versus technology-related policy instruments that have proven to be most effective. In the WP 2, existing studies on “Lessons Learned Biofuels” were evaluated. In WP 3 and 4, case studies were provided to illustrate examples of successful progress in developing and scaling up conventional/existing and advanced/emerging biofuels production technologies and supply chains. The structure of the project is presented in Figure 1, indicating which theme each the WP addressed specifically. Each WP was led by a different IEA TCP Bioenergy Tasks (T39, T40, and T45). One of the objectives of the project is to assess the broad topic “Lessons Learned” in Phase I, being foreseen a as Phase II of the project in the next triennium. The position and main objective of WP 5 is also presented in the Figure 1.

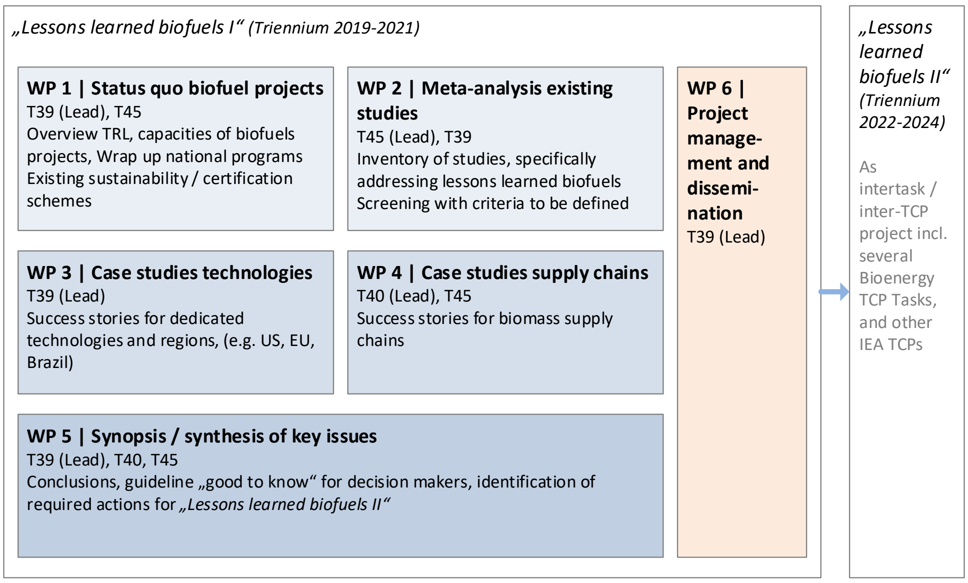

Figure 1 Project WP structure

The Covid pandemic and the recent invasion of Ukraine have posed additional challenges to environmental goals and setbacks on bioenergy policies in several countries. After the end of the current crisis and the easing of the economic constraints, renewable energy and biofuel policies will have to be revised, and action taken to recover the time lost.

This project will discuss the technical, economic, societal, and political reasons underlying the past and ongoing development of biofuel technologies, demonstration, deployment, and replication to identify technology successes and the best policy framework conditions and measures for stimulating increased future markets for production and consumption of sustainable transport biofuels.

The WP 2 (Meta-analysis on existing studies) examines several studies dealing with “successes and lessons learned for biofuel deployment” for advanced and conventional biofuels. Relevant studies were screened and indicators were established that made possible to compare different biofuels. Indicators included feedstocks, products, technologies, economics, environmental issues, social aspects, scalability and ease of implementation and reproduction in different countries or regions. For this WP, the success stories were limited to biofuels with a TRL of at least 7. WP 2 focused on the research question “What are key factors for the success of sustainable biofuel projects”. The standards and indicators of such biofuels are important to help ascertain the conditions that limit their expansion and implementation in other regions, define gaps, especially economic, and to devise solutions for the expansion and deployment of new or less mature biofuels.

The concept of “advanced biofuels” may vary depending on the region. For instance, in the USA, a minimum reduction of greenhouse gas (GHG) emission is required, whereas in the EU, other characteristics or restrictions may be involved, such as the nature of the feedstock. Therefore, the limits between “conventional” and “advanced” biofuels depend on the context.

Methodological approach

Several studies investigate "successes and lessons learned for biofuels deployment" on a direct or indirect level for different fuel options. This WP performed a review of existing studies. Because of limitations of time and resources, the study covered just a few dedicated biofuels. After screening relevant studies, criteria were established for the analysis that allowed comparing studies and compile the results in a comprehensive summary of conclusions. Each project team member reviewed the studies based on their specific views.

As the starting point for this analysis, publications (scientific papers, reports, and other studies) on lessons learned and success stories were selected but as only a limited number of biofuels were evaluated. The literature consulted is shown in the evaluation tables in the Appendix and is cited in this report.

A set of indicators was established beforehand to compare the biofuels, taking into account the type of biofuel and the technology used to produce it, the location where it is considered a success, its TRL, the biofuel main use, economics and social aspects, type of vehicles where it is used, feedstocks, relevant public policies, environmental impact indicators, implementation, replication, and scale-up potential, and contribution to the SDG of the United Nations. A summary of the indicators used to evaluate the biofuels as well as criteria established to rate the indicators is given in Table 1.

Table 1 Criteria to evaluate biofuels and grades used to draw spider diagrams

Criteria	Biofuel/Biofuel Technology	Criteria evaluation (point attributed to each answer)
TRL	TRL 7 - system prototype demonstration in operational environment	TRL 7 = 1 (integrated in implementation)
	TRL 8 - system complete and qualified	TRL 8 = 2 (integrated in implementation)
	TRL 9 - actual system proven in operational environment	TRL 9 = 3 (integrated in implementation)
Biofuel main use	Application	-
Main feedstock	Type of feedstock	Crop = 1; Residue = 2
	Indicate if domestic or imported	
	Feedstock availability	Low = 1; Medium = 2; High = 3
	Feedstock yield	Low = 1; Medium = 2; High = 3
	Commercially available biofuels	No = 0; Medium = 1; High = 2
	Co-products - low value	Yes = 1 (For each product); No = 0
Products	Co-products - medium value	Yes = 1.5 (For each product); No =0
	Co-products - high value	Yes = 2.0 (For each product); No =0
	Economics considered?	No grading
	Biofuel production cost (or selling price)?	No grading
Economics	CAPEX available?	No grading
	OPEX available?	No grading

Criteria	Biofuel/Biofuel Technology	Criteria evaluation (point attributed to each answer)
	Does any blending mandate support the introduction of biofuels?	Yes = 1; No =0
	Does it require subsidies?	Yes = 1; No =0
Public policies	There are relevant laws and regulations?	Yes = 1; No =0
	Does it have public acceptance?	Yes = 2; Partially = 1; No =0
	GHG Emissions (g CO2e/MJ)	Savings > 80% = 3; Savings 60 to 79% = 2; Savings 40 to 59% = 1; Savings < 40% = 0
	Competition with food?	Yes = 0; Partially = 1; No =2
Environmental impact	Land requirement?	Not applicable = 3; Low = 2; Medium = 1; High = 0
	Air quality impact?	Yes = 1 (Positive effect); No =0
	Water usage?	Yes = 0; Partially =1; No =2
	Land impact?	Yes = 0; Partially = 1; No =2
	Sustainability issues: additional remarks	-
	See Report	No grading
	Low, medium, or high and if this is at local/regional, national or international level	Low = 1; Medium = 2; High = 3
Employment	See Report	National = 1; International = 2
Implementation potential	Low, medium, or high and if this is at local/regional, national or international level	Low = 1; Medium = 2; High = 3 National = 1; International = 2
Replication potential	Low, medium, or high and if this is at local/regional, national or international level	Low = 1; Medium = 2; High = 3 National = 1; International = 2
Scale-up potential		Yes = 2; Partially = 1; No or Not applicable = 0
SDGs	1-17	

Based on the methodical approach the following biofuel options presented in Table 2 have been considered in more detail.

Table 2 List of biofuels covered in this review

Biofuel	Country/Region
Ethanol (Sugar cane 1G)	Brazil
Ethanol (Sugar cane 2G)	Brazil
Ethanol (Corn 1G)	Brazil
Ethanol (Corn 1G)	USA

Biofuel	Country/Region
Ethanol (Cellulosic 2G)	Europe
Biodiesel (fatty acid methy ester, FAME)	Brazil
HVO (hydrotreated vegetable oil)	Europe
Biomass to Liquid /Methanol or DME	Sweden
Biosynthetic Natural Gas (Bio-SNG)	Sweden

Spreadsheets were prepared to collect the data, which are available in (Table 4 – Table 12).

Instead of scrutinizing and summarizing individual studies, which may cover one or more biofuels, a decision was made to focus on specific biofuel/technologies (*e.g.*,1G ethanol from corn in the USA), and collect as much information as possible from different sources. This allowed a more comprehensive view of each biofuel to compare them qualitatively and derive the lessons learned from each one. The analysis of each biofuel was done by different members of Task. Figure 2 illustrates the process.

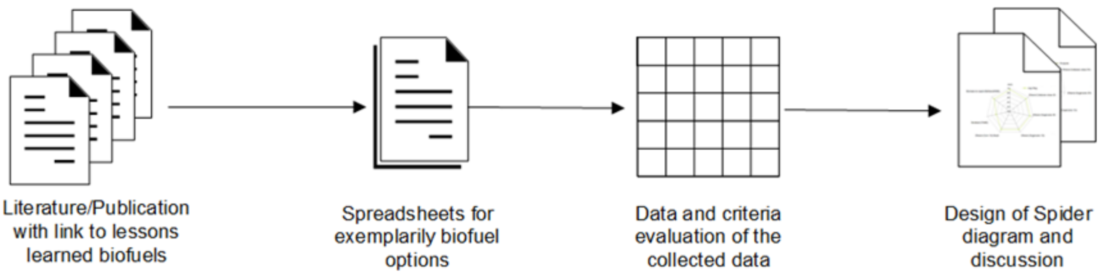

Figure 2 Illustration of the general approach in WP 2

Data of each biofuel were collected and summarized in a table using Table 1 as the model. For each topic evaluated for a given biofuel, numerical values or qualitative grades (e.g. "low", "medium" or "high") were attributed. For others, a "Yes" or "No" criterion was used. The items were grouped in diverse categories (e.g., SDG, feedstock) and normalized between 0 and 1 to drawn spider diagrams for each biofuel to make a visual representation of the data (Table 1 and Appendix of this Report).

Based on the data obtained from analysis of the literature, spider diagrams were elaborated for each biofuel. The diagrams aim at illustrating the grading instead of comparing the biofuels quantitatively, therefore supporting the discussion of the state-of-art of the technologies.

For the spider diagrams in Figure 3 – Figure 9, every criterion was scored and evaluated, so that after the normalization, the maximum score is fixed in 1 and the minimum in 0. The graphics were divided into feedstocks, by-products, public policies, implementation/replication potential, environmental aspects, and SDGs contributions.

For the representation of feedstock criteria, the variety and options of feedstock were key aspects considered. The biofuels that can be made from diverse feedstock, such as gasification-based biofuels, cellulosic ethanol, and HVO, had therefore higher grading in the representation, as they can be available worldwide.

For the criteria “Public policies” and “Implementation-Replication”, all biofuels had almost similar evaluation. The explanation for the success stories was that all of them needed initial policy support and could be broadly replicated. For biofuels based on crops, replication is more viable in countries with available land for sustainable cultivation. The contribution to the SDGs was also similar for the analyzed biofuels.

Results and discussion

This study focused mainly on biofuels with high TRL, especially ethanol and biodiesel, which are already widely used in many countries and therefore are mature in the market. Moreover, these biofuels represent current benchmarks as they can be considered success stories and can set the standards by which other potential biofuels can be measured.

We recognize that future biofuel options are not simply a reproduction of past successes. New standards, regulations, requirements, and legislations may strongly affect the characteristics of the biofuels that societies demand. In addition, success stories are usually highly country or region-dependent as the availability of land and feedstock affects the types of bioenergy that are feasible and cost-competitive. Furthermore, incentives, especially innovation, are critical determinants of what biofuels will be successful in the future. Therefore, examples of 2G ethanol, BtL/DME (dimethyl ether), and Bio-SNG were included.

A second phase of this study should investigate other biofuels such as Sustainable Aviation Fuel (SAF) and maritime biofuels. Perhaps, these are the most likely options to replace the fossil fuels for air and maritime transport along with synthetic fuels and hydrogen carriers.

Reliable cost and sustainability indicators data on 2G biofuels are challenging to obtain because the developments of these biofuels are still ongoing. Pioneer facilities usually do not release sensitive information to protect industrial secrets. However, there are diverse initiatives that suggests that significant bottlenecks are being overcome after years of slow progress. For instance, large-scale 2G plants are finally being implemented. Other technologies such as Biomass-to-Liquid, Power-to-Liquids, and biorefineries utilizing waste resources are being built.

In general, all biofuels studied performed well in meeting SDG goals, with an average score of 0.7 (range 0 to 1), indicating that biofuels can contribute with society's sustainable development (Figure 3). All biofuels require or benefit from public policies and incentives, both as tax incentives and blending mandates for use. The scores were 0.8 or above (Figure 4). Producing by-products, in addition to biofuels was an important component becaue it contributes to biomass valorization. High grades were given to most of the biofuels studied, except to Bio-SNG (Figure 5). The potential of replicating and scaling-up biofuels production was rated high for all of them. Maximum grades (1) were attributed to all ethanol biofuels (1G and 2G), regardless of feedstock, and to HVO and FAME biodiesel. This is the result of mature technologies and the availability of feedstock in many parts of the world. However, restrictions may apply regionally because of issues of raw materials associated with food production. Scale-up and replication were rated 0.8 for Bio-SNG and BtL DME or methanol because of high costs and still developing technologies (Figure 6).

The environmental impact of biofuels is an important item of grading. In general, most biofuels performed well, with scores between 0.8 to 1 because of the high potential to decrease GHG emission compared to fossil fuels. HVO and biodiesel (FAME) were graded 0.7 because of the dependence on oil crop feedstock, whereas corn ethanol produced in the USA was graded 0.4 because of the GHG reductions relatively smaller than those of the other biofuels evaluated in this study. The GHG balances for biofuels in this report do not factor in direct or indirect land use changes, nor possible effects from displacement of organic residues and wastes. The availability of feedstock is determinant for the success of biofuel production. In this sense, all biofuels performed well, although feedstocks may be available in some regions but not in others (Figure 8). But, feedstocks, as well as the type of biofuel produced, are highly region-dependent, which, in a sense, is a favourable trait.

Figure 9 brings the ratings of biofuel's commercial availability. This is probably the ultimate measure of success stories up to now. High volumes of ethanol from sugar cane and corn are produced and used in several countries, proving real contributions to biofuel targets in different regions of the world. HVO and biodiesel (FAME) are also produced and used in sizeable volumes in many countries. On the other hand, 2G cellulosic ethanol is becoming a success story in Brazil and in Europe as discussed later. One success story will likely stimulate others, and it is hoped that in the near future other 2G ethanol plants will become viable. However, this depends both on feasible and cost-effective technologies as well as on feedstock available in large volumes and at low prices. Bio-SNG and Biomass-to-Liquid biofuels have stories that are partially successful but seem to have cost limitations that hold them in TRL 7. As these biofuels had favourable indicators in the grading system, they can move up to higher TRL given the right incentives and technological improvements.

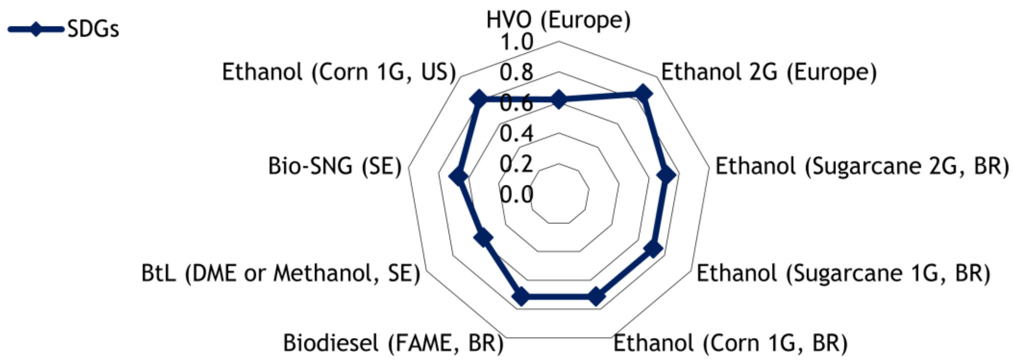

Figure 3 Spider diagram comparing SDG indicators

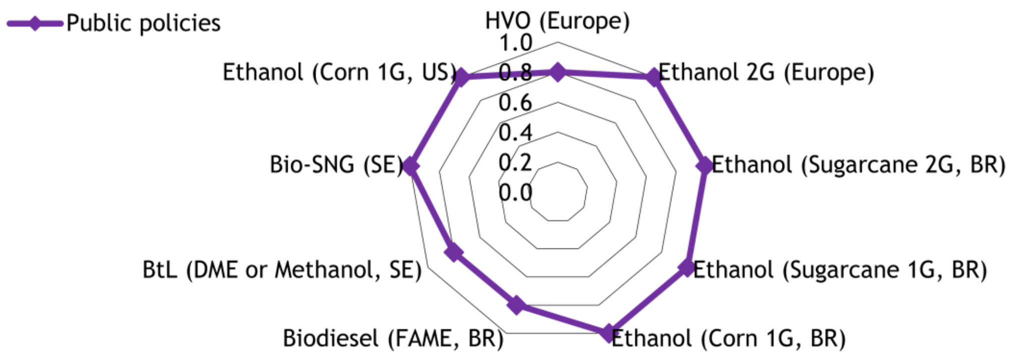

Figure 4 Spider diagram comparing public policies

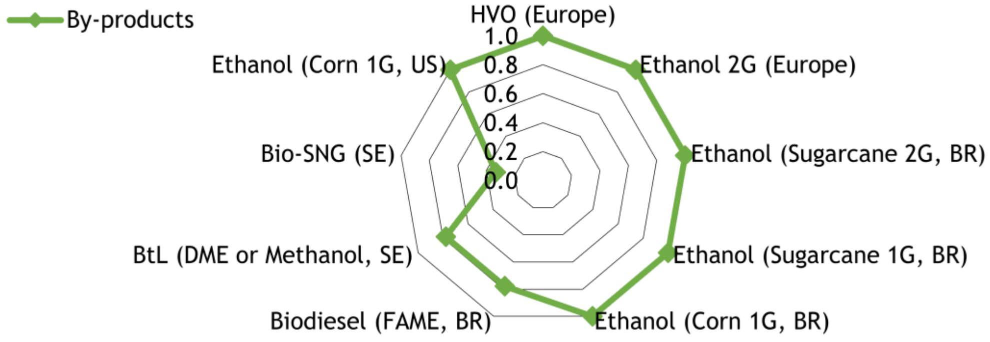

Figure 5 Spider diagram comparing biofuel by-products

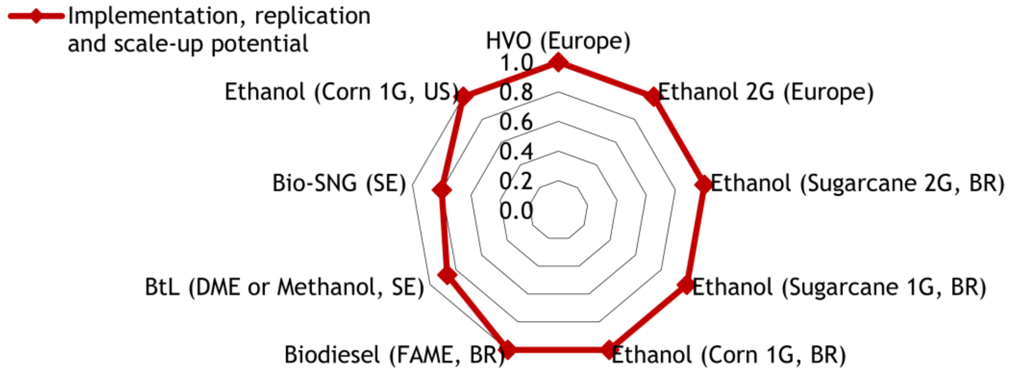

Figure 6 Spider diagram comparing implementation and replication of biofuel products

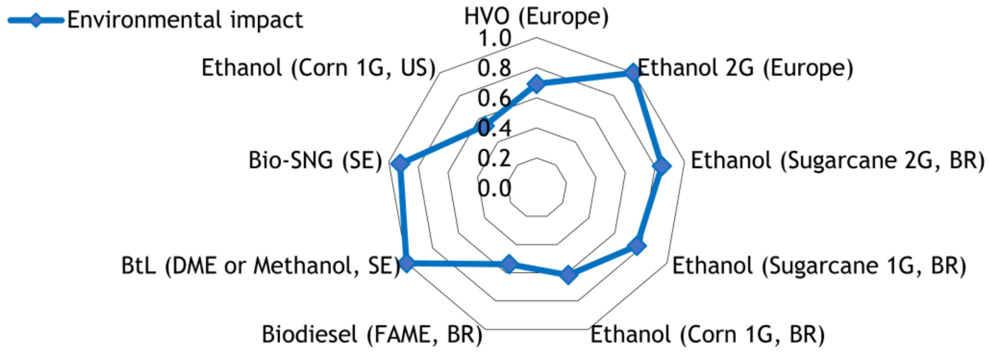

Figure 7 Spider diagram comparing environmental impact[1]

[1] An example of GHG mitigation development on average for biofuels in Germany is provided in Appendix 2

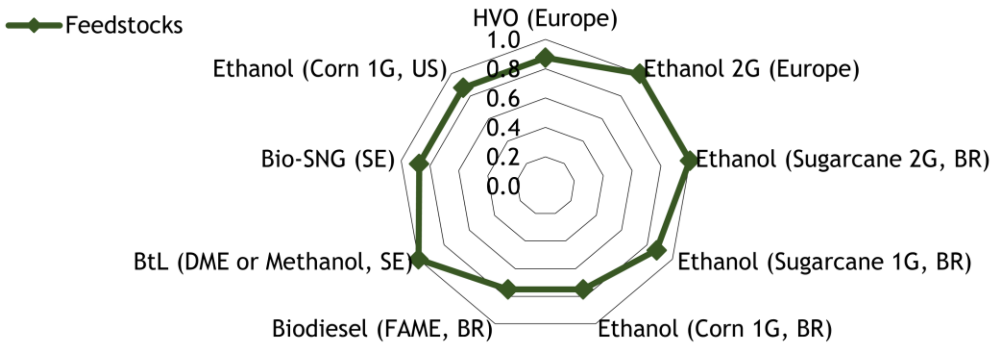

Figure 8 Spider diagram comparing feedstock.

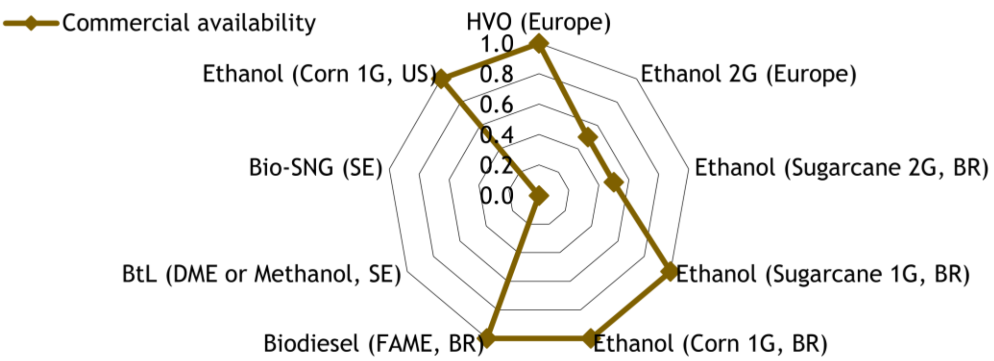

Figure 9 Spider diagram comparing commercial availability of the biofuels evaluated

Table 3 summarizes the indicators for the selected biofuels (cf. Table 2). Ethanol from sugar cane, corn, or crop residues rate high in feedstock availability and yields, justifying the large volumes of biofuel produced. Most of the biofuels showed marked reductions of GHG emissions compared to those of fossil fuels (gasoline or diesel), which is the main justification for their production and use. This applies also to biofuels with TRL 7, indicating that there is room for continuous investment on their development. Cost (production cost or selling price) is not an easy item to evaluate because of subsidies and mandates that vary from country to country. Nevertheless, given the large volumes of ethanol and biodiesel in the market, these biofuels are relatively cost-competitive with their fossil counterparts.

Table 3 Summary of indicators for selected biofuels. Sources: (Art Fuels Forum Project and IEA Bioenergy, 2020; EIA, 2023; Lee et al., 2021; Lewandrowski et al., 2020; Rocha et al., 2014; Scully et al., 2021; Sunde et al., 2011); [a] Prices are variable by region. Ethanol: 0.0211 GJ/L; Biodiesel: 0.0321 GJ/L, [b] Reference GHG emissions of gasoline (90 g CO_2e/MJ) and diesel (88 g CO_2e/MJ).

Biofuel / Country	TRL	Feedstock	Feedstock Yield	Planted area	Biofuel Output	Biofuel Yield	GHG emission[a]	Price/-Cost[b]	Blending mandate
			t/ha	Mha	m^3/y	m^3/ha	g CO_{2e}/MJ		
Ethanol (Sugar cane 1G, BR)	9	Sugar cane	80	10 M	33 M	6.8	23	0.88 US$/L (42 US$/GJ)	Yes
Ethanol (Sugar cane 2G BR)	8	Sugar cane	16+10	10 M	0.12 M	0.231 m^3/t (6.0 m^3/ha)	12	1.33 US$/L (83 US$/GJ)	Yes
Ethanol (Corn 1G BR)	9	Corn	5.5	19 M	3.0 M	2.3 m^3/ha	23	0.88 US$/L (42 US$/GJ)	Yes
Ethanol (Corn 1 G US)	9	Corn	10.5	33 M	55 M	4.4	52	0.90 US$/L	Yes
Ethanol (Cellulosic 2G, Europe)	7	Straw (wheat)			55 M t (potential)	0.2 m^3/t	14	n.a.	Yes
Biodiesel (FAME, BR)	9	Soybean	3.5 (grain) 0.59 m^3 oil/ ha	38.3	6 M	0.68 m^3/t oil	16	1 US$/L 31 US$/GJ	Yes
HVO (Europe)	9	UCO, vegetable oils	-	-	0.5 Mt	0.77 t/t feedstock	12 to 48	0.72–1.09 US$/L	Yes
BtL (DME, SE)	7	Black liquor	-	-	-	0.25 MWh/t black liquor	10	0.76–1.24 US$/L	Yes
Bio-SNG (SE)	7	Multiple	-	-	20 MW	0.57 MW CH_4/MJ dry feedstock	19	24–39 US$/GJ	Yes

CONVENTIONAL BIOFUELS

Ethanol is the main biofuel in the global market, although the production is concentrated (~80%) in only two countries: USA and Brazil. Most of the ethanol currently consumed is derived from corn (USA) and sugar cane (Brazil), from well-established industries (TRL = 9). The USA supplies 55 million m^3/y ethanol, whereas Brazil produces 33 million m^3/y of sugar cane ethanol and 3 million m^3/y of corn ethanol.

Sugar cane ethanol from Brazil has high yields (6.8 m^3 per ha, on average) but this amount can be considered a lower limit because of the high quantities of plant residues generated, such as bagasse (approximately 10-12 tons per ha, dry matter) and harvest residues (10-12 tons per ha dry matter dry of leaves and plant tops). Bagasse is used to generate electricity, which makes the sugar and ethanol mills self-sufficient in energy and in many cases still exporting electricity to the grid (Leal and Hernandes, 2020). Although harvest residues are important to reduce erosion, retain water, and recycle nutrients to the fields (Carvalho et al., 2017; Castioni et al., 2019; Cherubin et al., 2021; Cherubin et al., 2019; Menandro et al., 2017), it is possible to preserve most of the straw benefits to soil and still remove and use the fraction that exceeds approximately 7 tons per ha for energy production (Carvalho et al., 2017), as heat, electricity, and also 2G ethanol. Figure 10 shows the evolution of the sugar cane and the ethanol yields in Brazil.

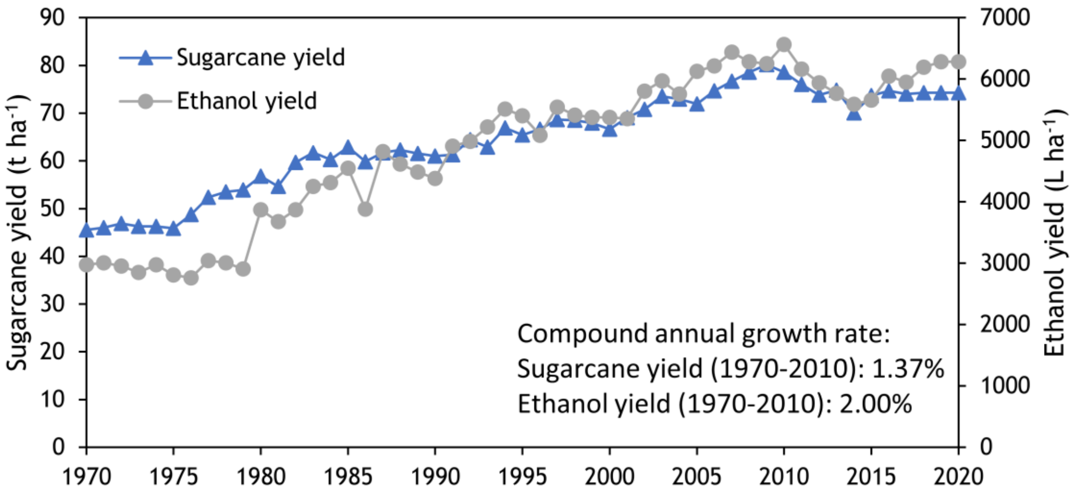

Figure 10 Evolution of sugar cane and ethanol yields in Brazil from 1970 to 2020. Source (EPE, 2021; MAPA, 2021). Data about the rate of sugar cane and ethanol yield increases refer only to 1970 to 2010.

Figure 10 illustrates how continuous investment on the long term is important for yield improvement. Yields are important for economic returns because the relative weight of land, labour, and machinery costs tend to decrease as yields increase. This figure shows the learning curves of sugar cane and ethanol yields in Brazil, which increased steadily for 40 years at compound annual growth rate of 1.37% for sugar cane and 2.00% for ethanol. The reduction in investments in sugar cane production caused by low ethanol prices around 2012, due to the Brazilian government policies that lowered the prices of fossil fuel to control inflation, led to a decline in yields. That was aggravated by the adoption of mechanical harvest that may damage plants in sugar cane ratoons. Only after the 2020's yields started to increase again as adjustments in agricultural practices were made.

Ethanol comprises approximately 40% of the fuel used in light vehicles in Brazil. Ethanol is blended into gasoline (27%) or sold as hydrated ethanol in all gas stations throughout the country. Most of the Brazilian fleet is composed of flex-fuel cars that can run on any mixtures of ethanol and gasoline.

In the USA, ethanol makes up more than 10% of the gasoline market (Lee et al., 2021). The USA is the largest producer of corn globally. The corn ethanol program was created as American farmers were looking for markets for excess grain production and became the world's largest biofuel program. Corn ethanol in the USA showed a sharp increase both in production and number of distilleries in the past 20 years. In 2000 there were 56 biorefineries in operation in the USA; this number increased to 208 in 2020. At the same time, the ethanol capacity increased from 7.63 $Mm^3\ a^{-1}$ in 2000 to 66.13 $Mm^3\ a^{-1}$ in 2020 (RFA, 2021). The American first-generation corn ethanol program is an example of how continuous investments allowed ethanol yields to go up, costs and GHG emissions to go down, as shown in the 2005-2019 retrospective analyses of Lee *et al.* (2021) and the GHG assessment of Lewandrowski *et al.* (2020). The American ethanol industry generates 62,180 direct jobs, 242,600 indirect jobs, and a household income of US18.6 billion per year (RFA - Renewables Fuel Association, 2021).

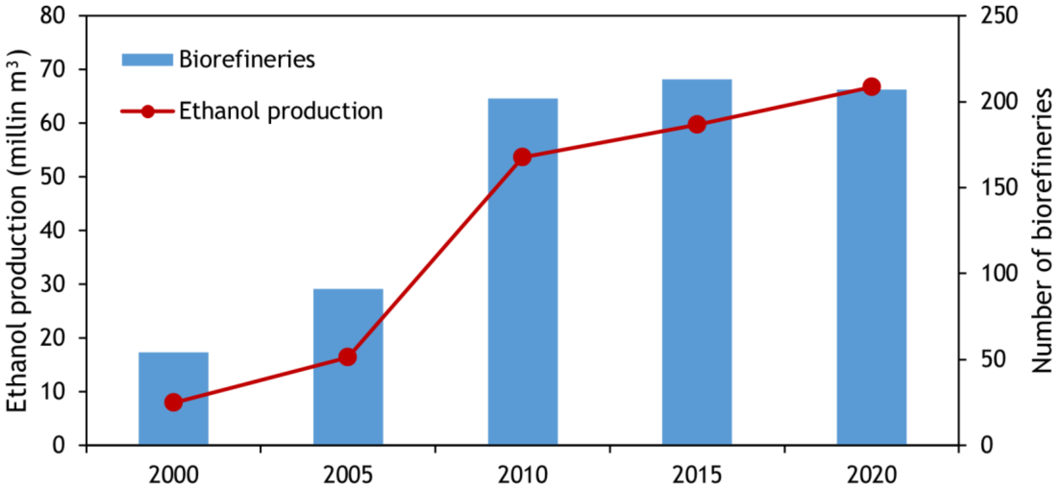

Figure 11 Evolution of corn ethanol capacity and number of biorefineries in the USA from 2000-2020. (Source: RFA - Renewables Fuel Association, 2021)

The average ethanol yield in the USA is 4.4 m^3 per ha, thanks to the high yields of corn grain in the USA (10.5 tonne ha^{-1}) and the high conversion rate of corn into ethanol (~0.4 L ethanol kg^{-1} corn) (Table 4). Important by-products such as corn oil (18 L $tonne^{-1}$ corn), distilled grains with solubles at a rate of 300 kg dry DDGS t^{-1} of corn (distillers grain with solubles, DGS or DDGS, with 32% protein, a feed for animals), and food grade CO_2 from fermentation, collected in most ethanol plants. DGS and the captured CO_2 also reduce GHG emissions associated with corn ethanol (Lee et al., 2021; Lewandrowski et al., 2020; Scully et al., 2021). Approximately 30% of the ethanol plants in the USA capture CO_2 from fermentation — 0.45 kg CO_2 L^{-1} ethanol (Scully et al., 2021).

At the same time that ethanol production increased in the USA, its carbon intensity has steadily decreased from about 87.5 to 62.1 g CO_{2e} MJ^{-1} in 10 years (RFA - Renewables Fuel Association, 2021), which represents a 46% reduction compared to GHG emissions from gasoline (Scully et al., 2021). This is a result or a learning process; improvements came from farm operations as well as gains at the distilleries. Part of the GHG emissions is allocated to valuable co-products such as DGS. According to Xu et al. (2022), the deep decarbonization of corn ethanol is possible by replacing 50% of the natural gas in the ethanol plants with syngas from biomass or biomethane from agricultural residues. This would allow a further reduction of GHG of 12–24 g CO_{2e} MJ^{-1} ethanol. Adding carbon capture and storage (CCS) technologies to the existing corn ethanol plants may cause them to become net-zero emitters.

Brazil started to produce corn ethanol in 2017 (Barbieri, 2017). Currently, there are 18 operating ethanol plants, 16 in Central Brazil, where most of the corn is produced in the country. The current ethanol output is 3.36 million m^3 y^{-1} in standalone plants or plants integrated with sugar cane ethanol mills (flex plants). Corn ethanol represents 8.5% of the Brazilian ethanol production. Because of the high transportation cost to the sea ports, the price of corn in Central Brazil is relatively low. This, in addition to the high demand for ethanol, stimulated the transformation of grain into ethanol. Although not all industrial facilities can be shared, integrating corn and sugar cane ethanol plants takes advantage of synergies such as the period in which the sugar cane plants are not operating after the end of the sugar cane harvest season. Sugar cane cannot be stored; therefore, from November to April, when sugar cane is not being harvested in the South-Central region, the industrial plants remain idle.

The average corn yields in Brazil (5.5 tonne ha^{-1}) are half of those in the USA; therefore, the potential ethanol yield is much smaller (2.3 m^3 ha^{-1}). The low corn yields in Brazil are partially explained because most of the grain is produced in the second season, usually after soybean harvest in the same year. Second-season corn tends to have lower yields because of the relatively marginal weather conditions (low rain). However, the inputs of fertilizers, including N, are much lower than in the USA because of soybean rotation, helping to decrease the C footprint of corn ethanol. Nitrogen fertilizers have a great impact on the GHG balances of biofuels (Carvalho et al., 2021; Crutzen et al., 2008).

The GHG emissions associated with ethanol production and use, and vary from 23 g CO_{2e} MJ^{-1} for sugar cane and corn ethanol in Brazil to 52 g CO_{2e} MJ^{-1} for corn ethanol in the USA (Table 4), much lower than that of gasoline (~100 g CO_{2e} MJ^{-1} in the USA or 87.4 g CO_{2e} MJ^{-1} in Brazil (Carvalho et al., 2021; Lee et al., 2021). The lower carbon footprint of the corn ethanol produced in Brazil is explained by the lower use of fertilizers, but mostly because Brazilian corn ethanol plants use renewable energy (*i.e.*, forestry residues or sugar cane bagasse) (Moreira et al., 2020) instead of natural gas or other fossil-based energy sources such as in the USA. Therefore, the corn ethanol industry in Brazil already demonstrates the benefits of the routes Xu et al. (2022) proposed to reduce the carbon footprint of USA corn ethanol.

Furthermore, ethanol of low GHG emissions can be used in other processes, such as in the process to produce Sustainable Aviation Fuel (SAF) with the Alcohol-to-Jet (AtJ) process. The integration of this process into conventional sugar cane biorefineries presents significant synergies (Klein 2018).

According to the Brazilian Ministry of Mines and Energy Research Office (EPE, 2021), in 2020, the avoided GHG emissions, relative to gasoline and diesel, due to the use of biofuels in Brazil were 22 Tg CO_{2e} for hydrated ethanol; the corresponding figures for anhydrous ethanol, biodiesel, and bioelectricity were 24.8, 18.1, and 2.4 Tg CO_{2e}.

In addition to having a proper biofuel industry in place, appropriate policies can stimulate more sustainable production of biofuels. For example, in 2020, the Brazilian Government started to implement the RenovaBio program, which is part of the Brazilian efforts to reduce the GHG emissions, as a component of the commitment with the 2015 Paris Agreement (Nastari, 2020). RenovaBio issues decarbonization certificates — called CBIOs — to biofuel producers that prove to reduce GHG emission with their bioenergy fuels compared to the fossil fuel they replace. There are national targets for issuing CBIOs up to 2030. CBIOs are traded in the stock exchange. The amounts of avoided GHG stimulated by CBIOs will reach 91 Tg (million tonne) CO_{2e} in 2030, summing up approximately 620 Tg CO_{2e} in 10 years (Figure 12)[2]. Since the flex vehicle technology was launched in Brazil in 2003, the use of ethanol instead of gasoline has prevented the emission of 515 Tg of CO_{2e} (Unica, 2021).

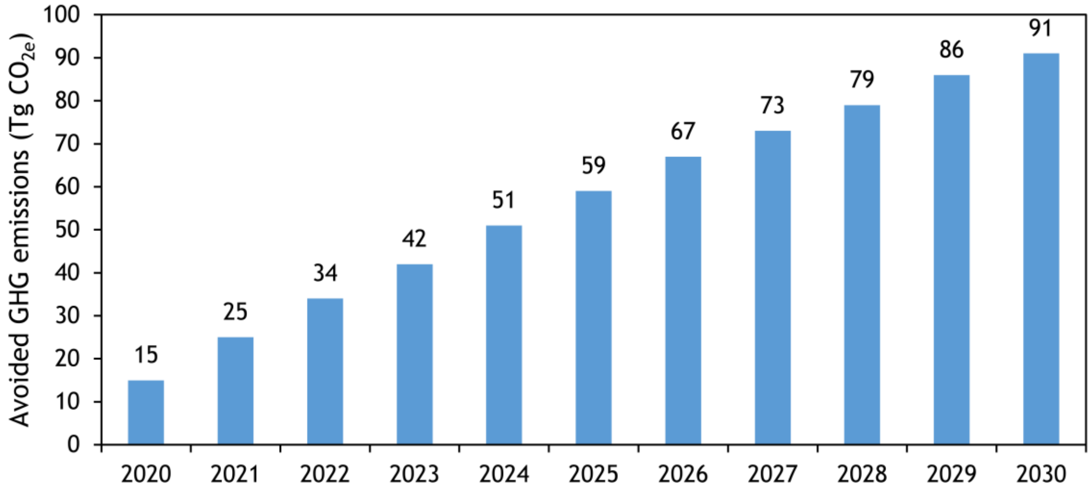

Figure 12 *Estimated avoided GHG emission to be achieved by the RenovaBio policy in Brazil. Decarbonization certificates (CBIO), equivalent to 1 tons avoided CO_{2e}, foreseen to be put in the market to reward bioenergy producers (ethanol, biodiesel, biomethane) with proven GHG reduction compared to fossil fuel (Brazil - Ministry of Mines and Energy - EPE (Energy Research Interprise), 2021).*

Because of the RenovaBio legislation the bioenergy companies are tracking all steps in the production process where significant amounts of GHG are emitted and adjusting procedures to reduce emissions. For instance, nitrogen fertilizers may account up to 50% of the GHG emitted to produce ethanol (Carvalho et al., 2021). Decreasing N fertilizer rates in the field or increasing N use efficiency may generate extra CBIOs; thus, farmers are optimizing field management in that direction. The same applies to the use diesel oil in farm machineries and trucks. Optimization of logistics and field operations may allow substantial reductions in diesel use.

Biomethane from sugar cane residues is another option to improve the carbon footprint of the sugar cane ethanol industry. Esteves (2020) estimated that the potential for 2030 of the sugar-ethanol sectors in Brazil to produce biomethane using vinasse, filter cake and straw is 7.4 to 11.4 billion m^3(STP) per year of biogas, equivalent to 4.1 to 6.3 billion m^3(STP) per

[2] The law that establishes the CBIO targets became a matter of dispute as the price of CBIOS increased in the marked and fuel retailers complained of high costs. However the general acceptance of this scheme of GHG reduction is high in the Brazilian society.

year. Many ethanol plants are within a 20 km distance from one of the natural gas pipelines that link producers and consumers. The residues of the biodigesters are recycled as fertilizer in the fields. Biomethane in this case is an additional biofuel with no need for more crops or farming land. It helps to decrease the overall C footprint of the original biofuel plant.

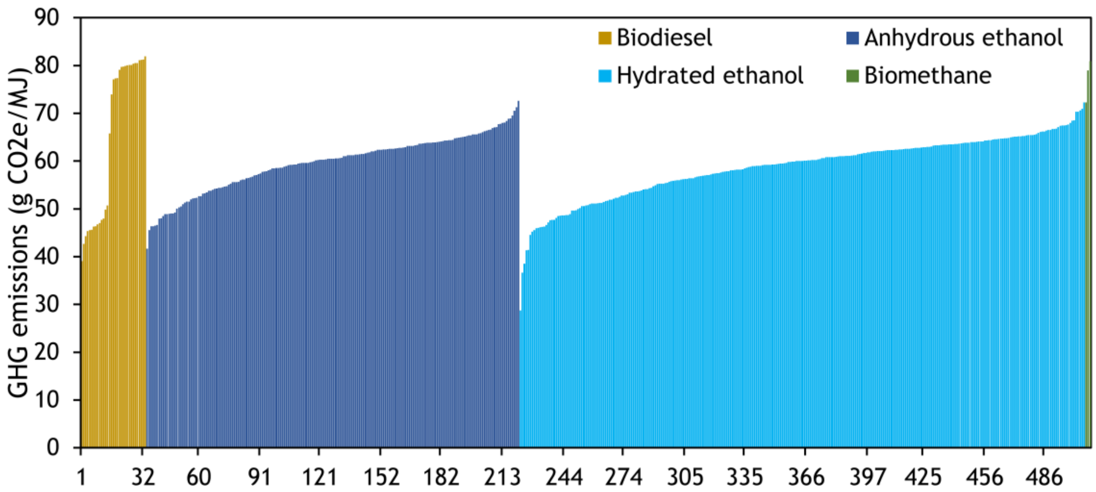

Figure 13 Certificates given to facilities in Brazil for production of biodiesel, anhydrous ethanol, hydrated ethanol and biomethane, grouped into biofuel produced and ordered according its GHG emissions in gCO_2/MJ (Data from March 30th 2023, based on ANP 2023)

Biomethane facilities can be replicated in biofuels other first-generation sugar cane ethanol. Biomethane production from organic residues is a win-win situation that further stimulates cleaner biofuels that benefit producers and the society (Carvalho et al., 2021; Gonçalves et al., 2021). Cocal, a sugar and ethanol producer in Southwest Brazil, invested R$150 million (approximately US25 million) in a biomethane facility using residues (vinasse and filter cake). The biogas will be sold to third parties including for feeding in the gas grid; in addition, part of the biogas is to produce electricity (5 MW) and a small part will replace diesel in trucks and farm machinery. Food grade CO_2 is also a by product of sirup fermentation to produce ethanol. All this adds to the economic and environmental sustainability of the sugar and ethanol business. The business model successfully adopted in the Cocal unit will we be replicated in other mills of the same company (Ramalho, 2022). Raizen, the largest ethanol producer in Brazil, has one biomethane plant in operation in Guariba and others are being planned. Part of the biomethane from Raizen plants is under contract with Yara, a fertilizer company, for the production of green ammonia in one of its nitrogen fertilizer plants in Brazil (Ramos, 2021).

SECOND-GENERATION ETHANOL

As regulations in several countries restrict the use of food crops for biofuel production, second-generation (2G) biofuels made of lignocellulosic materials became important options because crop residues and other inexpensive plant materials do not compete with food. High expectations were placed on 2G biofuels, and by this time, large amounts of 2G ethanol were expected to be already delivered to the market. However, technological hurdles and cost issues are slowing the maturation of the 2G biofuels industry. Recent developments suggest that the barriers of producing 2G ethanol are being overcome (FutureBridge, 2019). For example, Raizen, in Brazil is operating the first plant at commercial scale in the world, using proprietary technology developed over the past 15 year (Bonomi et al., 2019; Chandel et al., 2021). Clariant is starting to operate a wheat straw-based facility in Romania (Clariant, 2021) and ENI has announced that its 2G ethanol plant in Crescentino, Italy, started to operate in 2022 (ENI, 2022).

The benchmark of conventional ethanol will help to guide the necessary improvements of the developing 2G ethanol industry. In addition, 2G ethanol will benefit from the large biofuel market opened throughout the world over the past 20 years. 2G biofuels can use the existing infrastructure, fuel existing vehicles and be the best option for attaining environmental and social goals in some regions.

Current 2G ethanol production in Brazil, approximately 120,000 m^3/y, is a small fraction of the total ethanol production. Cost is still an issue, but Raizen is seeking markets that pays a premium price for biofuel with a small carbon footprint (12 g CO_{2e} MJ^{-1}), made from biomass residues. Raizen officials state that currently they sell their 2G ethanol at a 70% premium compared to conventional ethanol. In addition to the Costa Pinto Unit, Raizen is already building a second plant in Guariba and announced the construction of two other plants that are expected to be commissioned in 2024. Investment of 2 billion Brazilian Reais (~US$ 400 million) has been approved by the company board and communicated to the market as the company's stocks are traded in the São Paulo B3 Stock Exchange (Raizen, 2022). Each of these three new plants will have a capacity of 82,000 m^3 yr^{-1}, bringing the total 2G ethanol capacity to 280,000 m^3 per year and turning Raizen into the world's only producer of 2G ethanol to have four cellulosic plants in operation (Raizen, 2022).

Another successful example of the development of cellulosic ethanol is the Sunliquid technology developed in Germany by Clariant for the processing of wheat straw (and possibly other feedstocks). Clariant has finished the building of an industrial facility with a capacity of 50,000 tons per year in Podari, Romania (Clariant, 2021). The company reports a reduction of GHG emissions of about 95% (or 5 g CO_{2e} MJ^{-1}). The facility will utilize the wheat straw produced in the surroundings and will not utilize extra cultivation area. It will benefit local farmers by valorizing straw and creating approximately 100 jobs (Clariant, 2021). Furthermore, the development of the technology was supported by financial grants from the European Union and the trading of the production will be supported by the blending mandates in European countries. The Renewable Energy Directive (RED II) may facilitate the access to the market.

The Podari plant went through a thorough commissioning process in the first semester of 2022 resulting in the successful start of production. The plant is energy self-sufficient as it uses lignin residues as the energy source (Clariant, 2022). ENI also started to operate in 2022 a 2G ethanol plant in Crescentino, Italy, using crop residues and its proprietary Proesa ® technology. The plant can process up to 200,000 tonne of biomass per year with a production capacity of 25,000 tonne of ethanol per year (ENI, 2022). The energy to run the plant comes from lignin and other residues.

GLOBAL ETHANOL MARKET

There are more than 100 countries in the tropical and subtropical regions of the world that cultivated sugar cane (Cantarella et al., 2012) and can produce ethanol. However, presently, significant ethanol production is concentrated in a few countries. USA and Brazil accounts for 84% of the global ethanol outputs (Figure 14).

Ethanol became the leading biofuel for transportation in the world thanks to the successful stories of the USA and Brazil to produce large volumes of ethanol and the well-documented benefits of ethanol not only as an oxygenate for gasoline but mostly because of its potential do reduce GHG emissions from the transport sector. Currently, more than 60 countries in the world have mandates to blend ethanol into the fossil fuel or use it in cars; at least 17 countries have mandates for advanced biofuels (REN21 Secretariat, 2021).

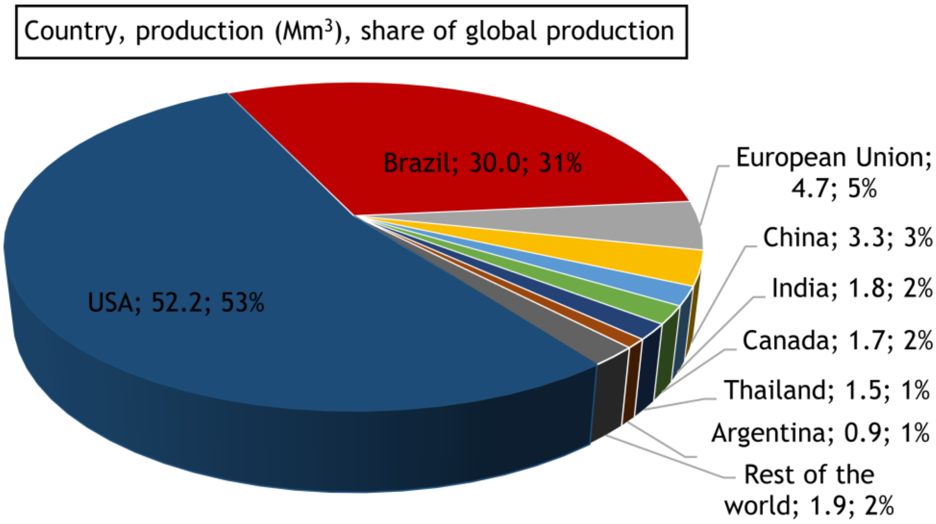

Figure 14 Global ethanol production per country in 2020. Numbers indicate production (million m^3 in 2020) and share of global production. Source: RFA (2021)

According to a survey conducted by The Biofuels Digest (2021), there are 65 countries around the world with biofuel blending mandates or targets for biofuels: 24 in the European Union-27, 4 in non-EU Europe, 14 in the Americas, 12 in Asia-Pacific, and 11 in Africa and the Indian Ocean. The survey was released in January 2021, but it builds on previous surveys; therefore, not all data may be up to date (cf. Table 13 in

Appendix 2). Furthermore, in Europe, individual countries also have specific obligations, either energetically or by volume, for utilization of biofuels. Also, in 2021, some countries have established commitments with advanced biofuel targets.

Competition for land has driven the search for crops, both sugar, starch, and oil crops, that can grow in marginal lands, usually of low fertility and with limited rainfall and high salinity conditions. It is a big challenge to produce the high amounts of biomass in unfavourable climate and land, and above all, at the low costs that biofuels require (Schmer et al., 2014). For biofuels produced with these alternative feedstocks, the benchmark of more conventional biofuels is useful because their environmental, economic, and social indicators allow to estimate the size of the gap and the technological advances that are necessary.

More recently, especially after the 2000's, global warming became a major society concern, and it became clear that biofuels represent an option to decrease the emissions of GHG. Biofuel's production and use started to grow in many countries. Initially, attention was given to biofuels with the best-known and proven technologies, such as ethanol, biodiesel, and biomethane. However, the debate around biofuels became more complex and demanding because of the need to ascertain that the biofuel significantly contributes to reducing GHG emissions, in addition to issues such as land-use emissions associated with biofuel production, feedstock diversity, and social matters, such as the food versus fuel dilemma. Investigation around new biofuels or new biofuel production routes were stimulated by the need for biofuels with sound sustainability indicators, made with biomass residues, feedstocks that do not compete with food, or plants able to grow in lands not used for food production. Such biofuels or new routes not always benefit from the learning curves of the more traditional biofuels and usually require increased research efforts, innovation, stimulus, and public policies to ensure that they can cross the death valley of novel products. One important step for their graduation toward viability and acceptance is their comparison with benchmark biofuels. The lessons learned with some traditional biofuels indicate gaps that may help new biofuels to be successful (Chen et al., 2012).

BIODIESEL (FAME) AND HVO

The main biodiesel producing countries are the USA and Indonesia, followed by Brazil. Soybeans are the main feedstock for production of biodiesel in the United States, Brazil, and Argentina. The biodiesel blend into diesel in Brazil started with 2% in 2008, increased to 5% in 2010, and gradually increased to 12% (B12) in 2020 (Figure 15). Soybeans account for 71% of the feedstock for Brazilian biodiesel, followed by cattle tallow (9%); UCO comprises 1.2%. Because of the large production of soybean in Brazil, only 16% of the cultivated soybean is used to produce biodiesel as most of the soybean is exported as grain (Brazil - Ministry of Mines and Energy - EPE (Energy Research Interprise), 2021). Biodiesel accounts for only approximately 11% of the diesel consumption in Brazil (70% of the fossil diesel is locally produced and 19% is imported). Blending mandates have stimulated the expansion of biodiesel production in Brazil. The biodiesel capacity (10.4 billion liters), distributed among 49 biodiesel plants is much higher than the present consumption (6.4 billion liters) (Figure 16). Therefore, there is plenty of room to increase production and use in Brazil. However, in 2021, following the Covid and the increase in international oil prices, the Brazilian government temporarily reduced the biodiesel mandate to control diesel prices at the pump because of the high prices of soybean. For the same reasons, changes or postponement of mandates were also observed in other countries.

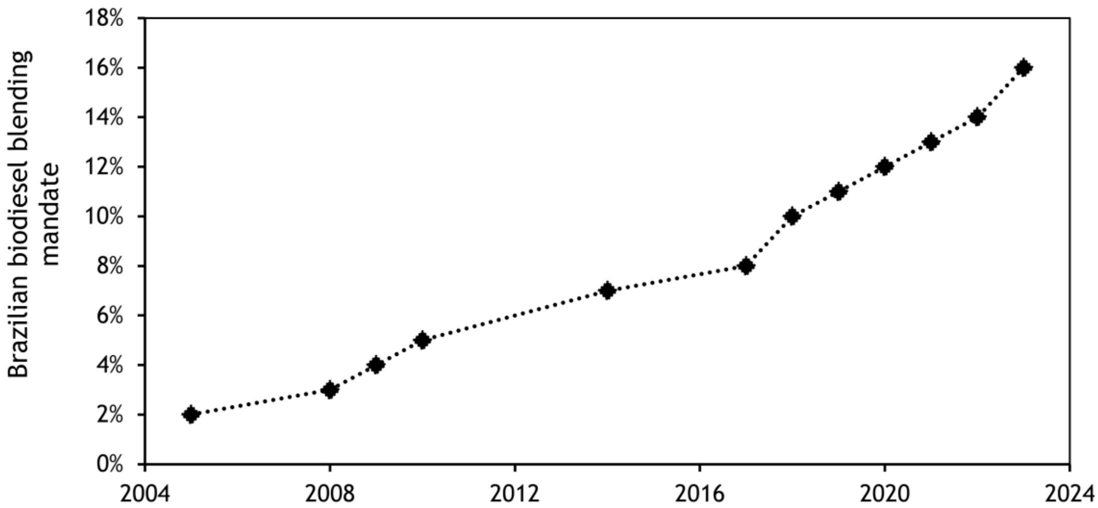

Figure 15 Biodiesel blending in Brazil. (EPE 2021)

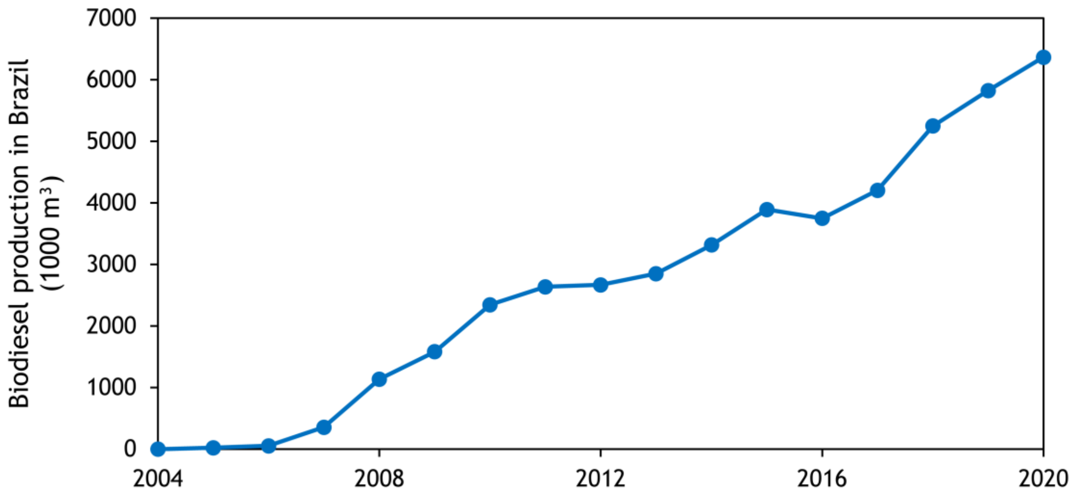

Figure 16 Biodiesel production in Brazil. (EPE 2021)

Argentina is also a major producer of biodiesel in Latin America, with an output of around 2.5 billion liters of biodiesel from soybean oil in 2019. About 48% of the biodiesel was exported to Europe. At least 33 biodiesel plants should be operating in Argentina in 2021, with a total capacity of 4.43 billion liters, stimulated by recent legislation by the Argentinean government (New Biofuels Law 27640 – July 2021, MAGPA, 2021).

A competing biofuel, the Hydrotreated Vegetable Oil (HVO) is an option favoured by the oil companies to produce the so-called green diesel, making use of their facilities to process esters and fatty acids (HEFA) produced via hydroprocessing of oils and fats. HVO may contribute to maintaining high idle capacity of biodiesel plants. HVO production is under discussion in Brazil. The interest in HVO is increasing. The La Mède biorefinery project in France is an example of success in market introduction of HVO. Due to the flexibility of feedstock and possibility of processing resources from other regions, the biorefinery has a production capacity of 500,000 tons per year. HVO plants, during the hydrogenation processing, also produce naphtha and propane as by-products, which can be directed to other markets (Art Fuels Forum Project and IEA Bioenergy, 2020). HVO has the potential to be replicated and implemented worldwide. The biofuel production from tallow oil is another European example. Furthermore, other refineries are being built, such as the Omega Green project in Paraguay, with a capacity of 1,150,000 m^3 yr^{-1} (ECB Group, 2021). Shell has announced the construction of a facility with 820,000 tonne yr^{-1} in Rotterdam to produce renewable diesel and sustainable aviation fuel (SAF) (Shell, 2021).

BIO-SNG

Biobased synthetic natural gas (Bio-SNG) can be produced from wood residues through gasification, although it could also use imported biomass (pellets, for example). The GoBiGas project, operated by Göteborg Energi in Gothenburg, Sweden, has an output capacity of 20 MW (Art Fuels Forum Project and IEA Bioenergy, 2020). The resulting biofuel can be used both in light and heavy-duty vehicles, producing also district heating as by-product. Supported by the Swedish Energy Agency, the project received about 20 million Euro and also tax exception for the sale of Bio-SNG. The biofuel produced reduces GHG emissions by approximately 80% compared to fossil fuel (Art Fuels Forum Project and IEA Bioenergy, 2020). The replicability and implementation could also be done worldwide, as the gasification uses residual biomass. The facility was planned to achieve a full capacity of 100 MW (Thunman, 2018). However, according to a statement, the Board of Directors of Göteborg Energi decided to terminate the project in advance in a bid to reduce the financial impact of the plant which was put up for sale in April 2017 (Bioenergy International, 2018).

BIOMASS-TO-LIQUID (BTL)

Residual crop feedstock can also be processed thermochemically through gasification, which produces synthesis gas (syngas) that is suitable for different BtL routes to produce biomethanol and other biofuels via Fischer-Tropsch synthesis. Residual biomass is a resource that does not directly compete with other land utilizations, but the sourcing of feedstock might be an issue. For example, a thermochemically synthesized biodiesel made with switchgrass and short rotation plantation is estimated to emit -12 and -29 gCO_{2e} MJ^{-1} (Achinas et al., 2019).

Another non-edible biogenic resource for using in gasification is black liquor, which is the liquid separated from cellulose fibers in the Kraft process. In the BioDME project, black liquor from the pulp industry is separated and gasified to produce biomethanol and bio-DME. The project produced about 390 tons of DME between 2011 and 2013 and performed field tests with trucks for over 800.000 km (Salomonsson 2013). As observed in the spider diagrams, there is a lack of further political support to develop the technology, although it could be replicated in several regions, as the Kraft process is the main pulping process worldwide. In 2016, the production of black liquor was estimated in 206 Mtonne (Kuparinen 2019).

In 2013, the demonstration facility of the BioDME project was transferred to the Luleå University of Technology, and the technology is being further developed, for example through the co-gasification of biomasses with high heating value and low reactivity, to balance the low heating value and high reactivity of black liquor. Furthermore, there is also the possibility of coupling electrolysis to the process to increase the overall carbon efficiency (Gebart 2018; Carvalho 2018)

Other concept of BtL process is related to economy of scale from gasification. The bioliq process from Karlsruhe Institute of Technology combines a decentral step within the production of pyrolysis oil from biomass for the intensification of energy content, and a central step with gasification and fuel synthesis (Dahmen 2017). Furthermore, the concept of synergies of biomass- and electricity-based technologies (SynBioPTx) explores the advantages of integration of BtL and Power-to-X processes (Mueller-Langer 2021). With that concept it is expected the increase of carbon efficiency and possibly the decrease of production costs (Dietrich 2017).

The BtL processes is often limited by high costs. Indeed, it is estimated that the capital costs are above 50% the total production costs. Nevertheless, some industrial facilities have construction planned or finalized, such as the Sierra Biofuels Plant from Fulcrum Bioenergy, with capacity of producing about 42 million L y^{-1}, and the facility from Enerkem in Alberta, Canada, with a capacity of about 38 million L y^{-1}. Other facilities are planned with above 100 million L y^{-1} capacity (Mesfun 2021, Enerkem 2021). With the completion and operation of these industrial facilities, the risk of the technology is expected to reduce.

LIMITATIONS FOR THE EXPANSION OF CONVENTIONAL OR ADVANCED BIOFUELS AND CRITICAL ANALYSIS OF OPTIONS

The successful cases of several biofuels indicate that it is possible to supply large amounts of biofuels to help replace fossil fuels and reduce global warming. However, the expansion of biofuels production and the replication of successful country or regional models in other places is not without challenges. The dependency on crop feedstock availability and price fluctuations may limit biofuel production, as shown by changes and postponements of mandates in several countries (Table 13).

The Covid-19 pandemic caused a significant reduction in ethanol production in 2020 because of lower demands and low economic returns (8% reduction), although biodiesel was less affected. In Brazil, Raizen produced 20 million L of 2G ethanol in 2019, overcoming most technological challenges. In 2022 the company announced investments in three new units of ethanol 2G with an 82 million L y^{-1} capacity each, with a long-term customer for commercialization of 91% of its production. 2G ethanol plants in Europe are also being implemented. Although promising, the production volume of 2G biofuels is still much too low to supply the demand for biofuels. At the same time, there was a sharp increase in HVO and HEFA fuel production (REN21 Secretariat, 2021).

It must be understood that most biofuels in the market have crops, often food crops, as their main feedstock. This applies to 1G ethanol, biodiesel, and HVO. However, despite being success stories, according to metrics of some regions in the world, their production or consumption should decrease or be discontinued soon. This poses a dilemma that must be addressed. Biofuels, although not exclusively, are important components of the strategy to decarbonize the transport sector and to mitigate the climate crisis. For instance, in many regions of the world, electric vehicles driven by batteries are not viable in the short term because of their cost. In addition, Diesel and Otto cycle engines will be around for decades to come. The current energy shortage in Europe caused by the Russo-Ukrainian war, which has prompted the emergency increase of fossil fuels such as coal, probably is an indication that some policies restricting biofuel options must be revised or their implementation postponed until realistic options are available.

Biofuels are region-dependent, but the European point of view ends up prevailing in this matter. Pertinent questions include:

- Should we place restrictions on feedstock for biofuels when we still do not have viable biofuels that can use only crop residues?
- Can we sustainably use land to produce food and biofuels feedstock?
- Is land availability a global problem, or is it restricted to some countries or regions?
- Is it meaningful to extrapolate food and land use issues to all countries?

Alternative biofuels to those listed above have technological, cost, or feedstock availability challenges that eventually will be overcome, but this takes time and research efforts. Meanwhile, solutions must be found in a society committed to biofuels considering the currently available and successful technologies.

Conclusions

Conventional biofuels such as ethanol (both sugar cane and corn) and biodiesel are being produced and commercialized in substantial quantities in several countries. Up to this point they are the most relevant to replace fossil fuels worldwide. Yields, costs, and environmental indicators have improved over time. Mandates and proper public policies have been important to support implementation and technological improvements.

The economic crisis over the last years related to the COVID-19 pandemic and the Russo-Ukrainian war affected biofuel blending mandates and use in several countries. The COVID-19 pandemic has had a negative impact in the production and trade of conventional biofuels. The pandemic also delayed the development of the advanced biofuel market and reduced investments around the world. Action shall be taken to recover biofuels production and use.

Most of the biofuels available in the market today are 1G ethanol, biodiesel, and HVO. Their main feedstock are crops, often food crops, which face restrictions to produce biofuels in some parts of the world. This poses a dilemma that must be addressed because the main success stories on biofuel production are facing limitations for global implementation. Nonetheless, lessons learned from these biofuels turned them into relevant benchmarks and set standards for novel biofuels with low TRL.

Published indicators for 2G/advanced ethanol are seldom available but there is evidence that technological bottlenecks are being overcome and several 2G ethanol plants are already in operation. Besides ethanol from different feedstock, BtL, Bio SNG, and HVO show suitable indicators of environmental impact, SDG, and feedstock diversity to be replicated in different regions. Technological and cost limitations must be overcome. This requires research efforts and time to solve the main hurdles. And the clock is ticking.

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Abbreviations

1G	First generation (biofuels)
2G	Second generation (biofuels)
BtL	biomass to liquids. Process that involves gasification and utilize the entire plant to produce biofuel.
CAPEX	Capital Expenditure
DME	Dimethyl ether. Synthetic second-generation biofuel which can be produced from lignocellulosic biomass.
FAME	fatty acid methyl aster: Rout to produce biodiesel from vegetable oils, animal fats or waste cooking oils.
GHG	Greenhouse Gases
HVO	Hydrotreated Vegetable Oil. Biofuel made by the hydrocracking or hydrogenation of vegetable oil.
IEA	International Energy Agency
LCA	Life Cycle Assessment
OPEX	Operational Expense
RED	Renewable Energy Directive
SAF	Sustainable Aviation Fuel
SDG	Sustainable Development Goals
SNG	Biosynthetic Natural Gas
TCP	Technology Collaboration Program
TRL	Technology Readiness Level
WP	Work Package

Appendices

APPENDIX 1 | SPREADSHEETS FOR DATA COLLECTION

Table 4 Sugar cane ethanol 1G

Ethanol (Sugar cane 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	Ethanol (Sugar cane 1G)		
Source:		11		Rocha, M. H., et al. (2014). "Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis." Renewable and Sustainable Energy Reviews 37: 435-459
Location:	Country, region, city where it is considered a success	Brasil	May apply to other countries that produce sugar cane	
TRL	Technology Readiness Level	9	Actual system proven in operational environment	
Biofuel main use		Light vehicle		
Main feedstocks:	Type of feedstock	Sugar cane		
	Please indicate if domestic or imported	Domestic		
	Feedstock availability	High		
	Feedstock yield	High	80 t/ha of sugar cane stalks	
	Planted area	High	10 Mha (approximately half to produce sugar and half to produce ethanol)	
	Soil-climate requirements	Medium	Sugar cane requires at least 1000 mm of rain (or need irrigation). Feedstock production requires proper agronomic practices, such as fertilization, weed control etc.	
Products:	If commercial production include output (m3/y, t/y, other)	33.2 million m^3/y		
	Biofuel yield (per unit feedstock, land, etc.)	6.8 m^3/ha		
	Commercially available: No: 0; Medium scale 1; Large scale 2	2	Ethanol represents almost 40% of the fuel in light vehicles in Brazil. Avalilable in several contries for blending with gasoline in different proportions	
	Co-products - low value	Yes	Vinasse (fertilization, biogas)	
	Co-products - medium value	Yes	Bagasse, harvest residues (heat, electricity)	
	Co-products - high value	Yes	Chemicals (citric acid, others)	

Ethanol (Sugar cane 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
Economics:	Economics considered?	Yes		
	Biofuel production costs (or sales cost)?	Yes	0.53 US$/L (Nov 2020) (24.2 US$/GJ). At the mill gate: 0.33 to 0.39 US$/L (15.05 US$/GJ to 17.8 US$/GJ) (2020 Source: ÚNICA (Sugar cane Industry Association) www.unica.com.br. Accessed on 3rd Dec 2020).	Source: UNICA (Sugar cane Industry Association) www.unica.com.br. Accessed on 3rd Dec 2020. The ethanol density and net heating value were adopted as 0.8 kg/L and 6,525 kcal/kg, respectively.
	CAPEX available?	Yes	$106 for each t of sugar cane processing capacity per year (reference capacity: 4 million t of sugar, 200 operating d/y)	(Bonomi et al., 2016).
	OPEX available?	Yes	Operating expenses available in the literature.	(Bonomi et al., 2016).
Public policies:	Does any mandate supported the introduction?	Yes	At least 27% of ethanol in gasoline in all Brazil. 100% ethanol also available at gas stations	
	Does it require subsidies?	Yes	Consumer tax lower than that of gasoline in most States in Brazil	
	Are relevant laws and regulations?	Yes	Minimum requirement of ethanol in gasoline (see above). Taxes (see above). RenovaBio rewards biofuel producers that prove to reduce GHG emission.	
	Does it have public acceptance?	Yes	Ethanol is available at all gas stations in Brazil. >40% of biofuel used in light vehicles	
Environmental impact:	GHG Emissions (g CO_{2e}/MJ or another unit)	23 g CO_{2e}/MJ	Cradle to wheels LCA. Avoided 70 to 90% GHG emissions compared to gasoline. Recent legislation (RenovaBio, 2017) stimulates reduction of GHG associated with biofuels.	
	Competition with food?	No	Although land could be used to produce other crops and sugar is a food, the amounts of land available in Brazil makes food competition irrelevant	
	Land requirement?	Medium	High yield crop.	
	Air quality impact?	Yes	Negative impact due to pre-harvest burning, but now legally phasing out; Positive: cars using ethanol decreases urban air pollution.	
	Water usage?	Yes	Feedstock production is mostly rainfed (except in Northeast Brazil and partially in Central Brazil). Water is also required for sugar/ethanol production, but amounts are being reduced. Water use in industry is regulated in some parts of Brazil	
	Land impact?	Yes	Large farms; risks of erosion during some stages of feedstock production. Proper agronomic practices are required to control negative impacts. The Brazilian Forest Code establishes that at least 20% of the land in private properties must be set aside as legal reservation (native species) promoting biodiversity, land, and water preservation. Zoning	

Ethanol (Sugar cane 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
			establishes areas in which sugar cane cannot be cultivated.	
	Sustainability issues: additional remarks		Many positive issues: cycling of by-products (vinasse, industry residues) in the field are commom practices in the sugar cane industry. Retention of harvest residues (8-15 t dry matter per hectare) helps to recycle nutrient in increase soil C sequestration.	
Employment:	If available, please describe DIRECT jobs created and/or indication of employment number related to a project	Yes Direct Jobs	More than 1 million jobs in the sugar/ethanol mills (2012). 27% of the agriculture jobs (2012) (Moraes et al., 2015); 550 thousand jobs (REN21, 2021)	Acording to IRENA, in 2018 there were 216100 jobs in sugar cane cultivation and 158600 in the biorefineries. Source: https://irena.org/publications/2020/Sep/Renewable-Energy-and-Jobs-Annual-Review-2020
		Yes Indirect Jobs	Many jobs created in the whole chain	Source: Moraes, M. A. F. D., Oliveira, F. C. R., and Diaz-Chavez, R. A. (2015). Socio-economic impacts of Brazilian sugar cane industry. Environmental Development 16, 31-43. REN21 Secretariat (2021). "Reneawables 2021 Global Status Report," REN21, Paris. http://dx.doi.org/10.1016/j.envdev.2015.06.010
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Implementation viable in many coutries of the tropical-subtropical zones. More than 100 countries in the world cultivate sugar cane to produce sugar. The same industry, with few modifications, can produce ethanol.	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	The technology to produce ethanol is not complex and can be replicate in countries that produce sugar cane. The large scale of the Brazilian model may not be replicated in all countries.	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Is it feasible to scale-up this technology/ biofuel? (if presently used in small scale or pilot plants)	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		
Additional remarks:	Any additional information or constraints that should be mentioned here?	The Brazilian sugar cane biorefinery model has demonstrated to be cost-competivive using the simple sugar-ethanol-electricity model, but it can be expanded to produce other products to increase the robustness of the investment.		Source: Leal Silva et al., 2022

Table 5 Sugar cane ethanol 2G (Brazil)

Ethanol (Sugar cane 2G BR)		Answer	Space for commentary / annotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	Ethanol (Sugar cane 2G)		
Source:				Chandel, A. K., Forte, M. B. S., Gonçalves, I. S., Milessi, T. S., Arruda, P. V., Carvalho, W., and Mussatto, S. I. (2021). Brazilian biorefineries from second generation biomass: critical insights from industry and future perspectives. Biofuels, Bioproducts and Biorefining 15, 1190-1208. (https://doi.org/10.1002/bbb.2234); Raizen S.A. (2022). Inform to the Market: Construction of the 3rd. and 4th. 2G ethanol plants. pp. 1p. Raizen S.A., https://ri.raizen.com.br/divulgacoes-e-documentos/avisos-comunicados-e-fatos-relevantes/.
Location:	Country, region, city where it is considered a success	Brazil	May apply to other countries that produce sugar cane	
TRL	Technology Readiness Level	9	Actual system proven in operational environment	
Biofuel main use		Light vehicle		
Main feedstocks:	Type of feedstock	Sugar cane bagasse		
	Please indicate if domestic or imported	Domestic		
	Feedstock availability	High		
	Feedstock yield	High	162.2 Mtons/y	Sourcce: Nacional Energy Balance (2019) http://shinyepe.brazilsouth.cloudapp.azure.com:3838/ben/ Acessed on 17Feb2021
	Planted area	High	10 Mha (approximately half to produce sugar and half to produce ethanol)	
	Soil-climate requirements	Medium	Sugar cane requires at least 1000 mm of rain (or need irrigation). Feedstock production requires proper agronomic practices, such as fertilization, weed control etc)	

Ethanol (Sugar cane 2G BR)		Answer	Space for commentary / annotations	Literature for specific information
Products:	If commercial production include output (m3/y, t/y, other)	34.000 m^3/y	Raizen operates one 2G plant (34 million L/y), has another in construction, and two other announced, each with 82 million L/year capacity. As a company listed in the São Paulo Stock Exchange, Raizen announced an investment of R$ 2 billion (US$ 400 million) to built the new 2G plants. The ethanol capacity will be 280 million L/y in 2024. The Raizen group produced 2.5 billion L of ethanol in 2019-2020	Source: Raizen S.A. (2022). Inform to the Market: Construction of the 3rd. and 4th. 2G ethanol plants. pp. 1p. Raizen S.A., https://ri.raizen.com.br/divulgacoes-e-documentos/avisos-comunicados-e-fatos-relevantes/.
	Biofuel yield (per unit feedstock, land, etc.)	0,231m^3/ t SCB		
	Commercially available: No: 0; Medium scale 1; Large scale 2	1	Ethanol represents almost 40% of the fuel in light vehicles in Brazil. Avalilable in several contries for blending with gasoline in different proportions	
	Co-products - low value	Yes	Vinasse	
	Co-products - medium value	Yes		
	Co-products - high value	Yes	C5 sugars for butanol and furfural production	
Economics:	Economics considered?	Yes	Price of 2G ethanol still higher than 1G. Probably sale as biofuel does not generate profits. However, other large markets (pharmaceutial, chemicals, cosmetics) that pay for less GHG emissions are targets.	
	Biofuel production costs (or sales cost)?	Yes	1.33 US$/L (2019) --> 60.7 US$/GJ	The ethanol density and net heating value were adopted as 0.8 kg/L and 6,525 kcal/kg, respectively. (1 kcal = 4.198 kJ)
	CAPEX available?	Yes	3.77 MUS$ (2019)	
	OPEX available?	Yes	1.77 MUS$ (2019)	
Public policies:	Does any mandate supported the introduction?	Yes	At least 27% of ethanol in gasoline in all Brazil. 100% ethanol also available at gas stations	
	Does it require subsidies?	Yes	Consumer tax lower than that of gasoline in most States in Brazil	
	Are relevant laws and regulations?	Yes	Minimum requirement of ethanol in gasoline (see above). Taxes (see above). RenovaBio rewards biofuel producers that prove to reduce GHG emission.	

Ethanol (Sugar cane 2G BR)		Answer	Space for commentary / annotations	Literature for specific information
	Does it have public acceptance?	Yes	Ethanol is available at all gas stations in Brazil. >40% of biofuel used in light vehicles	
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)	11.8 g CO_{2e}/MJ	Cradle to gate LCA. Avoided about 50% GHG emissions compared to 1G ethanol. Recent legislation (RenovaBio, 2017) stimulates reduction of GHG associated with biofuels.	Source: Maga, D. et al (2019). Comparative life cycle assessment of first- and second-generation ethanol from sugar cane in Brazil. The International Journal of Life Cycle Assessment (2019) 24:266-280. https://doi.org/10.1007/s11367-018-1505-1
	Competition with food?	No		
	Land requirement?	Medium	High yielding crop.	
	Air quality impact?	Yes	Negative impact due to pre-harvest burning, now legally phasing out; Positive: cars using ethanol decreases urban air pollution	
	Water usage?	Yes	Feedstock production is mostly rainfed (except in Northeast Brazil and partially in Central Brazil). Water is also required for sugar/ethanol production but amounts are being reduced. Water use in industry is regulated in some parts of Brazil	
	Land impact?	Yes	Large farms; risks of erosion during some stages of feedstock production. Proper agronomic practices are required to control negative impacts. The Brazilian Forest Code establishes that at least 20% of the land in private properties must be set aside as legal reservation (native species) promoting biodiversity, land and water preservation. Zoning establishes areas in which sugar cane cannot be cultivated.	
	Sustainability issues: additional remarks		Many positive issues: cycling of by-products (vinasse, industry residues) in the field are commom practices in the sugar cane industry. Retention of harvest residues (8-15 t dry matter per hectare) helps to recycle nutrient in increase soil C sequestration.	

Ethanol (Sugar cane 2G BR)		Answer	Space for commentary / annotations	Literature for specific information
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	More than 1 million jobs in the sugar/ethanol mills (2012). 27% of the agriculture jobs (2012) (Moraes et al., 2015)	IRENA (2018): 216 100 jobs in sugar cane cultivation and 158 600 jobs in biorefineries. FONTE: https://irena.org/publications/2020/Sep/Renewable-Energy-and-Jobs-Annual-Review-2020
		Yes Indirect Jobs	Jobs created in the whole chain	Source: Moraes, M. A. F. D., Oliveira, F. C. R., and Diaz-Chavez, R. A. (2015). Socio-economic impacts of Brazilian sugar cane industry. Environmental Development 16, 31-43. http://dx.doi.org/10.1016/j.envdev.2015.06.010
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	For 1G ethanol, implementation is viable in many countries of the tropical-subtropical zones. More than 100 countries in the world cultivate sugar cane to produce sugar. For 2G high investments are necessary in addition to technology licenses.	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	The technology to produce ethanol is not complex and can be replicate in countries that produce sugar cane. The large scale of the Brazilian model may not be replicated in all countries.	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Is it feasible to scale-up this technology/ biofuel? (if presently used in small scale or pilot plants)	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		
Additional remarks:	Any additional information or constraints that should be mentioned here?	Technology licenses or development		

Table 6 Corn ethanol (Brazil)

Ethanol (Corn 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	Ethanol (Corn 1G)		

Ethanol (Corn 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
Source:	Literature			Moreira, M. M. R., Seabra, J. E. A., Lynd, L. R., Arantes, S. M., Cunha, M. P., and Guilhoto, J. J. M. (2020). Socio-environmental and land-use impacts of double-cropped maize ethanol in Brazil. *Nature Sustainability* **3**, 209-216; Neves, M. F., Valério, F. R., Marques, V. N., Delsin, F. G., Cambaúva, V., Martinez, L. F., Moreira, M. M. R., Arantes, S. M., and Teixeira, G. O. (2021). "Corn Ethanol: present scenario and prospects for the chain in Brazil)," UNEM - União Nacional de Etanol de Milho, Ribeirão Preto.
Location:	Country, region, city where it is considered a success	Brazil	May apply to other countries that produce corn	
TRL (Technology Readiness Level)	Success story should at least be TRL 7	9	Actual system proven in operational environment	
Biofuel main use		Light vehicle		
Main feedstocks:	Type of feedstock	Corn	If more information available, please indicate here	
	Please indicate if domestic or imported	Domestic		
	Feedstock availability	High		
	Feedstock yield	Medium	5.5 ton/ha	
	Planted area	High	19 Mha	
	Soil-climate requirements	Medium	Corn production in medium to large farms require fertilizers, agrochemicals and machinery. Weather conditions are adequate in Brazil for two corn crops per year (summer, and second crop, in the autumn	
Products:	If commercial production include output (m3/y, t/y, other)	3.0 million m^3/y	1 tonne corn: 420 L ethanol, 300 kg DDGS (32% protein), 18 L oil	Canaviral (2022). Destilarias de etanol de milho no Brasil 2022. In "https://www.canaviral.com.br/wp-content/uploads/2022/07/MapaMilho-2022-maio-web.pdf" (Canaviral, ed.), pp. 1. Canaviral.
	Biofuel yield (per unit feedstock, land, etc.)	2.3 m^3/ha		

Ethanol (Corn 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
	Commercially available: No: 0; Medium scale 1; Large scale 2	2	18 ethanol plants operate in Brazil in 2022: 8 full and 10 flex, accounting for 8.51% of the ethanol production in Brazil (35.5 billion L in 2022 - sugar cane + corn).	
	Co-products - low value	Yes	Vinasse (fertilization, biogas)	
	Co-products - medium value	Yes	Destilery dried grains with solubles - DDGS (generally used to animal feed)	
	Co-products - high value	Yes	Corn oil for biodiesel production	
Economics:	Economics considered?	Yes	There are 18 corn ethanol plants in Brazil and new being planned	
	Biofuel production costs (or sales cost)?	25 US$/GJ (sale at the pump)	Sales price (consumer) 0,88 US$/L = 25US$/GJ	
	CAPEX available?	No		
	OPEX available?	No		
Public policies:	Does any mandate supported the introduction?	Yes	At least 27% of ethanol in gasoline in all Brazil. 100% ethanol also available at gas stations	
	Does it require subsidies?	Yes	Consumer tax lower than that of gasoline in most States in Brazil	
	Are relevant laws and regulations?	Yes	Minimum requirement of ethanol in gasoline (see above). Taxes (see above). RenovaBio rewards biofuel producers that prove to reduce GHG emission.	
	Does it have public acceptance?	Yes	Ethanol is available at all gas stations in Brazil. >40% of biofuel used in light vehicles	
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)	23 g CO_{2e}/MJ	Cradle to whell LCA. Low emissions because of low fertilizer use and renewable energy (planted wood or sugar cane bagasse used as energy at the corn ethanol plants). Avoided 70 to 90% GHG emissions compared to gasoline. Recent legislation (RenovaBio, 2017) stimulates reduction of GHG associated with biofuels.	
	Competition with food?	No	There is plenty of land in Brazil. Biofuel production is increasing alongside with food production.	
	Land requirement?	Medium	High yielding crop.	
	Air quality impact?	Yes	Ethanol fuel reduces air pollution	
	Water usage?	Yes	Corn is rainfed in Brazil.	

Ethanol (Corn 1G BR)		Answer	Space for commentary / annotations	Literature for specific information
	Land impact?	Yes	Thousands of farmers produce corn throughout Brazil. Most of the corn is produced as a second crop, after soybeans (two crops per year). Low N inputs because of rotation with legume. The Brazilian Forest Code establishes that at least 20% of the land in private properties must be set aside as legal reservation (native species) promoting biodiversity, land and water preservation.	
	Sustainability issues: additional remarks			
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	Corn ethanol is part of a long chain, which includes farm inputs and labor, industrial processing, and the meet protein food chain which uses DGGS.	
		Yes Indirect Jobs	Jobs created in the whole chain	
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Implementation viable in many coutries that produce corn (or other grains). Restrictions to the use of grains for biofuel production apply in some countries.	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	The technology to produce ethanol is not complex and can be replicate in countries that produce corn.	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Technology is mature and scalable, Feedstock available at low price is required.	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		
Additional remarks:	Any additional information or constraints that should be mentioned here?	Opportunity to take advantage of the sinergy between maize and corn ethanol production. Part of the infrastructure is shared by both. The surplus energy of sugar cane mills can be used for processing corn ethanol. Sugar cane ethanol is produced only in 7-9 months of the year. Industrial facility may be used to produce corn ethanol, with due adaptations.		

Table 7 Corn ethanol USA

Ethanol (Corn 1G)		Answer	Space for commentary / annotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	Ethanol (Corn 1G)		
Location:	Country, region, city where it is considered a success	USA	May apply to other countries that produce 1G ethanol	
TRL (Technology Readiness Level)	Success story should at least be TRL 7	9	Actual system proven in operational environment	
Biofuel main use		Light vehicle		
Main feedstocks:	Type of feedstock	Corn	If more information available, please indicate here	
	Please indicate if domestic or imported	Domestic		
	Feedstock availability	High		
	Feedstock yield	Medium	10.5 tonne/ha	
	Planted area	High	33 Mha (40% for ethanol = 13 Mha of corn for ethanol)	
	Soil-climate requirements	Medium	Corn grown in the summer. If rain is less than 600 mm, irrigation might be required. Corn is grown in many parts of the world.	
Products:	If commercial production include output (m3/y, t/y, other)	54.5 million m^3/y	14.4 billion gallons per year in 2019 in the USA	
	Biofuel yield (per unit feedstock, land, etc.)	4.4 m^3/ha	0.40 to 0.43 L/kg corn; [25] uses 0.427L/kg, data from 2019	
	Commercially available: No: 0; Medium scale 1; Large scale 2	2		
	Co-products - low value	Yes	Vinasse (fertilization, biogas)	
	Co-products - medium value	Yes	Destilery dried grains with solubles - DDGS (generally used to animal feed)	
	Co-products - high value	Yes	Corn oil for biodiesel production	
Economics:	Economics considered?	Yes	As corn has other competing markets (food, feed, other industrial uses) and is widely traded worldwide, price fluctuation may affect ethanol costs.	
	Biofuel production costs (or sales cost)?			
	CAPEX available?			
	OPEX available?			

Ethanol (Corn 1G)		Answer	Space for commentary / annotations	Literature for specific information
Public policies:	Does any mandate supported the introduction?	Yes	RFS-2 (36 billion gallons in 2022, of which 16 billion gallons of 1G ethanol and 21 billion gallons of advanced biofuel (2G ethanol and others)	
	Does it require subsidies?	Yes		
	Are relevant laws and regulations?	Yes	Mandates as the RFS-2. Fuel mixture requirements	
	Does it have public acceptance?	Yes	Ethanol is available at gas stations in most USA	
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)	51.4 (37.6-65.1) g CO_{2e}/MJ	Well to whell LCA. Avoided 46% GHG emissions compared to gasoline (93 g CO2e/MJ in average petroleum gasoline [25]). Derived from recent LCA that uses updated data of farming practices, energy use to produce ethanol and LUC). GHG emission 48 gCO2e/MJ according to [25], withouth LUC = 7,4 g CO2e/MJ, that is 48+7,4 = 55.4 g CO2e/MJ, similar to [23]	
	Competition with food?	Yes	Corn is a staple food in many countries. At the same time, it is grown in different areas of the world. Corn is widely tradable and no shortage of corn for food has been reported. Corn is also used to feed animals - another competing market.	
	Land requirement?	Medium	High yielding crop.	
	Air quality impact?	Yes	Improve air quality by replacint fossil fuels	
	Water usage?	Yes	But most corn produced in the USA is rainfed	
	Land impact?	Yes	But farming operations have been steadily improving in the USA as environmental impacts are increasing monitored (conservation tillage, decreasing amounts of fertilizer, crop residue preservation) (See 25)	
	Sustainability issues: additional remarks		Valuable co-products allow allocation of part of the GHG emissions to produce ethanol. 30% of the ethanol plants captures CO2 from fermentation ~0.45 kg CO2/L ethanol	
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	Many jobs created in the whole chain	
		Yes Indirect Jobs	Many jobs created in the whole chain	
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	Corn is widely cultivated in many countries.	
		International		

Ethanol (Corn 1G)		Answer	Space for commentary / annotations	Literature for specific information
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	The technology to produce ethanol is not complex and can be replicate in countries that produce corn.	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	Large corn ethanol plants are already operating. Scale depends on feedstock availability. Corn is produced in many countries, is widely traded worldwide and can be easily stored for processing at any time.	
		International		
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		
Additional remarks:	Any additional information or constraints that should be mentioned here?	The sustainability indicators of corn ethanol have increased with progresses in cultivation and ethanol production. The GHG emission indicators, compared with gasoline (46% less) still have potential to improve. Corn ethanol production may be easily replicated elsewhere. However, food vs fuel competion is an issue in many markets and the feedstock price may hinder the economic viability in some places.		

Table 8 Ethanol 2G (residue, Europe)

Ethanol (Cellulosic various 2G)		Answer	Unit	Space for commentary / annotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	Ethanol (Cellulosic various 2G)			
Source:					Art Fuels Forum Project and IEA Bioenergy (2020). Success stories of advanced biofuels in transport - Position Paper, IEA Bioenergy: 95p (http://artfuelsforum.eu/wp-content/uploads/2020/02/Success-Stories.pdf); Maier, A. (2022). Clariant completes construction of first commercial sunliquid cellulosic ethanol plant in Podari, Romania. Clariant, Muttenz (https://www.clariant.com/en/Corporate/News/2021/10/Clariant-completes-construction-of-first-commercial-sunliquid-cellulosic-ethanol-plant-in-Podari-Rom)
Location:	Country, region, city where it is considered a success	Europe		May apply to other countries that produce wheat and do not use the straw	
TRL	Technology Readiness Level	7		System prototype demonstration in operational environment	

Ethanol (Cellulosic various 2G)		Answer	Unit	Space for commentary / annotations	Literature for specific information
Biofuel main use		Light vehicle			
Main feedstocks:	Type of feedstock	Straw/stove		Wheat and other cereal straw	
	Please indicate if domestic or imported	Domestic			
	Feedstock availability	High		Agricultural residue	
	Feedstock yield	Medium		0.2 t ethanol / t feedstock	
	Planted area	High		No direct planted area, but crops will have to be grown somewhere. Crescentino and Clariant reports a radius of biomass collection of 70 km	
	Soil-climate requirements	Medium		As it uses several crop residues, crops can be adapted to different weather conditions. Crescentino and Clariant report a radius of biomass collection of 70 km	
Products:	If commercial production include output (m3/y, t/y, other)	50 million t/y			
	Biofuel yield (per unit feedstock, land, etc.)	0.2 t ethanol /t feedstock		At full capacity the plan is designed for processing 250 million tonne wheat straw into 50 million tonne ethanol	
	Commercially available: No: 0; Medium scale 1; Large scale 2	0		TRL 7: We need to confirm whether these plants are operating and delivering biofuel to the market	
	Co-products - low value	Yes		Vinasse (fertilization, biogas)	
	Co-products - medium value	Yes		Electricity	
	Co-products - high value	No			
Economics:	Economics considered?	Partially		At time only CAPEX available	
	Biofuel production costs (or sales cost)?	No		US$/L. Convert to $/GJ. No data available	
	CAPEX available?	Yes		Over 100 million EUR (2020) for Clariant. About 240 million EUR Crescentino	
	OPEX available?	No			
Public policies:	Does any mandate supported the introduction?	Yes		Blend mandates in Europe support the introduction of advanced bioethanol	
	Does it require subsidies?	Yes		Renewable Energy Directive (RED II) facilitates market introduction	
	Are relevant laws and regulations?	Yes		The production of 2nd generation ethanol is supported by the RED2 introduction in Europe	
	Does it have public acceptance?	Yes		Ethanol is already available in blend with gasoline at gas stations in Europe and the advanced ethanol avoids the critics of biofuel x food	

Ethanol (Cellulosic various 2G)		Answer	Unit	Space for commentary / annotations	Literature for specific information
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)	14g CO_{2e}/MJ		-	Clariant reports 95% GHG reduction. 85% typical value in RED 2
	Competition with food?	No		As it uses agriculture residues, it does not compete with the wheat harvest	
	Land requirement?	Not applicable		Not applicable as it is residue of wheat crop	
	Air quality impact?	Yes		Positive: cars using ethanol decreases urban air pollution	
	Water usage?	Partially		Not direct usage as it is used agricultural residue; however, crops demand water (variable amounts for different crops)	
	Land impact?	No		Altough the wheat farms have land impact, the implementation of an advanced ethanol production facility in the region does not implies in additional land usage or impact	
	Sustainability issues: additional remarks			Cycling of by-products (vinasse). Energy self-sufficient through burning of residual lignin	
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes	Direct Jobs	About 100-120 jobs for operation of the production facility	
		Yes	Indirect Jobs	About 300 jobs for activities related to the facility operation (e.g. agriculture acitivites)	
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International		The technology has already given license agreements for construction of facilities in Bulgaria, Poland and China.	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High		The technology uses feedstock available worldwide and is designed to operate also in regions "isolated" from established supply chains for chemicals or enzmes reception, with adaptations for example: Self-sufficiency in energy, enzyme production in-site and chemical-free pre-treatment	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International		The sunliquid technology has full capacitiy ranging from 50 - 150 million tonne/year. Crescentino built for 40 million tonne/ year	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.			

Table 9 Biodiesel FAME

Biodiesel (FAME, BR)		Answer	Space for commentary / nnotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	Biodiesel (FAME)		Rocha, M. H., et al. (2014). "Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis." Renewable and Sustainable Energy Reviews 37: 435-459; Brazil - Ministry of Mines and Energy - EPE (Energy Research Interprise) (2021). "Análise de Conjuntura dos Biocombustíveis - Ano 2020. Nota Técnica EPE/DPG/SDB/2021/03 (Analysis of Biofuels' Current Outlook - Year 2020. Technical Note)." EPE - Empresa de Pesquisa Energética, Brasilia.
Source:	Please indicate from the OneNote list which article/publications is/are the source of information	Multiple		
Location:	Country, region, city where it is considered a success	Brazil	If necessary, make a comme here	
TRL	Technology Readiness Level	9	Actual system proven in perational environment	
Biofuel main use		Light and heavy uty		
Main feedstocks:	Type of feedstock	Soybean	Around 70% of biodiesel production are from Soy. Th other 30% are divided in mar raw material such as animal - 9% Tallow (Bovine, Chicker and Pork), Cotton Oil, Canol Oil, Corn Oil, Sunflower oil a Used cooking oil UCO (1.2%).	
	Please indicate if domestic or imported	Domestic	As of November 18, 2020, Br began to allow soybean impo in biodiesel production	
	Feedstock availability	High		Source: https://www.fas.usda.gov/data/brazil-razil-allows-imported-soy-biodiesel-production
	Feedstock yield	High	3.5 t/ha	
	Planted area	High	38.3 Mha	Source: National Supply Company (CONAB) - ttps://portaldeinformacoes.conab.gov.br/safra-erie-historica-graos.html
	Soil-climate requirements	Medium	Soybean is grown in medium large farms, with modern technology, requiring the us fertilizers, agrochemicals an machinery. High productivity and economic returns. Only of the soybeans used to proc biodiesel. Most of the grain exported.	
Products:	If commercial production include output (m3/y, t/y, other)	6 million m^3/y		

Biodiesel (FAME, BR)		Answer	Space for commentary / nnotations	Literature for specific information
	Biofuel yield (per unit feedstock, land, etc.)	0,68 m^3/t oybean oil		
	Commercially available: No: 0; Medium scale 1; Large scale 2	2	ABIOVE - https://abiove.org.br/estatias/	
	Co-products - low value	No		
	Co-products - medium value	Yes		
	Co-products - high value	Yes		
Economics:	Economics considered?	Yes		
	Biofuel production costs (or sales cost)?	Yes	Price of biodiesel to the producer (Government bid i Aut 2021): R$5.60/L. Price c Diesel at the pump (Jan2022 R$5,65/L or , That is, more less the same price. 1 L dies 32.1 MJ (0.0321 GJ/L = 1 US = 31.15 US$/GJ	
	CAPEX available?	Yes		
	OPEX available?	No		
Public policies:	Does any mandate supported the introduction?	Yes	At least 12% of ethanol in di oil in all Brazil.	
	Does it require subsidies?	Partially		
	Are relevant laws and regulations?	Yes		
	Does it have public acceptance?	Yes		
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)	15,8g CO_{2e}/MJ	Cradle to whell LCA. Avoide to 90% GHG emissions compa to biodiesel. Recent legislati (RenovaBio, 2017) stimulate reduction of GHG associated with biofuels.	

Biodiesel (FAME, BR)		Answer	Space for commentary / nnotations	Literature for specific information
	Competition with food?	No	Only 17% of the soybean oil i for biodiesel. Most of the soybeans is exported.	ANP - National Agency for Oil, Natural Gas and Biofuels https://app.powerbi.com/view?r=eyJrIjoiNzk4Y2IzZWMtNGI1Zi00MGFiLTkwYWYtMjMyZDg3ZjBjMDJlIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmLTEyNGFmY2FkYzkxMyJ9&pageName=ReportSection0635f8a3dd0f76599659
	Land requirement?	High		
	Air quality impact?	Yes		
	Water usage?	No		
	Land impact?	Yes		
	Sustain-ability issues: additional remarks		Soybens are grown without fertilization because of biological N fixation. N2O emission during crop cultivation is highly reduce	
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	In 2019, 264 100 jobs were offered in the biodiesel cha	
		Yes Indirect JJobs	In 2019, 200 000 jobs in equipment manufacturing v offered in the whole liquid biofuels chain (including biodiesel and ethanol)	Source: Renewable Energy and Jobs - Annual Review 2020 - https://irena.org/publications/2020/Sep/Renewable-Energy-and-Jobs-Annual-Review-2020
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	Medium International	Viability of implementation the biofuel production technology at the local or international level.	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	Medium National	Viability of replication of th biofuel technology in other regions or countries, includ climate constraints to feedstock production	

Biodiesel (FAME, BR)		Answer	Space for commentary / nnotations	Literature for specific information
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High National	Is it feasible to scale-up this technology/ biofuel? (if presently used in small scale pilot plants)	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		

Table 10 HVO Europe

HVO Europe	Answer	Answer	Space for commentary / annotations	Literature for specific information
Biofuel/ Biofuel Technology:	Technology used to produce the liquid biofuel	HVO		
Source:	Please indicate from the OneNote list which article/publications is/are the source of information	1	1,21, 22	Art Fuels Forum Project, and IEA Bioenergy (2020). "Success stories of advanced biofuels in transport - Position Paper." IEA Bioenergy. (http://artfuelsforum.eu/wp-content/uploads/2020/02/Success-Stories.pdf); European Parliament, and Council of the European Union (2018). Directive (EU) 2018/2021 of the European Parliament and the Council. - RED II. pp. 84p. European Union, Official Journal of the European Union. (. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC); IEA - International Energy Agency (2019). "Renewables 2019. Analysis and forecast to 2024," IEA, Brussels (https://www.iea.org/reports/renewables-2019); La Mède (2022). La Mède: a multipurpose facility for the energy of tomorrow. (https://totalenergies.com/energy-expertise/projects/bioenergies/la-mede-a-forward-looking-facility, ed.), Vol. 2022, pp. webpage of Total, La Méde biofuel plant.
Location:	Country, region, city where it is considered a success	Europe	May apply to other countries that produce wheat and do not use the straw	
TRL	Technology Readiness Level	9	Actual system proven in operational environment	
Biofuel main use		Heavy duty		

HVO Europe	Answer	Answer	Space for commentary / annotations	Literature for specific information
Main feedstocks:	Type of feedstock	Multiple	Vegetable oils, waste and residues (e.g. UCO)	
	Please indicate if domestic or imported	Domestic + Imported	Part of the vegetable oil used by La Mede is imported	
	Feedstock availability	High	Vegetable oils, fats, oil residues (UCO)	
	Feedstock yield	High	0,77 t HVO biodiesel/t feedstock	
	Planted area	High	Most feedstock still is vegetable oils	
	Soil-climate requirements	Medium	Oil crops have different climate and soils requirments, depending on the species	
Products:	If commercial production include output (m3/y, t/y, other)	500.000 t/y	Based on HVO refinery La Mède	
	Biofuel yield (per unit feedstock, land, etc.)	0.77 t HVO bio-diesel/t feed-stock	At full capacity the plan is designed for processing 650.000 tonne wheat straw into 500.000 tonne HVO biodiesel	
	Commercially available: No: 0; Medium scale 1; Large scale 2	2		
	Co-products - low value	No		
	Co-products - medium value	No		
	Co-products - high value	Yes	Renewable propane, naphtha and chemicals	Via NESTE refinery and IEA
Economics:	Economics considered?	Partially	At time only CAPEX available	
	Biofuel production costs (or sales cost)?	No	US$/L. Convert to $/GJ	
	CAPEX available?	Yes	275 million Euros for the HVO refinery La Mède	
	OPEX available?	No		
Public policies:	Does any mandate supported the introduction?	Yes	Blend mandates in Europe support the introduction of HVO	
	Does it require subsidies?	Yes	Renewable Energy Directive (RED II) facilitates market introduction of UCO based HVO	
	Are relevant laws and regulations?	Yes	The production of HVO based on waste oils is supported by the RED2 in Europe	
	Does it have public acceptance?	Partially	HVO from dedicated vegetable crops may face restrictions in	

HVO Europe	Answer	Answer	Space for commentary / annotations	Literature for specific information
			Europe and other places. HVO from residues (fats, UCO) does not have restrictions	
Environ-mental impact:	GHG Emissions (g CO2e/MJ or another unit)	12 to 48 g CO_{2e}/MJ	Data from RED 2. HVO from UCO 87% and animal fats 83% reduction. From vegetable oil from 51 to 58%. La Mède: 50% reduction	Data from RED 2; Considering emission from diesel (95 g CO2e/MJ) and the reductions by HVO based on UCO, fats, and oil seeds, the range of emissions is 12 g CO2/MJ (UCO), 16 g CO2e/MJ (Fats), 43 g CO2e/MJ (oil seeds), 48 g CO2e/MJ (average La Mède)
	Competition with food?	Partially	Vegetable oils may compete; wastes do not	
	Land requirement?	High	Land necessary for oil crops. At La Méde most of the feedstock is vegetable oils	
	Air quality impact?	Yes	Less air pollutants due to lower aromatics content	Data from IEA
	Water usage?	Yes	Water may be necessary for irrigation of vegetable oil crops, depending on where it is cultivates. This requirement does not apply for wastes	
	Land impact?	Partially	Has land impact if vegetable oil is pursuid for that reason. Does not apply in the case of waste streams	
	Sustainability issues: additional remarks			
Employ-ment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	Estimated 250 jobs maintened with operation of La Mède	
		No Indirect Jobs	Information not available	
Implemen-tation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	The HVO technology is applied to general vegetable oils and waste oils (UCO). Feedstocks available worlwide available	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High	The process technology and feedstock are not constrained. Technology can be internationally replicable	
		Internatio nal		

HVO Europe	Answer	Answer	Space for commentary / annotations	Literature for specific information
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	Medium International	waste oils and fats may have limited supply to sustain large operations, but vegetable oils have ample suppy, although there are restrictions to food crops used for bioenergy in certain regions	
Contribu-tion to Sustainable Develop-ment Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		
Additional remarks:	Any additional information or constraints that should be mentioned here?	Accounting for the renewable portion of feedstock in HVO may be an issue. Restrictions on food crops or crops grown on land that compete with food crops may limit the potential of HVO in some countries.		

Table 11 Bio-SNG

Bio-SNG		Answer	Space for commentary / annotations	Literature for specific information
Biofuel/Biofuel Technology:	Technology used to produce the liquid biofuel	Bio-SNG	Bio synthetic natural gas	
Source:	Please indicate from the OneNote list which article/publications is/are the source of information	1	If multiple, please indicate which	Art Fuels Forum Project, and IEA Bioenergy (2020). "Success stories of advanced biofuels in transport - Position Paper." IEA Bioenergy. (http://artfuelsforum.eu/wp-content/uploads/2020/02/Success-Stories.pdf)
Location:	Country, region, city where it is considered a success	Sweden		
TRL	Technology Readiness Level	7	System prototype demonstration in operational environment	
Biofuel main use		Light and heavy duty	Applicable to diesel engines	Maybe differenciate in Otto and Diesel engines
Main feedstocks:	Type of feedstock	Multiple	Multiple biomass possible	
	Please indicate if domestic or imported	Domestic	With possibility for using foreign feedstock (for example importing pellets)	
	Feedstock availability	High	Wood residues	
	Feedstock yield	Medium	0,57 MW biomethane / MW dry feedstock	

Bio-SNG		Answer	Space for commentary / annotations	Literature for specific information
	Planted area	Not applicable	As it uses residues the technology does not have direct planted area	
	Soil-climate requirements	Not applicable	As it uses residues the technology does not have direct planted area	
Products:	If commercial production include output (m3/y, t/y, other)	20 MW	20 MW output gas (32 MW feedstock)	
	Biofuel yield (per unit feedstock, land, etc.)	0.57 MW biomethane / MW dry feedstock	Capacity of 30-35 MW and production of 20 MW biomethane	
	Commercially available: No: 0; Medium scale 1; Large scale 2	0		
	Co-products - low value	No		
	Co-products - medium value	Yes	5 MW district heating	
	Co-products - high value	No		
Economics:	Economics considered?	No	At time only CAPEX available	
	Biofuel production costs (or sales cost)?	No		
	CAPEX available?	Yes	150 million EUR for the Giobigas project (1500 million swedish crowns)	
	OPEX available?	No		
Public policies:	Does any mandate supported the introduction?	Yes	Tax exception for Bio-SNG	
	Does it require subsidies?	Yes	20 million EUR from Swedish Energy Agency for the project (250 million swedish crowns)	
	Are there relevant laws and regulations?	Yes	-	
	Does it have public acceptance?	Yes	-	
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)	18,8 g CO_{2e}/MJ	-	80% GHG reductions.
	Competition with food?	No	As it uses woody residues, it does not compete with food	
	Land requirement?	Not applicable	As it uses residues the technology does not have direct planted area	
	Air quality impact?	Yes	-	
	Water usage?	Yes	-	

Bio-SNG		Answer	Space for commentary / annotations	Literature for specific information
	Land impact?	No	As it uses residues the technology does not have direct planted area	
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	30 full time employment to operate the facility	
		No Indirect Jobs		
Implementation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High National	-	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High National	-	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	Medium International	Further scale-up was planned for 100 MW	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		

Table 12 BtL

BTL		Answer		Space for commentary / annotations	Literature for specific information
Biofuel/Biofuel Technology:	Technology used to produce the liquid biofuel	Biomass to Liquid		Biomass to liquid (DME or Methanol	
Source:	Please indicate from the OneNote list which article/publications is/are the source of information	1			Art Fuels Forum Project, and IEA Bioenergy (2020). "Success stories of advanced biofuels in transport - Position Paper." IEA Bioenergy. (http://artfuelsforum.eu/wp-content/uploads/2020/02/Success-Stories.pdf)
Location:	Country, region, city where it is considered a success	Sweden		Pitea	
TRL	Technology Readiness Level	7		system prototype demonstration in operational environment	
Biofuel main use		Light and heavy duty		Applicable to diesel engines (??)	

BTL		Answer	Space for commentary / annotations	Literature for specific information
Main feedstocks:	Type of feedstock	Black liquor	Multiple biomass possible	Also utilizable with pyrolysis oil, therefore flexible for feedstock (liquids derived from biomass)
	Please indicate if domestic or imported	Domestic	With possibility of using internationally (for example importing pellets)	
	Feedstock availability	High	Suitable for diverse forest residues	
	Feedstock yield	Medium	0.15 MWh/tonne of Black Liquor	
	Planted area	Low	Does not have direct planted area but requires biomass of planted forests that must be produced	
	Soil-climate requirements	Medium	Diverse biomass; may be from plant species of low or high soil-climate requirement	
Products:	If commercial production include output (m3/y, t/y, other)			
	Biofuel yield (per unit feedstock, land, etc.)	0.15 MWh /tonne	Success story: 20 tonne Black Liquor corresponds to about 3 MWh	
	Commercially available: No: 0; Medium scale 1; Large scale 2	0		
	Co-products - low value	No		
	Co-products - medium value	Yes	Supplies steam for the pulp plant	
	Co-products - high value	No	Green liquor to return to the pulp plant	
Economics:	Economics considered?	No	At time only CAPEX available	
	Biofuel production costs (or sales cost)?	No	Biofuel was rpdoced Only for tests in heavy duty vehicles	
	CAPEX available?	Yes	Approximately 75 million EUR	
	OPEX available?			
Public policies:	Does any mandate supported the introduction?	Yes	Methanol can be used in minor proportions in gasoline, but in the specific year it was given tax exemption	
	Does it require subsidies?	Yes	Project was supported directly with grants from EU and Swedish Energy Agency	
	Are there relevant laws and regulations?	No	-	
	Does it have public acceptance?	Yes	-	

BTL		Answer	Space for commentary / annotations	Literature for specific information
Environmental impact:	GHG Emissions (g CO2e/MJ or another unit)		-	
	Competition with food?	No	By-product of pulp industry	
	Land requirement?	Not applicable	Black Liquor from the pulp industry. Does not have direct planted area	
	Air quality impact?	Yes	-	
	Water usage?	Yes	-	
	Land impact?	No	As it uses residues the technology does not have direct planted area	
	Sustainability issues: additional remarks		-	
Employment:	If available, please describe jobs created and/or indication of employment number related to a project	Yes Direct Jobs	In the Pitea facility about 35 jobs. In scaled-up facility is estimated about 80 employees	
		Yes Indirect Jobs	Scaled-up plant would employ about 8-10 times the number of direct jobs	
Implemen-tation potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Kraft pulping is an worlwide activity and ist feedstock would is also available worlwide. Technology, scaling up and cost of investment may be an issue. Competing uses of black liquor to produce other energies (heat, electricity)	
Replication potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	High International	Pulp industries are operating worldwide and the model could be replicated. In the BioDME project was analysed and identified 70-80 places in Europe and 300 worldwide possible of receiving such project	
Scale-up potential:	Please indicate if it is low, medium or high and if this is at local/regional, national or international level	Medium International	The scale-up is limited to the black liquor availability in the pulp mill	
Contribution to Sustainable Development Goals:	Please indicate the contributions to SDGs	Affordable and clean energy; sustainable cities and communities; industry, innovation and infrastructure; responsible consumption and production; and climate action.		

APPENDIX 2 | EXCURSES

In Germany, the main biofuels are bioethanol, biodiesel, HVO, biomethane and direct usage of vegetable oil. The saving emissions are reported annually, and since 2015. The fulfilment of the biofuel quota in BIMSCHG(§37) changed from energy content to GHG emissions reduction obligation. With that, higher emissions savings confirmed with a sustainability certificate are a market competitive factor, and this measure stimulated greater GHG emission reductions from the biofuels utilized in Germany. Figure 17, illustrates the middle value of emissions reduction from the biofuels utilized from 2011 to 2019.

The values do not differentiate neither the raw material utilized to produce these biofuels nor the origin of the feedstock. In 2011, the emissions savings from bioethanol, biodiesel, and HVO were respectively 48%, 40% and 50% respectively. By 2019, the emissions savings increased for bioethanol, biodiesel and HVO respectively 88%, 81% and 80%, respectively. Furthermore, the usage of other alternative fuels was reported in distinct years: the usage of diesel produced by Fischer-Tropsch synthesis achieved an GHG emission reduction of 91% in 2018. Biomethanol was reported to cause emission savings of 69%, 68% and 73%, in 2012, 2013, and 2015, respectively.

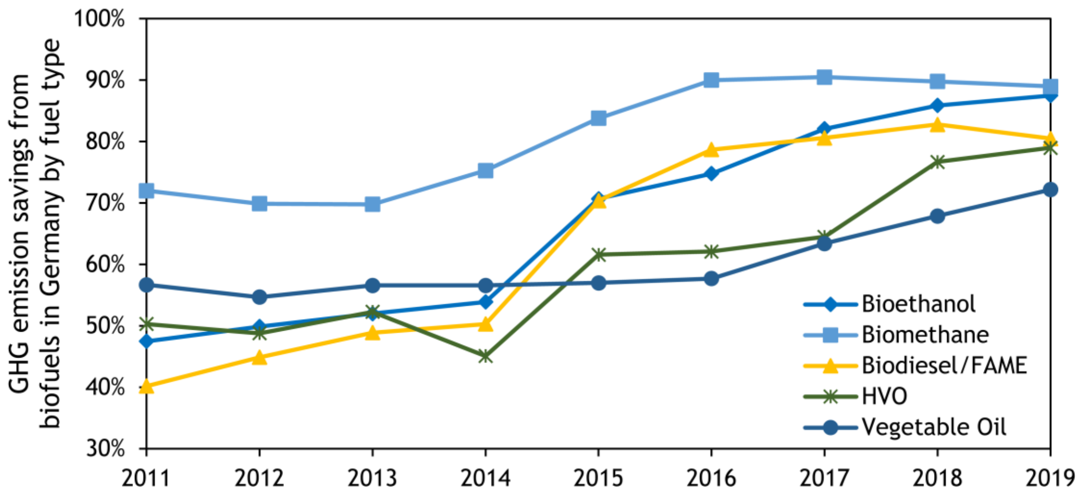

Figure 17 Average value for GHG emission savings from biofuels utilized in Germany by fuel type between 2011 and 2019 (No specificity from feedstock utilized). ©DBFZ based on BLE (2014,2015, 2017, 2018 and 2020)

Table 13 List of countries with biofuel mandates. https://www.biofuelsdigest.com/bdigest/2021/01/06/the-digests-biofuels-mandates-around-the-world-2021/ (verified on 10th Nov 2021)

Country/Region	Mandate		Observation
	Ethanol	Biodiesel	
North America			
USA			Legislation in the USA varies with States. There are mandates for volumes of different biofuels to be produced. Blending mandates for biodiesel may vary with season, i.e., in Minnesota B-20 can be used in the summer months but in the winter biodiesel is required to remain at B-5
Canada	E-5 to E-10	B-2 to B-4	Mandates vary by province. Regulations are linked with carbon intensity reduction targets

Country/Region	Mandate		Observation
	Ethanol	Biodiesel	
Central and South America			
Argentina	E-12	B-5	Problems with implementations due to internal production, export (biodiesel) and changing rules. Law 27.640 (4Aug2021) reduced from B-10 to B-5
Bolivia	E-12		Plans to increase to E-20 by 2025
Brazil	E-27 (minimum)	B-12	E-100 also available in all gas stations. Flex-fuel cars can run on any mixture of gasoline and ethanol. Biodiesel project to increase to B-15 by 2023
Chile	E-5	B-5	These are targets (no mandates)
Colombia	E-10	B-12	Varies by region. Mandates adjusted by ethanol supply availability. Laws 693, from 2001, and Law 939, from 2004
Costa Rica	E-7	B-20	Implementation of new blending pending legal matters
Equador	E-5	B-5	Plans to increase biodiesel blending
Jamaica	E-10		Plans to increase to E-15. Biodiesel in trial as acceptance is an issue. B-5 could be viable
Mexico	E-5.8		Police to increase to E-10 is pending court decisions as the benefits of increasing ethanol have been challenged.
Panama	E-10		Gradually increasing from E-2 mandate from 2013
Paraguay	E-26	B-2	Paraguay Energy Plan: Plans to increase to E-27 to mirror Brazil as both countries are part of Mercosur. Biodiesel production growth by 69%. Plans to increase biodiesel to B-15 but local industry wants a slow ramp up to prevent a fast opening of the biodiesel market to imports
Peru	E-7.8	B-5	Plans to gradually increase to B-5 (According to Decree 021-2007) B-5 should be in place from 2011.
Uruguay	E-9 to E-10	B-6	Plans to decrease transportation fossil fuel by 15% (2005-2030)
Europe (EU-27)			RED II establishes rules for the EU-27 countries, effective from June 2021. Main points are non-binding Member States quotas; 1,5% (2020) to 6.8% (2030) quota of low -emission renewable fuels in the transport sector; cap on biofuels from food or feed crops (e.g. max. 7% at present).
Norway		B-3.5	Standard is B-5 but B-7 are also available. Actual use of biofuels in Norway is well ahead of mandates. Mandates also starting to be applied to SAF
Turkey	E-3		Mandate suspended due to Covid to free up ethanol to produce disinfectants
Ukraine	E-4.8	B-2.7	Mandates postponed due to shortage of biofuels
United Kingdom	E-10		
Asia-Pacific			

Country/Region	Mandate		Observation
	Ethanol	Biodiesel	
Australia	E-10	B-5 or B-20	Varies with states. Queensland is implementing a E-10 blending policy; New South Ales has E-10 and B-2 mandates, but targets have not been met because of market exceptions to oil companies
China	E-10		E-10 in 10 provinces. China government is seeking to increase the mandate to E-15 and expand the E-10 mandate to more provinces. Ethanol expansion was based on the use of stocks of spoiled corn, but that may not be enough. In most regions targets have not been met because of limited refining capacity and difficulties with corn supply; China expects to make use of 2G ethanol in the future, but plans are behind schedule
Fiji	E-10	B-5	Mandates seem not to be implemented
India	E-5		India increased the goals to E-10, and lately, to E-20, but blending has reached only 5%. Feedstock supply, drought, flood, and other problems have delayed implementation
Indonesia	E-2	B-20	Mandate was increased to B-30 in 2020 and the government is studying the technical viability to increase it to B-40. Feedstock is palm oil. The ethanol mandate was planned to E-5 but there was not feedstock available, and the mandate was lowered to E-2 when the program began in 2015. Plans are to increase to E-20 in 2025.
Malaysia	E-10	B-20	Implementation of B-20 has been delayed because of Covid-19
New Zealand	E-10	B-7	Mandates that were in place were revised by new government. Topic of local political disputes (Source: Increasing the use of sustainable biofuels in Aotearoa New Zealand; Ministry of Business, Innovation & Employment (mbie.govt.nz)
The Philippines	E-10	B-2	High prices of biofuels make it difficult to maintain the present mandates
South Korea		B-2.5	The mandate was planned to be raised to B-3. The biodiesel is based on imported palm oil. High costs have made full implementation difficult
Taiwan		B1-B-2	The mandate was phased out over fuel contamination concerns
Thailand	E-10	B-20	The Thai government is taking steps to move to E-20, but most gas stations do not sell the fuel. E-10 will be phased out. Biodiesel rely on palm oi production mandate may be waived because of fluctuations in agricultural production
Vietnam	E-5		Implementation has been slow
Africa			
Angola	E-10		
Ethiopia	E-5		E-5 in place and E-20 target but ethanol supply will delay deployment so E-10 will be used, instead. It is not clear whether the Ethiopian fleet can run on E-20
Kenya	E-10		Mandate not valid nationwide

Country/Region	Mandate		Observation
	Ethanol	Biodiesel	
Malawi	E-10		Use of E-10 depends on availability
Mauritius	E-5		Should be in place in 2016 but deployment is not secured
Mozambique	E-10	B-3	The mandate was planned to be raised to E-20 and B-10. Source: National Biofuels Policy an... - Mozambique - Climate Change Laws of the World (climate-laws.org
Nigeria	E-10	B-20	Source: Biofuels blending mandate – Policies - IEA
South Africa	E-2 to E-10	B-5	Mandate implementation has been postponed but the intention to deploy it remains. Source: 1-35623 23-8 Energy_Layout 1
Uganda			Uganda introduced in June 2015 compulsory blending mandate of biofuels with fossil fuels up to 20%
Sudan	E-5		
Zambia			No mandate but E-10 is possible with existing molasses supplies
Zimbabwe	E-10 to E-20	B-2	Ethanol producers are allowed to supply it to the local market, but Implementation of mandate has been in and out because of political woes. The strategy is E-10 in 2020 and E-20 in until 2030. B-2 from 2020. Source: Biofuels Policy of Zimbabwe - FINAL.indd (zera.co.zw)

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