Monitoring RESfuels

D1.5 Monitoring framework and the KPIs – Update

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ADVANCEFUEL at a glance

ADVANCEFUEL (www.ADVANCEFUEL.eu) aims to facilitate the commercialisation of renewable transport fuels by providing market stakeholders with new knowledge, tools, standards and recommendations to help remove barriers to their uptake. The project will look into liquid advanced biofuels – defined as liquid fuels produced from lignocellulosic feedstocks from agriculture, forestry, and waste – and liquid renewable alternative fuels produced from renewable hydrogen and CO_2 streams.

In order to support commercial development of these fuels, the project will firstly develop a framework to monitor the current status and future perspectives of renewable fuels in Europe, in order to better understand how to overcome barriers to their market roll-out. Following this, the project will investigate individual barriers and advanced new solutions for overcoming them.

The project will examine the challenges of biomass availability for second-generation biofuels, looking at non-food crops and residues, and how to improve supply chains from providers to converters. New and innovative conversion technologies will also be explored in order to see how they can be integrated into an energy infrastructure.

Sustainability is a major concern for renewable fuels, and ADVANCEFUEL will look at socio-economic and environmental sustainability across the entire value chain, providing sustainability criteria and policy recommendations to ensure that renewable fuels are truly sustainable. A decision support tool will be created for policy makers to enable a full value chain assessment of renewable fuels, as well as useful scenarios and a sensitivity analysis on the future of these fuels.

Stakeholders will be addressed throughout the project to involve them in a dialogue on the future of renewable fuels, and to receive feedback on ADVANCEFUEL developments to ensure applicability to the end audience, validate results, and ensure successful transfer and uptake of the project results. In this way, ADVANCEFUEL will contribute to the development of new transport fuel value chains that can contribute to the achievement of the EU's renewable energy targets, and reduce carbon emissions in the transport sector by 2030 and beyond.

To stay up to date with ADVANCEFUEL's stakeholder activities, sign up at:
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Executive Summary

This is the final monitoring report of key performance indicators (KPIs) within the ADVANCEFUEL project. The objective of the ADVANCEFUEL monitoring reports is to inform the stakeholders (i) on the status of advanced renewable fuels (RESFuels) in Europe and globally, related policies in different countries, and the developments on feedstock prices, and (ii) on key performance indicators (KPIs) of the project. The results presented here are based on a monitoring framework of selected key performance indicators (KPIs) previously presented in the ADVANCEFUEL, i.e. Deliverable D1.2 "Monitoring framework and the KPIs for advanced renewable liquid fuels (RESFuels)". The project related KPIs are provided by the project partners responsible from related work package.

This report is an update of the results presented in Deliverable D1.4 "Monitoring framework and the KPIs for advanced renewable liquid fuels (RESfuels)" published in March 2019.

In summary, the following conclusions (non-exhaustive) can be drawn from the updated presentation of project and market-based KPIs:

- The advanced biofuels industry continues to struggle to reach commercialisation in the EU and in other parts of the world.
- Recent developments show that the US no longer holds the largest installed capacity of ethanol production from lignocellulosic feedstocks. Production of biodiesel using lignocellulosic feedstocks is limited in comparison to lignocellulosic ethanol.
- In recent years, difficult market conditions coupled with high operational costs and financial difficulties companies were facing, have forced the closure of several lignocellulosic ethanol plants. Majority of these plants remain closed.
- There was a small spike in investments in advanced biofuels in the EU following the adoption of REDI in 2009, but barriers affecting investments in advanced biofuels remain numerous, mostly due to the complex nature of the business environment. Not only does the technology remain immature, but the operational problems of first-of-a-kind (FOAK) projects persist and costs remain high. Additional challenges include an array of environmental, infrastructure-related, social and political issues.
- The US and Italy were the first two countries to introduce dedicated mandates for advanced biofuels. With the adoption of REDII, there will be an EU-wide obligation for fuel suppliers in Europe to utilise advanced biofuel, starting in 2022. EU Member States are slowly but surely taking steps to implement mandates for advanced biofuels.
- Feedstock prices next to the capital costs are the dominant cost factor in effecting the advanced biofuel production costs. While there are currently no established markets to define feedstock prices once the sector matures, the feedstock prices may follow an increasing trend depending on the buying capacity of the biofuel plants and the market supply of certain feedstock (i.e. straw). Little has developed in this domain since the previous ADVANCEFUEL monitoring report, published in early 2019.
- Project results show that production costs of dedicated energy crop can be reduced by applying innovative approaches such as propagation by seeds and/or by stem segments, planting density increase, economy of scale and learning effects. The cost reduction can be in the order of 7-25% lower when compared to reference scenarios (before innovation implementation).
- Fuel properties are essential when assessing advanced biofuel applicability in various transport sectors. Drop-in biofuels are preferred due to compatibility issues (BTL, HVO) but engine and infrastructure modifications are also technologically proven (for alcohols).

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1. Introduction

This is the final monitoring report of Work Package 1 of the ADVANCEFUEL project. It is based on the ADVANCEFUEL monitoring framework, which includes selected KPIs related to RESfuels market progress as well as project KPIs. These are presented in Deliverable D1.2 "Monitoring framework & KPIs for advanced renewable liquid fuels", and summarised in Table 1 below.

Table 1: Overview of RESfuel KPIs presented in this report

Project related KPIs		
WP No	**Project partner**	**KPIs**
WP2 feedstock supply	ATB & Utrecht University	Feedstock cost reductions due to innovative technologies
		Availability of marginal land in Member States
		Technical potential of dedicated cropping
WP3 conversion technologies	Chalmers University	Well-to-wheel system efficiency increase due to innovative approaches
		Time framed CAPEX need for TRL level increase of certain technologies
		CAPEX reduction due to opportunity for greening the fossil infrastructure
WP4 sustainability and certification	Utrecht University	A set of additional sustainability criteria for RESfuels
		A set of recommendations on the harmonisation of voluntary schemes focusing on RESfuels
WP5 end use	Imperial College & Aalto University	Best practices in Europe or outside
		Fuel performance data
WP6 integrated analysis	TNO Energy Transition	Gross employment effect of the selected pathways
	Utrecht University	GHG emission reduction of selected pathways
Market progress KPIs		
Resource specific	TNO Energy Transition	Wood pellet & wood chip prices
		Straw prices
Conversion and end use specific		Existing RESfuel plant capacity
		RESfuel production and consumption
		Total Investments
		Public support to (advanced) biofuel technologies -EU funding R&D to advanced biofuels
		Status of the policy support to advanced biofuels

This report consist of two main parts:

- **Project monitoring,** where the aim is to share the main outcomes of the project and provide new knowledge to the stakeholders stemming from the continuous work within the ADVANCEFUEL project (Chapter 2).
- **RESfuel market progress monitoring,** where the aim is to systematically and continuously collect data regarding RESfuels and inform the stakeholders on the latest progress (Chapter 3).

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2. Project related KPIs

2.1. Resource specific: Feedstock supply

2.1.1. Innovative technologies and dedicated energy crop cost reductions

ADVANCEFUEL project has explored promising cropping systems to produce feedstocks for advanced biofuels in different regions in Europe. It has done so by assessing cost reduction potentials by innovative cropping systems, whilst avoiding greenhouse gas (GHG) emissions and other negative environmental and social impacts.

The production costs of dedicated crops (lignocellulosic biomass) are mainly influenced by two key factors; namely establishment costs[1] and achieved yields. Establishment costs depend mostly on the applied technology and, hence, related cost reduction potentials might be similar for different regions within Europe. Yields, on the other hand, can depend on technological improvements, but also on the natural environment, crop and variety selection, cropping management and farmers' knowledge. Table 2 presents biomass production cost reduction potentials for different innovations. The yield change potentials [%] or expected changes [+/-] for different innovations are presented in Table 3. Details concerning the methodology and analysis behind these calculations are provided in Deliverable D2.2 "Innovative cropping schemes for lignocellulosic feedstock production".

Table 2: Biomass production cost reduction potentials [%] for different innovations (negative reduction = increase of costs).

Innovation	Breeding (propagation by seeds)	Propagation by stem segments (not rhizomes)	Planting density increase by 3 times	Economy of scales	Learning effects	Cropping on marginal land
Miscanthus	7-16[1)]	9[1)]	7[1)]			-11[3)], -44[4)]
Switchgrass						-10[3)]
Willow SRC				10[2)]	25[2)]	
Giant Reed						-17[3)]

Data source: [1)] (Germer, et al., 2019), [2)] Sweden (Rosenqvist, et al., 2013), [3)] (Soldatos, 2015), [4)] former mining site compared to average of 6 agricultural sites (LfULG, 2014)

Table 3: Yield change potentials [%] or expected changes [+ / -] for different innovations.

Innovation	Breeding for yield increase	Breeding for quality increase	Cropping on marginal compared to agricultural land	Cropping on small compared to big scale[2)]	Learning effects
Miscanthus	+	-	-70[2)], -37[3)], -31[4)]	-80	+
Switchgrass	+	-	-31[2)], -42[3)]	-74	50[5)]
Willow SRC	+	-	0[2)]	-38	+
Poplar SRC	+	-16-24, >30[1)]	-39[2)]	-91	+
Giant Reed	+	-	-37[3)]	-	+

Data source: [1)] (Acker et al., 2014; Leplé et al., 2007), [2)] changes of maximum yield (Searle & Malins, 2014), [3)] changes of average yield (Soldatos, 2015), [4)] former mining site compared to average of 6 agricultural sites (LfULG, 2014), [5)] for

1 Crop establishment costs are costs that occur only before the first harvest of perennial corps including field preparation, herbicides, planting material. These costs need to be divided by the lifespan of plantations in order to derive annual costs.

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study case in the USA (Karp & Shield, 2008)

Cropping on small compared to large scale: Energy crop yields are usually overestimated if cropping takes place on small test fields compared to big commercial implementations. This overestimation is due to higher yields at field edges that have a higher proportion per field for small plots compared to big plots and due to manual harvest preventing significant biomass loss at small fields compared to mechanically harvest on commercial fields, where losses are unavoidable.

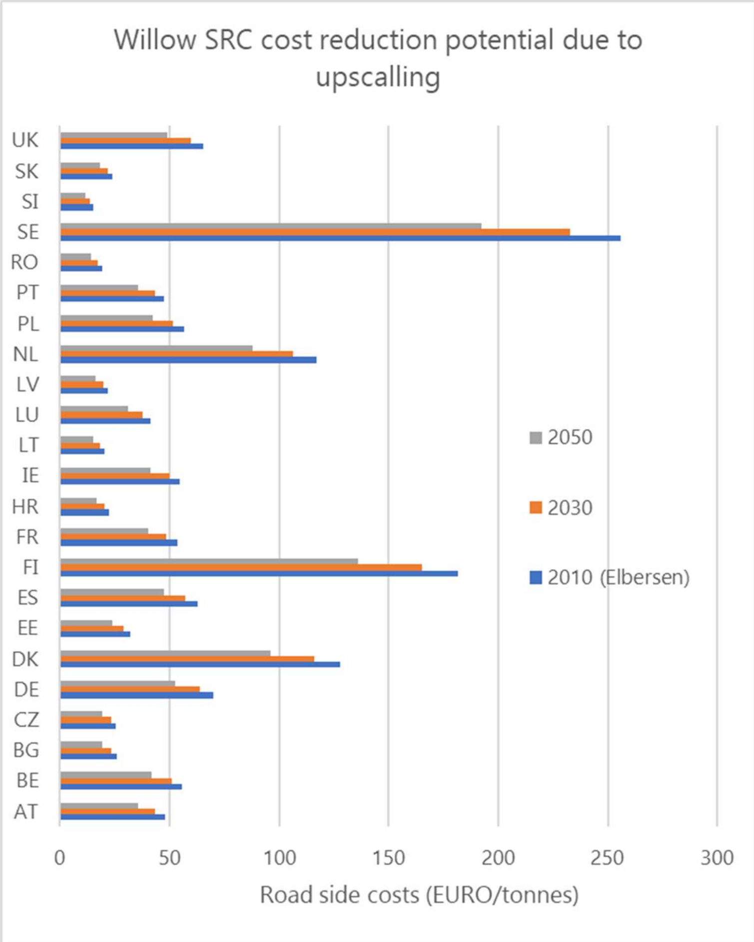

Figure 1 illustrates the cost reduction outlook for willow due to upscaling and learning effects until 2030 and 2050 as one of the results. The calculation is based on the methodology presented in Deliverable D2.2[2]. These results, however, must be perceived as a rather liberal outlook, since it is strongly simplified and does not address the future developments of production input costs.

2 See: Table 2.A of D2.2 for detailed methodology underpinning the calculations, and Annex I of D2.2 for cost reduction potentials for stem-based establishment for miscanthus, planting density increase and related cost reduction for miscanthus.

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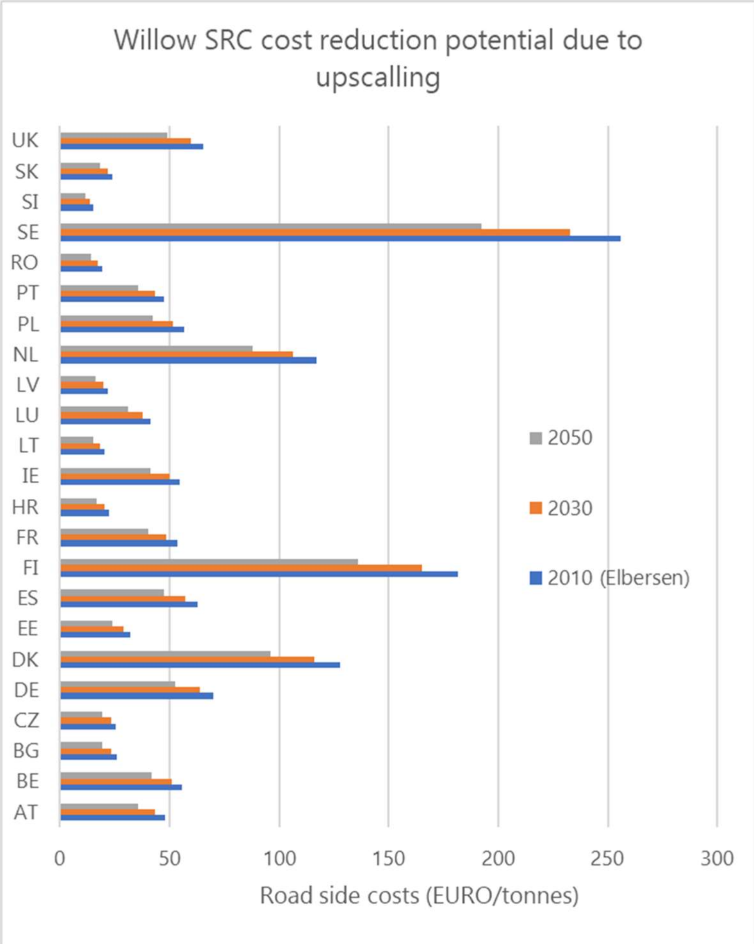

Figure 1: Country comparison of Willow SRC cost reduction potential due to upscaling.

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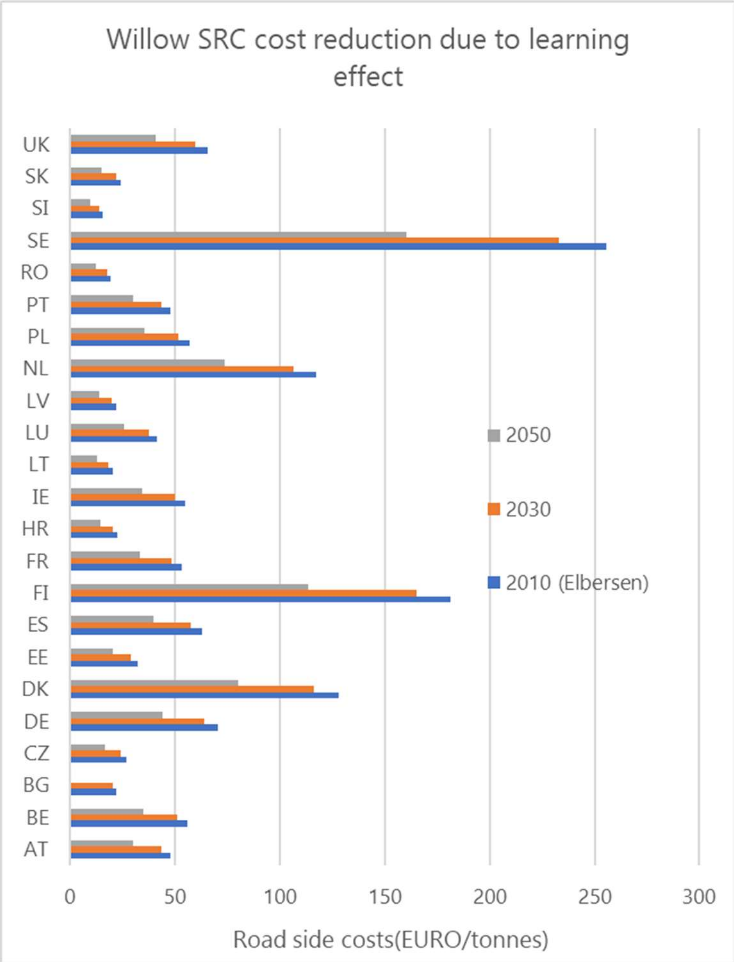

Figure 2: Country comparison of Willow SRC cost reduction due to learning effects (right).

2.1.2. Available marginal land in Member States

Here we cover the project KPI on available marginal land in Member States, with the objective to inform stakeholders on the future availability of land for dedicated energy crops (woody and grassy). Marginal lands refer to land on which cost-effective food and feed production is not possible under given site conditions and cultivation techniques. In Europe, the use of marginal lands is considered an advantageous option to increase land availability, reduce environmental pressure and to meet the continuous growth of bioenergy demand. Consequently, the use of marginal lands for, e.g. lignocellulosic energy crops production appears as a valuable strategy to provide biomass for energy purposes while minimizing negative environmental impacts and potentially inducing positive ones.

Currently, there are no high-resolution assessments that considers current and future marginal land availability under the recast Renewable Energy Directive (hereafter referred to as REDII) (Directive (EU), 2018) and related sustainability criteria, site specific biomass potentials and spatially explicit LUC-related environmental impacts for the EU. In WP4 of ADVANCEFUEL, a spatial assessment of the current and future land availability, potentials and environmental impacts of

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lignocellulosic energy crop production on marginal lands in Europe under the REDII land-related sustainability criteria has been carried out. This assessment is demonstrated for 2020, 2030, 2040 and 2050. The land availability for lignocellulosic energy crops was determined for each decade at a spatial resolution of 1 km^2 following a two-step approach; (1) Land use/cover projections for 2020, 2030, 2040 and 2050 were processed to determine the areas that are categorized as marginal under the H2020 project MAGIC[3] definition; and (2) from the marginal land selection, the land that does not meet the RED II sustainability criteria was filtered out and excluded. Further details on the methodology and assumptions behind the results can be found in [Deliverable D4.3 "Regional specific impacts of biomass feedstock sustainability"](). The main results are displayed in Figure 3. Land availability varies from approximately 208 000 km^2 in 2020 to 210 000 km^2 in 2050. The figure depicts that there is little variation in the total amount of available land over time, with the lowest amount projected for 2030 (205 thousand km^2). The largest share of available land corresponds to shrubland followed by open space suitable.

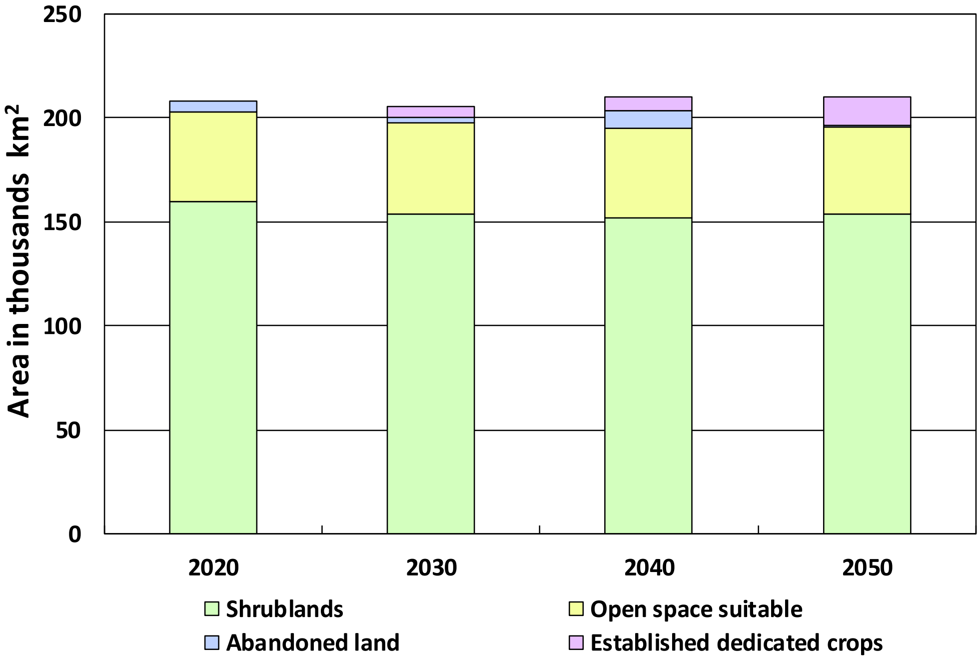

Figure 3: Available marginal land for lignocellulosic energy crops in Europe under REDII sustainability criteria for 2020, 2030, 2040 and 2050

2.1.3. Technical potential of dedicated cropping on marginal land

This sub-section presents the technical potential[4] of dedicated energy crops (woody and grassy) (PJ) on marginal lands. Figure 4 shows the development in biomass potentials for the 8 lignocellulosic energy crops and also the yield efficient total biomass potential (i.e. selecting the highest yielding lignocellulosic energy crop (in MJ/ha) for each location of available land) over time. Biomass potentials are estimated to vary between 1385 PJ/year in 2020 and 1610 PJ/year in 2050; considering for each plot of available land the crop with the highest yield. The highest biomass potentials are projected for Miscanthus, Reed canary grass and Switchgrass, followed

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[3] MAGIC defines marginal lands as: lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity" (Elbersen et al., 2017).

[4] Technical potential: Amount of biomass available under techno-structural conditions. It also takes into account spatial confinements due to other land uses

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by Eucalyptus and Cardoon. The higher potential of these crops is the result of relatively high potential yield as well as relative high suitability for various biophysical conditions.

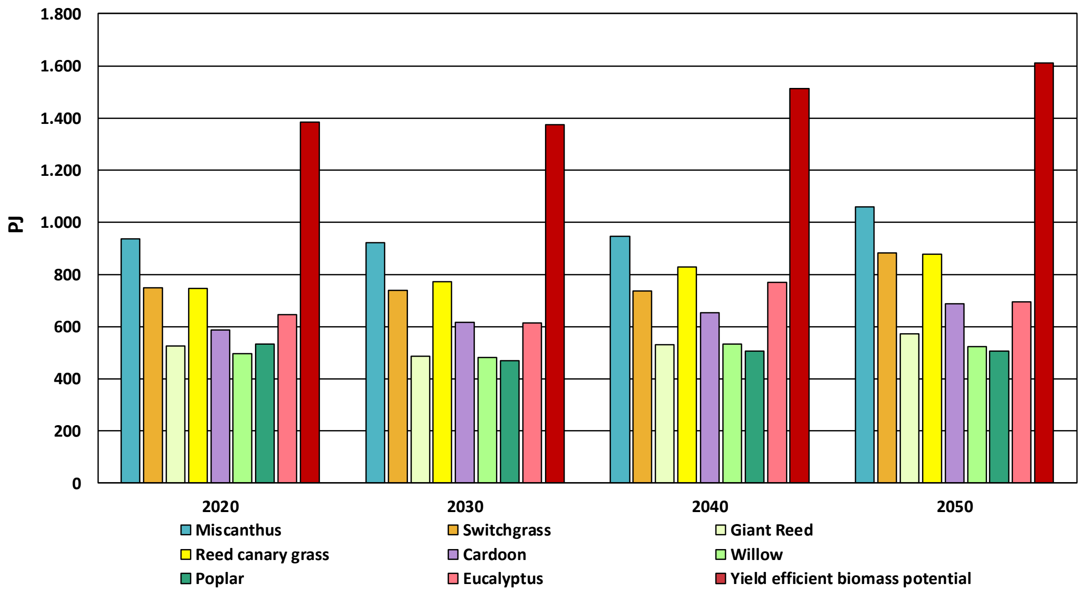

Figure 4: Biomass potentials for each lignocellulosic energy crop (i.e. all available land is allocated to one crop) and yield efficient biomass potential (for each location the crop with highest potential biomass yield is selected) in Europe for 2020, 2030, 2040 and 2050.

2.2. Conversion technologies

2.2.1. Well-to-wheel system analysis

The Well-to-Wheel (WtW) approach is applied for the cases of liquid biofuels, which were analyzed in D3.6 "Efficient, low-risk ramp-up of liquid biomass conversion technologies - from short time to long term". The analysis refers to the overall efficiency of the liquid biofuels value chains. WtW focuses on the energy use and GHG emissions in the production of fuel and its use in the vehicle or engine. Compared to LCA a WtW analysis can have the same system boundaries but does not consider energy or emissions involved in the construction of the facilities of the vehicles, consumption of other materials, water, and end of life disposal. The WtW analysis is divided into parts. The first part is well-to-tank (WtT) assessment, which refers to the energy expended and associated emissions to deliver the produced fuel in the fuel tank. The energy and GHG related impacts associated with this part are related with the different conversion technologies to produce one unit of fuel. The second part is the tank-to-wheel (TtW) assessment, which refers to the final conversion of the fuel in the vehicle.

The indicators used in the Well-to-wheel (WtW) analysis are:

- The WtW total energy [MJinput/MJout] that refers to the total fossil energy used to produce 1 MJout at the crankshaft of the engine[5], and the renewable content of biomass that is expended on lower heating value (LHV) basis.

[5] It includes besides engine's thermal efficiency (combustion-related), also other losses related to drag force (aero dynamics), rolling resistance, transmission losses, electrical systems, kinematic energy lost during braking

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- The total WtW energy [MJeqinput/MJout] is based on the WtT energy expended [MJeq/MJfuel] (i.e. same units as the cumulative energy demand in LCA) and the TtW energy consumption in the engine, [MJfuel/MJout] (i.e. same units as the cumulative energy demand in LCA)
- The WtW GHG emissions represent the total kg of CO_2 equivalent emitted in the process of producing 1 MJout from the engine, and are expressed in [kgCO_2eq/MJout].
- All the previous WtW indicators are expressed on a unit basis to consider specific end uses of the fuel (e.g., in light-duty or heavy duty vehicles, aviation and marine engines, etc.) MJ/(t*km), MJeq/(t*km) and gCO_2eq/(t*km), respectively.

The assessment of all indicators is based on the inventories provided in Appendix A of D3.6 “Efficient, low-risk ramp-up of liquid biomass conversion technologies - from short time to long term”. The WtT (MJeq/MJfuel) indicator was estimated based on the expended energy, which is required to produce 1 MJ fuel. The calculations include all the energy related streams of each inventory such as fuels and net power consumption. As for the feedstock, the energy loss of biomass energy content was taken into account in terms of the difference of the total energy content of the biomass from the total energy content of the energy products (all calculations are based on the LHV values of feedstock and products).

The WtT part of the indicators for total energy [MJeq input/MJout] and kgCO_2eq/MJout are calculated applying the Life Cycle approach, matching the inventory streams with upstream processes which correspond to LCA indicators for fossil Cumulative Energy Demand (CED) and the GWP100a from IPCC 2007 impacts. The values of the WtT part of the indicators Total Energy [MJinput/MJout], Total Energy [MJinput/MJout], and CO_2 emissions [kgCO_2eq/MJout] are provided in Table 4. LCA indicators used for estimations of total energy [MJeq input/MJout] and kgCO_2eq/MJout are provided in Table A 25.

For the analysis and the estimation of the indicators it was assumed that wastewater treatment facilities were not included in the current analysis, apart from ash disposal which was attributed to solid streams. Furthermore, biomass was partially considered as an energy stream in the calculations of the WtW indicator expressed in MJinput/MJfuel produced. The only part of the energy that was included in the analysis is the amount of the expended energy. As for the other two LCA factors for MJeq and kgCO_2eq, the production of corn stover was not available in the Ecoinvent database V.2.2. Thus, the particular kind of biomass was attributed zero impacts for MJeq and kgCO_2eq. For the cases studies that started from corn stover as reported in D3.6, there was not equivalent biomass process inventory for the corn stover that is a by-product of corn production.

The TtW indicator was calculated using the methodology provided in D5.5 for the end use performance of various types of engines in terms or TtW efficiency for fuel consumption and kgCO_2 per energy consumption. This is valid for different types of compression ignition engines for heavy-duty and shipping and jet turbines for aviation. Light-duty sector was divided into four segments: spark ignition engines of regular and compression ignition engines of regular passenger cars, flexi-fuel vehicles and fuel cells. For all above-mentioned technologies, the end-use performance of RESfuels was investigated in terms of fuel consumption and CO_2 emissions. In addition, numerous alternative fuels mixtures were analysed in the context of their compatibility with above-mentioned technologies, based on their property characteristics and their change in energy use and CO_2 emissions.

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The WtT and TtW values are presented in Table 4 and Table 5. The summary of WtW analysis for the various liquid fuels, various concentrations in fuels mixtures and applications in end uses are presented in Table 6. It should be noted that when aggregating the WtT and TtW values to obtain the values of WtW, biogenic carbon is considered as carbon neutral in the WtW calculation (i.e., carrying 0 instead of negative emissions and thus it would appear as positive emissions because of the use of auxiliaries and transportation) then the TtW CO2 emissions of using the fuel (100% biofuel) in the corresponding engine should also be set to 0.

Table 4: Well to Tank (WtT) results using the Life Cycle Approach

Product	Reference	MJinput fuel/ MJfuel	MJeq input fuel/ MJfuel	kg CO_2eq/MJfuel
Methanol	Direct, VTT (Hannula, et al., 2013)	0.76	0.41	0.03
DME	Direct, VTT (Hannula, et al., 2013)	0.62	0.45	0.03
FT(Diesel)	Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	1.04	0.08	0.002
FT(Diesel)	Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	1.55	0.08	0.001
FT(Gasoline)	Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	1.04	0.08	0.00
FT(Gasoline)	Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	1.55	0.08	0.00
Pyrolysis (Diesel)	Fast Pyrolysis, ex situ upgrading NREL & PNNL (Dutta et al., 2015)	0.44	0.07	0.004
Pyrolysis (Gasoline)	Fast Pyrolysis, ex situ upgrading NREL & PNNL (Dutta et al., 2015)	0.44	0.07	0.004
Liquefied bi-oMethane	GoBiGas (Thunman et al., 2019, Capra et al., 2019, Ahlström et al., 2017)	0.41	0.33	0.01
Ethanol 2G	NREL (Humbird et al., 2011) Ethanol fermentation	1.54	0.14	0.01
Jet fuels	Geleynse et al., 2018 Ethanol-to-Jet	1.42	0.84	0.02
n-Butanol	Jang and Choi, 2018 (scaled up) ABE fermentation	2.73	0.07	0.01
iso-Butanol	NREL (Tao et al., 2014) Isobutanol	1.57	0.14	0.001

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Table 5: Tank to Wheel (TtW) results for the selected end use technologies and scenarios

Tank to Wheel	Concentration of biofuel with fossil	End use	MJinput fuel/ MJoutput engine	MJeqinput fuel/ MJoutput engine	gr CO_2eq/ MJoutput engine	MJinput fuel/ Mjfuel	MJeqinput fuel/Mjfuel	g CO_2eq/ MJfuel	MJinput fuel/ton km	MJeqinput fuel/ tn km	gCO_2eq/ tn km
Methanol	100%	Light duty[1]	4.5	4.5	297.7	1	1	65.7	1.3	1.3	86.3
DME	100%	Heavy duty[2]	4.3	4.3	286.0	1	1	67.0	1.1	1.1	73.5
Ethanol	100%	Light duty	5.0	5.0	358.9	1	1	71.2	1.5	1.5	104.0
Jet fuels	100%	Aviation	3.2	3.2	224.2	1	1	70.3	12.4	12.4	871.6
Iso butanol	100%	Light duty	5.3	5.3	375.4	1	1	70.9	1.5	1.5	108.8
FT Diesel	100%	Heavy duty	3.9	3.9	278.4	1	1	70.5	1.0	1.0	71.6
MGO (FT Diesel)	100%	Marine[3]	2.4	2.4	177.3	1	1	74.3	0.3	0.3	30.0
MGO (Pyrolysis Diesel)	100%	Marine	2.4	2.4	177.3	1	1	74.3	0.3	0.3	30.0
Ethanol	10% mix with Gasoline[4]	Light duty	5.0	5.0	379.1	1	1	75.3	1.5	1.5	109.9
Jet fuels	50% mix with fossil kerosene[4]	Aviation3	3.2	3.2	227.9	1	1	71.4	13.6	13.6	928.1

1 LDV includes the average cargo (1 driver)

2 For HDV, it represents the average bus without passengers (no cargo). So for HDV, the total fuel consumption is slightly higher, approximately extra 2L/100km or 5% for 1000 kg inertia. However, specific fuel consumption expressed in g/kWh is lower: roughly 10% difference between empty and fully loaded bus.

3 For marine applications, average cargo transported by Ro-ro > 5 000 t and for aviation Boeing 737 with average cargo have been assumed.

4 For the case of mixture 10% mix with Gasoline and 50% mix with fossil kerosene the impacts of Petrol, unleaded, at refinery/RER S and of kerosene, at refinery, RER have been used, respectively

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Table 6: Scenarios of WtW estimations for various liquid fuel, mixtures and end use applications

Well to Wheel	Concentration with fossil	End use	MJinput fuel/MJoutput engine	MJeqinput fuel/ MJoutput engine	gr CO_2eq/ MJoutput engine	MJinput fuel/Mjfuel	MJeqinput fuel/MJfuel	g CO_2eq/ MJfuel	MJinput fuel/ton km	MJeqinput fuel/tn km	gr CO_2eq/tn km
Methanol	100%	Light duty	3.44	1.87	139.88	0.76	0.41	30.89	1.00	0.54	40.54
DME	100%	Heavy duty	2.63	1.92	140.94	0.62	0.45	33.03	0.01	0.00	36.24
Ethanol	100%	Light duty	7.75	0.70	44.13	1.54	0.14	8.75	2.25	0.20	45.14
Jet fuels	100%	Aviation	4.54	2.69	77.83	1.42	0.84	24.39	17.64	10.47	302.51
Iso butanol	100%	Light duty	8.31	0.77	30.84	2.73	0.07	5.82	4.20	0.11	8.94
FT Diesel	100%	Heavy duty	4.12	0.33	6.06	1.04	0.08	1.53	0.01	0.00	1.56
MGO (FT Diesel)	100%	Marine	2.49	0.20	3.66	1.04	0.08	1.53	0.31	0.02	0.46
MGO (Pyrolysis Diesel)	100%	Marine	1.06	0.16	8.93	0.44	0.07	3.74	0.13	0.02	1.11
Ethanol	10% mix with Gasoline	Light duty	1.63	1.50	450.73	1.23	1.13	14.23	1.79	1.65	45.06
Jet fuels	50% mix with fossil kerosene	Aviation	4.10	3.18	283.48	1.29	1.00	17.41	16.70	12.95	226.10

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2.2.2. CAPEX required to increase TRL of selected technologies

The focus in ADVANCEFUEL has been on the biofuel production technologies that have a TRL of 7-8 (i.e. system prototype demonstration and/or complete and qualified). In this regard, two steps of TRL increase are considered to calculate the CAPEX need for TRL level increase:

- TRL 8-9: technology is proven in operational environment at a sufficiently large scale for competitive production, even if this is only for a small number of plants, and possibly under specific favourable conditions (e.g. favourable logistics, regional policies, etc.). A TRL increase from 7-8 to 8-9 is defined by a metric based on the cumulative installed capacity (CIC), namely one order of magnitude bigger installed capacity compared to the one estimated for a first of a kind plant.
- TRL 9, i.e. mature technology: technology is competitive under various market conditions and has a non-negligible share in the market, which in the ANDVANCEFUEL scenarios vary from a small percentage, e.g. 1-3%, to a percentage that would potentially match a target of 20% share of the transportation biofuel compared to the overall production of the corresponding fuel.

CAPEX requirements to increase the TRL are calculated based on two scenarios. Both scenarios investigate the CAPEX needed to start from the assumed 1st of a kind to fully commercial production. The first scenario, herein mentioned as Scenario A, assumes an annual growth rate of the installed capacity (CAGR) that is marginally higher than the growth rate of the corresponding market of the fuel. Thus, it does not lead to a significant share of the market in short- to mid-term and the corresponding "greening" achieved is not enough to satisfy environmental targets for the time horizon considered in the ADVANCEFUEL project (i.e., 2030-2050). Although an increase of installed capacity by one order of magnitude may still be achieved in the considered time horizon with this approach, not being able to cover a significant share of the market may mean that a technology does not fully satisfy the criterion of competitive manufacturing, at least not for diversified manufacturing conditions in EU and/or around the globe. This scenario is constructed to calculate the CAPEX needs to move the technology from first of a kind commercial to a commercial plant (from 7-8 to 8-9).

Alternatively, Scenario B assumes an annual growth of installed capacity that is considerably bigger than the growth rate of the corresponding market of the fuel to an extent that it can satisfy targeted shares of the market in the considered time horizon. Scenario B estimates the CAGR of the biobased fuel in order to achieve a 20% contribution in the production of the respective fossil based fuel in the end of the time horizon of the ADVANCEFUEL project. This corresponds to European Commission scenarios that refer to the contribution of liquid biofuels in the future energy consumption in 2050 within a range of 13%-24% (EC, 2018).

It is important to clarify that the calculation of the specific investment cost of each process component is based on individually estimated CAGR parameters. For instance, the production of liquified biogas is divided into a methanation and a liquefaction technology step, the liquefaction step reducing its specific investment costs based on the overall growth rate of liquefied methane market (i.e. fossil and non-fossil), while the biomass based methanation step is characterized by annual growth rates as defined in Scenarios A and B. However, CIC for the corresponding technological pathway for the production of the RESFuels is determined by the CAGR of the biomass-based process step. This means that the CAPEX for the development of the RESFuels are based on the annual growth of the development of the biomass-based process step of the technological pathway but the specific investment cost of the technological pathway

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is also influenced by CAGR of process steps that are not specific to the biomass-based production, which may be different from those in scenarios A and B. Detailed methodology can be found in Deliverable D3.6 "Efficient, low risk ramp-up of liquid biomass conversion technologies - from short time to long term" (http://www.advancefuel.eu/en/publications).

Table 7 presents the resulting cumulative CAPEX needed for both scenarios A and B, which are differentiated according to the appropriate selection of CAGR to achieve increase of CAPEX by one order of magnitude and to reach a maturity level 9 respectively, are summarized.

Table 7: Cumulative CAPEX (MEuro) for Scenarios A and B

Bio-fuels	Scenario A Cumulative Capex (Meuro)		Scenario B Cumulative Capex (Meuro)	
	Increase of CIC by one order of magnitude	TRL 9/ maturity level	Increase of CIC by one order of magnitude	TRL 9/ maturity level
Bio-methane	2,1	2,1	3,0	429,0
Methanol	2,0 - 3,8	5,8 - 11,9	1,9 - 3,6	36,0 - 80,3
DME	1,8 - 4,1	5,4 - 12,4	1,8 - 3,9	7,0 - 16,1
FT liquids	3,0 - 4,9	9,0 - 14,9	3,2 - 5,3	222,2 - 398,3
Ethanol-Gasification based	3,9 - 5,0	11,7 - 15,5	4,3 - 5,6	178,9 - 230,3
Pyrolysis based liquids (diesel, gasoline)	1,6 - 3,4	5,6 - 10,5	1,7 - 3,5	442,6 - 918,7
Ethanol biochemical based	1,1	1,1	3,2	242,9
Jet fuels	1,7	1,7	4,6	1032,0
n-Butanol	4,3	4,31	7,9	384,8
Iso-Butanol	2202	2202	5,2	245,3

2.2.3. Greening of fossil fuel infrastructure and CAPEX and OPEX reductions

Given the importance of introducing policies to mitigate climate, the ADVANCEDFUEL project has assessed opportunities for the greening of fossil fuel infrastructure and its associated systems. Using the existing energy infrastructure for green fuels may offer near term and low risk options for emission mitigation. Three concepts in which RESfuel production can be integrated into existing fossil fuel production assets that result in CAPEX and OPEX cost reduction (%) are included in this KPI presentation; namely, (1) incorporation of bio-oil feedstock into existing oil refineries; (2) co-location of 1st and 2nd generation ethanol; and (3) Fischer-Tropsch synthesis co-location.

(1) Incorporation of bio-oil feedstock into existing oil refineries

(Fast) pyrolysis technology converts biomass into a liquid called pyrolysis oil, with much higher energy density. Pyrolysis oil can be further processed to be used in the transport sector. This further processing includes reducing the oxygen content and producing hydrocarbons suitable for internal combustion engines. This can be done in a dedicated, stand-alone biorefinery. This pyrolysis oil can also be refined along with fossil oil in existing refineries. Co-processing pyrolysis oil in an existing refinery would result in reduced CAPEX and OPEX. The most investigated co-processing approach is the use of pyrolysis oil with vacuum gas oil in a fluid catalytic cracking (FCC). Co-processing pyrolysis oil up to 5 wt% has beenmentioned to have limited or no impact on yield of the products in an existing refinery [10]. The indicative production cost of biofuels for co-processing compared to a stand-alone biorefinery based on pyrolysis is presented in Table 8.

Table 8: Cost of production in co-processing and stand-alone cases (ref: IEA, 2020[11])

Biofuel type production costs	Feedstock price EUR/MWh	Production cost range EUR/MWh	Production cost range EUR/GJ
Pyrolysis bio-oil co-processing	10-20	79-139	14-27
Pyrolysis bio-oil standtand-alone plant	10-20	82-127	23-33

The literature indicates the CAPEX reduction potential to be in the order of 23-51% when the co-processing in an existing refinery is compared with the stand-alone biorefinery case (IEA, 2020; Jones et al. 2009).

(2) Co-location of 1st and 2nd generation ethanol

Regarding this option, the production cost benefits of 2nd generation bioethanol integration into 1st generation sites have been identified in the literature in a range of 5-10%, compared to a stand-alone greenfield plant (IEA-RETD, 2015). The same report gives an example based on the experience of a case in Brazil from commercial 2G sugarcane bioethanol plants demonstrating that the cost of building a 2G plant co-located with a 1G plant is much lower than building a 2G plant from scratch: "The stand-alone Granbio 2G plant in Alagoas (cluster model, in the middle of a sugarcane region) required an investment of 237 M€ for an annual production capacity of 82 Ml. The investment in the Raizen 2G plant, co-located with the Costa Pinto mill in Piracicaba, was 56 M€ for a production capacity of 40 Ml".

This results in an investment of 2.9 €/l for a stand-alone plant and 1.4 €/l for co-located sugarcane ethanol plant. Even though, these numbers correspond to different (double) production capacities, they can be used as a reference for comparing the capital cost per litre involved in producing the fuel in a stand-alone plant andin aco-located plant . This difference corresponds to a 52% cost reduction potential of co-location of conversion processes

A more recent study from IEA (2020) indicates integrated cellulosic ethanol production with first generation ethanol plants can provide advantages. These advantages relate to the use of materials already collected and shared by some site facilities. The use of corn kernel fibre, a by-product in the 1G ethanol production from corn, provides one example. Another example is the integration of ethanol to sugar bagasse with sugar to ethanol production. With zero feedstock costs and the benefits associated with being integrated with a large-scale corn to ethanol plant, these costs are around 50% or less than those associated with a stand-alone plant.

(3) FT synthesis – Co-location

[10] https://www.kivi.nl/uploads/media/5cee875885aff/PRC%2019%20Europe%20-%20TechnipFMC-BTL%20-%20Advanced%20Biofuels%20from%20FPBO.pdf
[11] https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf

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Co-processing Fischer-Tropsch waxes at existing crude oil refineries is another potential innovation opportunity. However, extremely limited volumes of Fischer-Tropsch waxes from biomass are available so the extent of tests conducted so far is unclear. This opportunity also depends on various factors such as logistics, locations and the availability of existing refineries to co-process these streams. Plant CAPEX savings could amount to 15% but the use of third party equipment would probably come with additional cost (IRENA, 2016).

2.3. Sustainability and certification

2.3.1. Additional sustainability criteria

Sustainability criteria and verification through national legislations and voluntary certification schemes are important tools to ensure sustainable supply along the supply chain and bioenergy development in the European Union. REDII sets the framework for renewable energy support for the period 2021-2030 with updated and new sustainability criteria for bioenergy compared to the REDI. These criteria have been compared and contrasted with national legislation and voluntary schemes and with the main sustainability concerns raised by stakeholders and in recent literature in the ADVANCEFUEL project. Sustainability criteria defined in REDII (and REDI) are fundamental but not strict enough to ensure a full sustainability compliance. An establishment of additional and comprehensive sustainability requirements at an EU level is important to avoid sustainability risks.

Table 9 provides an overview of the sustainability requirements covered in REDII (indicated by '√') and recommendations from the ADVANCEFUEL project. In the recommendations column in Table 9, 'more stringent' refers to that the sustainability criteria in REDII should be made more stringent'; 'more comprehensive' means that more sectors and/or feedstocks should be included in the REDII sustainability criteria; and finally "additional' means that that the relevant sustainability categories, currently not included in the REDII, should be included. In particular, assessment carried out in the ADVANCEFUEL project shows that the REDII's sustainability criteria are deficient in avoiding some risks of unsustainable forest management, lack stringent protection of air, soil and water resources, and also lack socio-economic criteria which are considered relevant for biomass feedstocks imported to the EU. Transposition of the REDII criteria into national legislation and further implementation of REDII requires detailed guidance on sustainability criteria and their indicators.

Table 9: Sustainability criteria to assure bioenergy sustainability based on the most urgent concerns.

	REDII			Recommendations
Sustainability categories	**Waste and residues**	**Agricultural biomass**	**Forest biomass**	
Environmental criteria:				
- greenhouse gas emissions saving	√	√	√	--
- sustainable forest management			√	More stringent
- carbon stock preservation	√	√	√	More stringent
- biodiversity conservation		√	√	More stringent
- protection of air, soil and water	√	√	√	More comprehensive
- prevention of ILUC risks		√	√	--
Environmental category:				
- land use, land use change and forestry			√	--
Verification of sustainability compliance:				
- chain of custody	√	√	√	-
- risk based approach			√	*Additional*

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Socio-economic criteria: binding to imported feedstocks				
- labour rights	√	√	√	*Additional*
- land rights		√	√	*Additional*
- food security		√	√	*Additional*
- resource efficiency	a monitoring of efficient biomass use		*Additional*	

Based on a review of sustainability concerns of bioenergy use, the sustainability criteria defined in the REDII, and the sustainability criteria implemented in voluntary schemes and national legislations, the ADVANCEFUEL project finds, among others, that

- Socio-economic criteria are excluded in the RED II, but they are regarded as important for ensuring credible sustainability compliance. For comparison, some common socio-economic criteria for biomass feedstocks, including labour rights, land rights, and food security, have been implemented in a number of voluntary schemes.
- The REDII applies a risk-based approach (RBA) is for forest biomass to assess evidence of compliance with SFM and carbon stock criteria when harvesting criteria and LULUCF criteria are not addressed in national regulations or laws in the country of biomass supply. In theory, RBA could be used for agricultural biomass but since it has not yet been implemented for this biomass type, RBA was considered effective only for forest biomass for which it is already widely used in voluntary schemes, such as FSC. A RBA could be wider applied to regions that comply with the risk criteria in the RED II, but where certification is not available or certification or verification bodies are not present. Socio-economic criteria were considered important, particularly for feedstocks mobilised in sourcing regions where local laws and rights are not implemented or not stringent enough to assure sustainability compliance.

Further details can be found in Deliverable D4.2 "Sustainability criteria & certification for lignocellulosic biorefineries".

2.3.2. Harmonisation of voluntary schemes focusing on RESfuels

Sustainability compliance of biofuels and bioliquids needs to be verified either through national legislation or through voluntary schemes that are recognised by the European Commission (EC). Divergent sustainability approaches are used by lignocellulosic biorefineries processing products of various bioeconomy sectors. Given this situation, there is a need for a harmonized sustainability framework. To this purpose, the ADVANCEFUEL project has identified harmonisation possibilities and trade-offs to demonstrate the sustainability compliance of multi-output biorefineries. These are presented in Table 10 below.

Harmonisation is possible for a number of sustainability criteria and requirements: protection of high biodiversity; land-use, land-use change and forestry; sustainable forest management; risk-based approach; chain of custody and most elements of social and economic criteria. These sustainability criteria are commonly used by the bioenergy sector and they are relevant for lignocellulosic biorefineries as well. Other sustainability criteria which cannot be harmonised but important to be kept separately: chemical and toxicity which is more relevant for lignocellulosic biorefineries but not for bioenergy; ILUC is only relevant for bioenergy production but less appropriate for lignocellulosic biorefineries which process feedstocks of no competition with food.

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Table 10: Focused topics and indication for harmonization and trade-offs

	Indicators	Harmonisation possibilities	Harmonisation level	Trade-offs
PRODUCTION CAPACITY:		N		
ENVIRONMENTAL PERFORMANCE:				
Reduction of GHG emissions (Mitigation of climate change)	*Calculation method*	N		Y
	Allocation	N		Y
	Data collection	Y	Medium	
Biodiversity and ecosystem conservation	*Protection of high biodiversity*	Y	Low	
	Conservation of ecosystem	N		
LUC measurements	*LUC measurement*	N		
	ILUC measurement	N		
LULUCF requirement	*- LULUCF*	Y	High	
	- Carbon stock preservation	Y	Low	
Sustainable forest management	*- Legalisation*	Y	Medium	
	- Forest productivity & well-functioning	Y	Medium	
Resource protection	*- Monitoring and quality control of air, soil and water*	N		Y
Chemical use and toxicity		N		Y
Risk based approach		Y	Low	
Chain of custody	*- Mass balance*	Y	Medium	
	- Physical segregation	Y	Medium	
ECONOMIC PERFORMANCE: harmonisation assessed at scheme level				
Job creation		Y	Medium	
Cascading use of biomass/ Resource efficiency		Y	Low	
SOCIAL PERFORMANCE: harmonisation assessed at scheme level				
Worker rights		Y	High	
Human health impacts		Y	Medium	
Compliance with local law rights & international treaties		Y	Medium	

2.4. End use

2.4.1. Good practices in Europe and outside

For the purposes of this KPI, a good practice (FAO, 2014) is defined as '*a practice that has been proven to work well, produce good results and is designed to achieve some deliberative target*'. (Bretschneider, 2004). The policy related good practices analysed in ADVANCEFUEL refer to renewable fuel programs and strategies that have high performance in the following assets i) include a mix of policy mechanisms (regulatory, financing and information provision) which are integrated across the value chain (feedstock production, conversion, end use), ii) set ambitious targets that evolve with market development and address sustainability and iii) sustain and continuously improve a strong network of key stakeholders from policy and industry.

Table 11 below provides an overview of the main lessons learnt so far from policy formation in the field of advanced biofuels. Further details can be found in Deliverable D5.2 "Good practices along the RESfuels value chain".

Table 11: Lessons learnt, examples of good practice policies and barriers.

Lessons	Key asset(s)	Degree of transferability	Example of good practice policies	Barriers which lessons learned helps to remove
Strategy and vision should be carefully discussed and analysed with the local community and industrial actors who are likely to invest in advanced biofuels	Stakeholders	**High** since this is one of the first steps in the communication of policy makers and industries in order to agree on the focus of the strategy and introduce relevant policy mechanisms	**Denmark** has a €67 million plan for sustainable transportation development between 2020 and 2024 and a long-term strategy in place where biofuels will be mainly used in heavy-duty vehicles and aviation, this sends a positive message to the market players and security.	High capital costs, high risk investment and lack of long-term and unstable policy environment makes it difficult for the investors to invest. Difficulty to access the existing support schemes.

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Quota as a successful measure for increasing the overall biofuels share in transport	Policy mix Target setting	**High** since this is one of the most applied mechanism in the biofuels sector and it has led to high market uptake	Obligatory biofuel quota system with tradable or non-tradable green certificates. Germany, Finland, Denmark, Italy, Slovakia, Netherlands and the UK.	Lack of dedicated policy support to promote biofuel share among all renewable sources.
Policy must account for the local context under which the measures would be best suited and fit to local needs and infrastructures	Policy mix Target setting	**Moderate** as local context is subject to many socio-political forces through time so careful planning and monitoring systems must be in place to ensure the successful longevity of a certain sectorial policy.	**UK** started a 'development fuels' mandate to promote the feedstocks which can contribute in second generation advanced biofuels. **Slovakia** has legislative measures to promote the woody biomass resources from both agricultural and forestry sector. **Germany** expired their double counting but increased their GHG mandate in 2014 to make more competitive environment for advanced biofuels.	Lack of harmonised regulations on sustainable farming practices for residual biomass, dedicated energy crops and forest management practices Lack of harmonised regulations throughout EU concerning fuel taxes, biofuel tax reductions, obligation systems, RESFuel blends and fuel standards
Taxation of fossil fuels is considered a strong indirect support measure for the uptake of biofuels	Policy mix	**Moderate** as it depends on the overall taxation system and whether there is already a suitable mechanism from which advanced biofuels can be exempted	Energy and CO_2 tax reduction mechanisms in place to subsidise the advanced biofuels compared to fossil fuels. SE, SK, DK, NL, FI and DE.	Lack of policy mechanisms to make RES more competitive compared to the fossil fuels.
Policy should ensure long term consistency and high clarity of strategic messages	Policy mix Target setting	**Moderate** as long term policies are quite hard to implement and maintain; they require strong commitment from governments, regional authorities and administrative bodies.	All countries under study here have target set for the share of RES in transport sector in line with EU RES-T target. Some of the countries like NL, It, DE, DK, SK have national mandate for advanced fuel share by 2020 and 2030	Lack of harmonised policy support with dedicated targets for each sector.
Secure business commitment from industries	Stakeholders	**Moderate** as long term commitment requires economic and political stability, trust from investors and funding bodies as well as good success stories with high replication potential.	**Finland** and **Sweden** have a long collaboration with their advanced biofuel industries.	Lack of policy support to provide stability and security for the industry.

2.4.2. Fuel performance in comparison to fossil diesel and gasoline

The KPIs in this section concern the fuel performance of RESfuels in comparison with fossil gasoline and diesel in light-duty vehicles (LDV) and in comparison with fossil diesel in heavy-duty vehicles. Performance in both cases refers to fuel consumption measured in l/100km over standardized driving cycle like NEDC or Braunschweig.

(1) Fuel performance in light-duty vehicles in comparison to fossil gasoline and diesel

ADVANCEFUEL (WP5) has investigated the impact of alternative fuel properties on light-duty vehicle engine performance and greenhouse gases emissions. Two models were developed,

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one for spark ignition (SI) and one for compression ignition (CI) passenger car engines, that represent the impact of fuel properties on engine performance in a uniform and reliable way but also with very high accuracy (coefficients of determination over 0.95) and from the end-user point of view. The inputs of the model are represented by fuel properties, whereas output by fuel consumption (FC). The parameters are represented as percentage changes relative to standard fossil fuel, which is gasoline for spark ignition engines and diesel for compression ignition engines (further details on the structure of the modelling problem, methodology and assumption can be found in [Deliverable D5.5 "End-use performance of alternative fuels in various transport modes"](). Results are depicted in Figure 5 for spark ignition engines (left) and compression ignition engines (right).

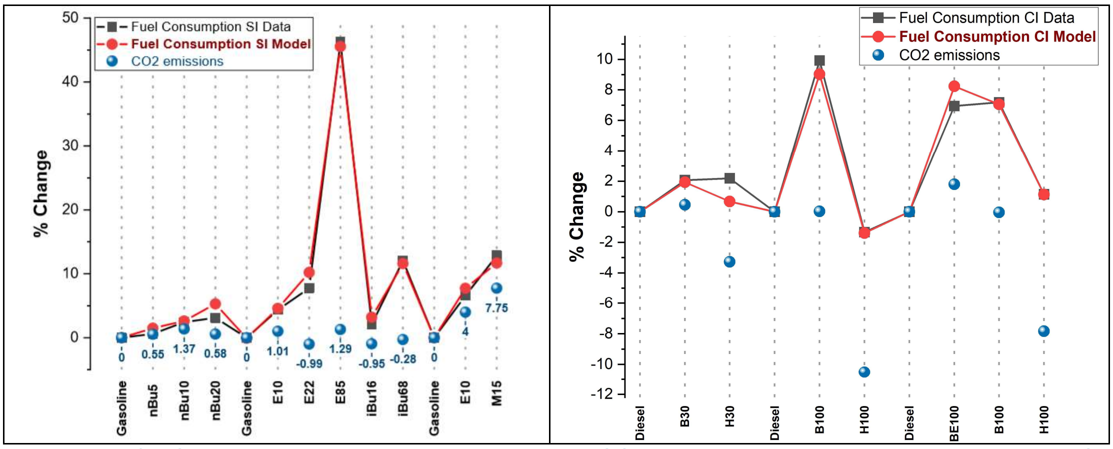

*Figure 5: (**left**): SI LDV modeling results and validation. CO_2 emissions are calculated based on the FC and carbon balance, (**right**): CI LDV modeling results and validation. CO_2 emissions are calculated based on the FC and carbon balance. Source; ADVANCEFUEL, D.5.5.*

(1) Fuel performance in heavy-duty vehicles

Majority of heavy-duty engines in the market are compression-ignition with various displacement depending on the vehicle category (buses, medium or heavy-duty trucks, etc.). Therefore, combustion process, engine operation and fuels are similar like in CI LDV passenger car segment. In this work, heavy-duty engines were analysed on the example of bus engines, which were tested over Braunschweig driving cycle. Fuel selection and modelling were executed accordingly.

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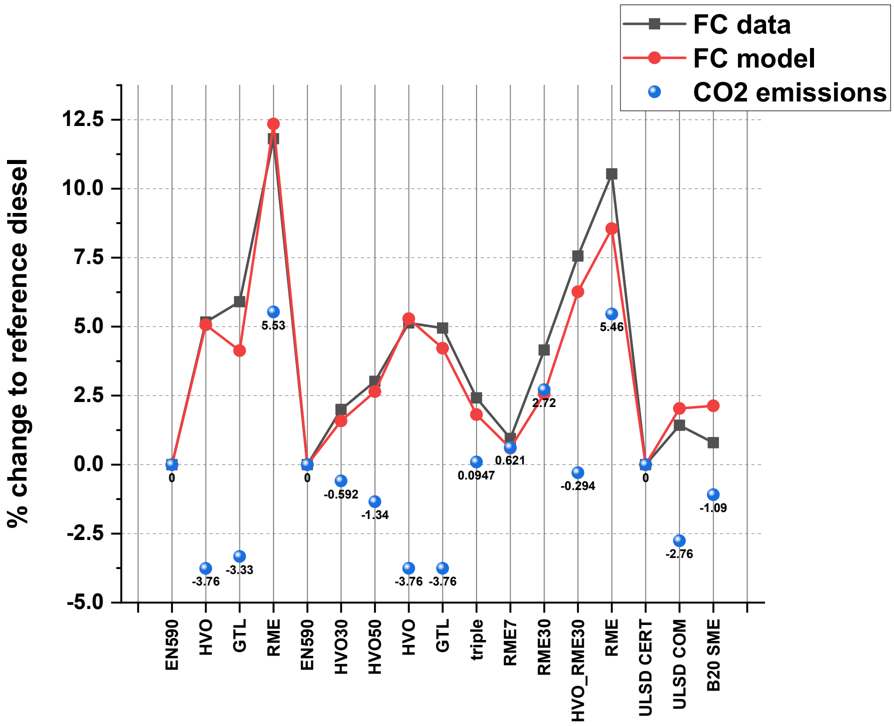

Figure 6: CI HDV modeling results and validation. Source: ADVANCEFUEL, Deliverable D.5.5.

As depicted in Figure 6, the most prominent solutions in heavy-duty trucks are foreseen in drop-in diesel-like fuels. Other promising options require dedicated solutions, such as ethanol compression ignition engines (ED95), DME powertrains or gas engines (using biogas). In the ADVANCEFUEL project, drop-in diesel fuels and ethanol are considered with special attention. For paraffinic diesel fuels like BTL or HVO, the same fuel property classification applies as in LDV fleet. However, ethanol requires dedicated engine technology resulting in very high compression ratio. In addition to ethanol, ED95 fuel contains roughly 5% of strong ignition improvers to enable operation according to CI combustion concept. There is only one engine manufacturer, Scania, who commercialized this technology that has not fully succeeded so far. This is contrary to HVO, which has gained higher market acceptance due to its fully drop-in characteristics. Owing to similar fuel properties characteristic, the same is expected for BTL fuel produced from lignocellulosic feedstock.

2.5. Integrated analysis

2.5.1. Gross employment effect

The employment effects of advanced biofuels are calculated based on the methodology developed by the Energy Centre of the Netherlands (ECN)[12] for the EurObserv'ER project[13]. The methodology uses a 'follow-the-money' approach, in which revenue streams generated from investment and exploitation of advanced fuel production capacity are attributed to different economic sectors. The employment effects are estimated through the share of revenues that are used to compensate employees in these sectors, based on economic statistics for these sectors.

[12] As of April 2018 ECN and TNO merged. TNO is currently member of the EurObserv'ER consortium.

[13] For the latest results see the 19th annual overview barometer on the EurObserv'ER project website: https://www.eurobserv-er.org/19th-annual-overview-barometer/. See ECN (2017) for an overview of the methodology used in the EurObserv'ER project.

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All calculations are performed at EU member state level and it is assumed that most activities use local workers. The employment conversion module, which estimates employment effects based on revenues, includes a correction factor based on differences in labour costs per member state (ECN, 2017). Only for equipment it is assumed that member states can trade with one another and with non-EU countries. Further details of the methodology and the results can be found in Deliverable D6.3. "Socio-economic assessment of advanced biofuels" (http://www.advancefuel.eu/en/publications).

Table 12: Estimated employment effects from advanced biofuels compared to literature

	Advanced ethanol	Advanced renewable diesel	Fast Pyrolysis
ADVANCEFUEL project calculations			
Construction-related employment	22-28 job years per MW	10-11 job years per MW	9-12 job years per MW
O&M-related employment	138-566 FTE per PJ	46-224 FTE per PJ	268-300 FTE per PJ
Zhang et al. (2016) for comparison			
Construction-related employment	27-180 job years per MW	37-275 job years per MW	25-160 job years per MW
O&M-related employment	111-623 FTE per PJ	179-988 FTE per PJ	108-629 FTE per PJ

2.5.2. GHG emission reduction effects

At the time of completing this report, the ADVANCEFUEL project results concerning this KPI were not finalised. When ready, the results are available in Deliverable 4.5 "Assessment of environmental (energy, GHG) and socio-economic performance of RESfuel supply chains" (http://www.advancefuel.eu/en/publications).

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3. Market progress of RESfuels

3.1. Advanced biofuels

3.1.1. Lignocellulosic ethanol plants

The total operational capacity of lignocellulosic ethanol production on a global scale has stagnated in recent years, and remains around 300 kt/a. Figure 6 depicts the share of total operational capacity according to different regions in the world. Brazil retains its position as a global leader in installed production capacity, followed by the US, China and Canada. Europe currently has the lowest share of installed operational capacity. Notably, available data indicates that nameplate capacities of the operational plants are far from reached (Nyström, 2019).

At the end of 2019, there were globally 10 operational plants. A distinction is made between commercial-scale and first-of-a-kind (FOAK) demonstration plants. The majority of these commercial-scale and first-of-a-kind (FOAK) demonstration plants are based on fermentation technology. There is at present only one operational FOAK demonstration plant in Europe, termed ChemCell Ethanol from Borregaard Industries AS in Norway. This plant has been producing lignocellulosic ethanol with an installed capacity of 15.8 kt/a, using sulphite spent liquor from spruce wood pulping since 1938.

FOAK demonstration plants play a vital role in "de-risking" technologies. They normally provide a technological performance guarantee in scaling-up and validating the conversion process performance pathways. They also verify how the CAPEX and OPEX private-sector financing can be secured.

The 'installed capacity' shares presented in Figure 7 are based on currently known operational plants. At present, Brazil has the largest share of installed capacity. Notably, since the first ADVANCEFUEL monitoring report, the US share has dropped from 25% to 1%. This is due to the fact that, in November 2019, it was announced that the US-based POET-DSM plant would pause its production of lignocellulosic biofuels and instead shift its focus towards R&D efforts on improving operational efficiency[14]. Before pausing its production facility, the POET-DSM plant had the largest capacity of all operational plants worldwide, with a capacity of 75 kt/a.

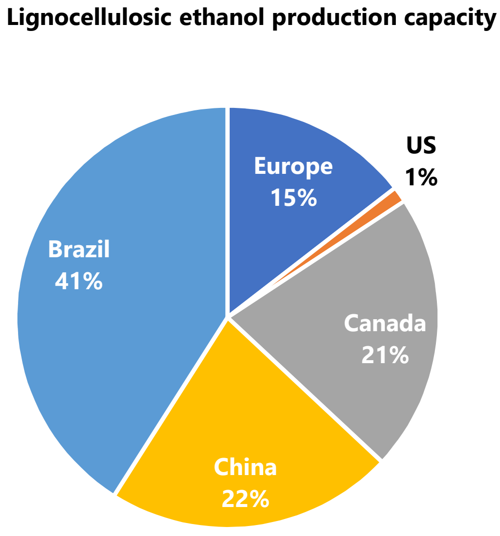

Figure 7: Lignocellulosic ethanol production capacity (Based on data from IEA Bioenergy Task 39 database)

[14] https://www.greencarcongress.com/2019/11/20191124-poetdsm.html. Accessed: 26-01-2020.

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Currently, there are two production facilities under construction: one in Romania (50 kt in 2021) and the other in Austria (30 kt in 2020). Additionally, capacity expansions have been announced in Finland (40 kt in 2024and 65 kt in 2021), Slovakia (50 kt), Poland (25 kt) Croatia (55 kt), Spain (25 kt in 2020), and outside the EU, in Norway (two 40 kt plants in 2024). It is anticipated that the EU capacity for cellulosic ethanol production could possibly increase to about 500 kt when all of the facilities (idle, under construction and the planned) become operational. Annex 1 provides an update list of all lignocellulosic plants.

Difficult market conditions coupled with high costs have forced the closure of several lignocellulosic ethanol plants. Several FOAK plants have in recent years been made idle (see Annex 1), such as the Mossi Ghisolfi Group's Beta Renewable plant in Crescentino, Italy which initially began its operation in 2013 as the world's first commercial-scale cellulosic ethanol facility. In the first four years, the operators dealt with extensive pre-treatment issues[15] and had to reconstruct its processing procedures. After having to downgrade its annual capacity from 75 to 50 million litres, it finally closed in 2017 (ICCT, 2018). The plant was shut down due its parent company having to file for bankruptcy. In 2018, Eni's chemical subsidiary Versalis acquired the Mossi Ghisolfi Group's green portfolio and it is currently in the process of defining an action plan to restart the activities of the Crescentino plant[16]. After two years of a slow ramp-up, DuPont sold its first large, 110-million litre (83 kt/a), facility in Nevada, Iowa and exited the business in 2018[17]. Eight additional demonstration plants which were previously operational are now idle. The majority of these are located in Europe and the US.

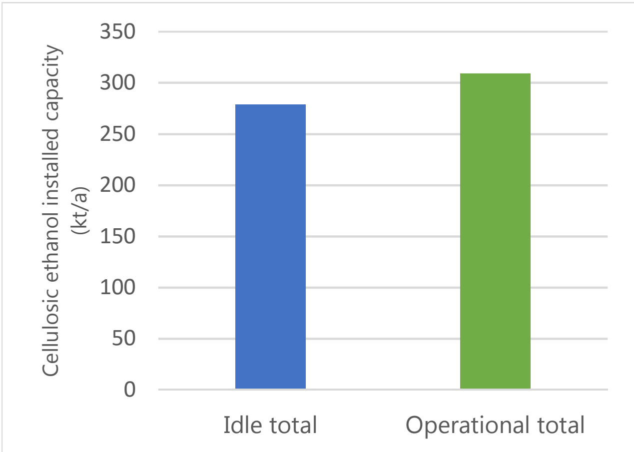

Figure 8: Operational vs idle cellulosic ethanol plants, globally (kt/a). Source: Own figure, data taken from IEA Bioenergy Task 39 database.

Figure 8 compares the current total operation plant production capacity with the total idle production capacity. The idle plant capacity is quite large, close to 90% of the total operational capacity. If idle plants were to become operational again, the total production capacity would increase to a potential 600 kt/a.

3.1.2. Lignocellulosic diesel plants and the gasification route

Production of biodiesel using lignocellulosic feedstocks remains slim in both Europe and other countries. There are only two biodiesel plants in Northern Europe (Finland and Sweden), using tall oil[18], as the main feedstock. The total installed capacity of these two has been reported to be around 120 kt/a.

15 Particularly due to rocks and dirt entering the pre-treatment system along with the feedstock
16 https://www.eni.com/en-IT/media/press-release/2018/10/versalis-closing-of-acquisition-of-the-bio-run-activities-of-mossi-ghisolfi.html
17 http://biomassmagazine.com/articles/15743/verbio-to-buy-dupont-cellulosic-ethanol-plant-convert-it-to-rng
18 Tall oil is a liquid by-product of wood pulp production using the kraft process.

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Thermochemical conversion (gasification and pyrolysis) of lignocellulosic feedstocks to fuel is a promising pathway that can produce different fuels such as methane (SNG), methanol, DME, FT liquids (diesel, gasoline and jet fractions) and hydrogen. There are two operational demonstration plants that produce Fischer Tropsch (FT) liquids but the total capacity is very small (<2 t/a). These plants are in the US (Thermo Chem Recovery International (TRI) and West Biofuels). Other operational gasification plants mainly, produce ethanol (i.e. Enerkem in the US uses municipal solid waste (MSW) as feedstock) dimethyl ether (DME) (Bioliq, Karlsruhe Institute of Technology (KIT) in Germany) and SNG (Surrey Biofuel in Canada).

Many gasification-based plants in Europe are currently idle, such as BioMCN[19]-Netherland, BioSNG Guessing in Austria, GoBiGas in Sweden. There are two plants under construction. One of them is in the United Kingdom (UK) with an SNG production capacity of 1.5 kt and the other one in France that aim to produce FT liquids. There are also a number of gasification facilities that are planned to be constructed in the coming period. Three of them aim to produce methanol (Netherlands, Spain and Sweden), two of them will produce SNG (Sweden and Netherlands) and there is one gasification facility planned to produce jet fuels in the UK.

3.2. Other renewable liquid fuels

Other renewable liquid fuels typically refer to synthetic fuels produced from CO_2 and H_2. In this pathway, H_2 is often considered to be produced through electrolysis using renewable electricity. The production of these synthetic fuels, also called power-to-X (or solar) fuels, is in a demonstration phase. In a recent review (Chehade et al., 2019), the majority of demonstration projects on power-to-X around the world since 1985 are analysed. They have identified 192 projects, mainly in Europe (154 projects), and around 2/3 of these were initiated after 2010. Most are dedicated to hydrogen production but also synthetic methane and other carbon-based products are subject in some of these demonstration projects. In these projects, alkaline electrolysers (AE) are mostly selected (50%), but novel electrolysis technologies, such as Proton Exchange Membrane (PEM, 42%) and high temperature, solid oxide electrolysers (SOE, 8%), are assessed as well. Further development of electrolysers has been achieved in these projects, with a combined installed capacity of more than 70 MW of which ca. 45 MW of AE, 27 MW of PEM, and only 0.5 MW of SOE. Alkaline electrolysis is, however, a mature technology with first commercial applications since the beginning of the previous century. Around 20 GW of cumulative alkaline electrolysis capacity has already been installed worldwide (Schoots et al. 2009; Detz, et al. 2018). Novel electrolyser technologies like PEM and SOE are still in an early development stage and the demonstration projects cover the majority of their cumulative installed capacity.

The total installed capacity of synthetic fuel production (excluding hydrogen) in Europe is estimated to be around 6 kt/a (Figure 9). With almost 70 demonstration plants, synthetic methane through CO_2 conversion with hydrogen is the major production route explored (IEA, 2019).

Despite of the existence of all these demonstration projects, the total production capacity is dominated by only two demonstration plants: the George Olah plant and the Audi e-gas plant. In Iceland, the George Olah plant of Carbon Recycling International (CRI) has the capacity to produce 4000 t methanol annually. The feedstocks are provided by the geothermal power plant, which emits CO_2 and produces electricity. In the Audi e-gas plant in Werlte (Germany), CO_2 from

[19] This plant focuses on methanol production from crude glycerin, thus, it is based not lignocellulosic feedstock.

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the adjacent biogas facility is reacted with H_2 to synthesize methane. A 6 MW alkaline electrolyser delivers the H_2. The electrolyser runs especially during periods with low-demand for electricity, for instance, in the weekends and nights. In the Store&Go project power to methane, technology is demonstrated in three plants; in Germany, Italy, and Switzerland. In the largest (Germany) a 2 MW alkaline electrolyser produces hydrogen to convert CO_2 from a bio-ethanol plant in methane (~1 MW). Several smaller scale methane projects (<1 MW capacity) have been conducted and are under development, but these are not included in our overview (Bailera, et al. 2017).

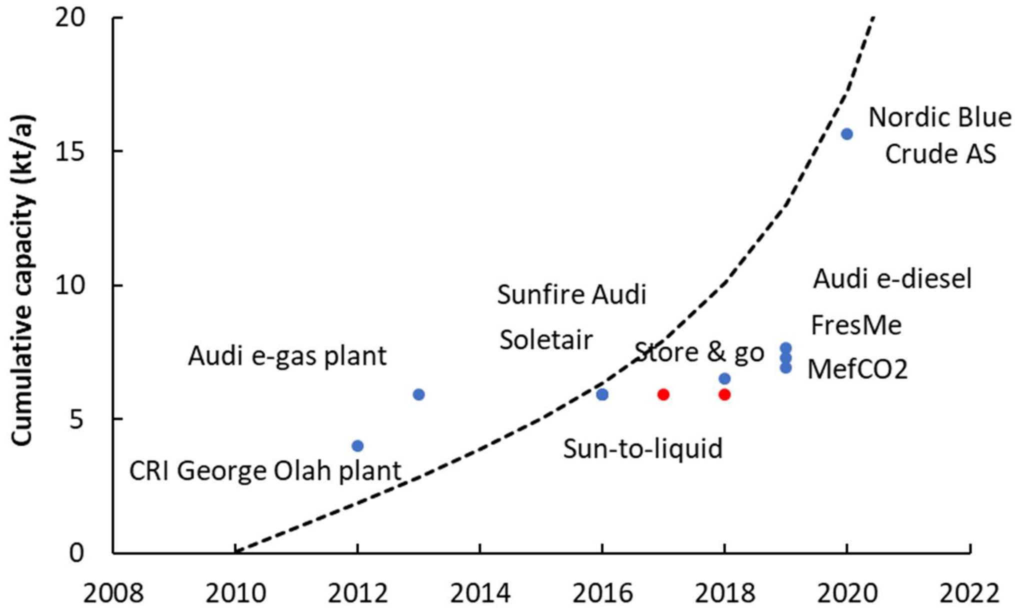

Figure 9: Cumulative production capacity of plants manufacturing synthetic fuels from CO_2 in Europe in kt per year. Beyond 2018, the capacity is based on planned projects. Striped line represents the estimated trend in growth. Plant additions are depicted in blue marks, decline in capacity (due to closure of a plant) is indicated by red marks.

In 2016, three related H2020 projects (STEPWISE, FresMe, and MefCO_2) were proposed to develop the value chain of CO_2 capture and conversion to methanol. In STEPWISE, CO_2 is captured from the blast furnace gas of a steel plant in Sweden using novel SEWGS purification technology. In the FresMe project the captured CO_2 from the steel plant is converted into methanol and evaluated as fuel for shipping. In the MefCO_2 project, CO_2 is captured from a coal-fired power plant and converted into methanol using H_2, which is produced by electrolysis driven on intermittent renewable electricity.

In other pilot studies, the FT synthesis of hydrocarbons (e.g. gasoline, kerosene, diesel) is explored for which the syngas is produced by the reverse water-gas-shift (RWGS) reaction. CO_2 from various sources and H_2 from electrolysis are used as feedstocks. Solid oxide electrolysis was used in the Sunfire plant in Dresden (Germany), which ran for approximately 1500 hours and produced around 3 t of oil. In the Solitair project (Finland) a similar concept is followed, now based on CO_2 capture from air. Via FT synthesis around 6 kg of oil and wax was produced in 300 hours. Instead of RWGS, the Sun-to-Liquid project (Spain) investigates the reaction of CO_2 and H_2O in a solar thermal reactor to produce syngas, which is converted by FT synthesis into fuel for aviation. Based on these pilot studies, several larger demonstration projects are

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now under development. Audi is constructing an e-diesel plant in Switzerland running on hydroelectricity. In Norway, Sunfire and Nordic Blue Crude AS plan to scale-up the Dresden pilot plant to a production capacity of 8000 t/a synthetic oil. In other projects synthetic kerosene production is considered based on Fischer-Tropsch synthesis. In Stade, for example, a consortium aims to construct an industrial-scale demonstration plant at the DOW chemical company. The project, "GreenPower2Jet", expects that the pre-engineering phase lasts until 2021/22. Lufthansa launched a project to produce 5% of their kerosene consumption at Hamburg airport through a low carbon route in 5 years. Together with researchers from the University of Bremen they plan to use electricity and CO_2 to produce electrofuel at the Heide refinery.

Developments in technology components

To deploy CO_2 conversion routes to produce RESfuels at scale, development of the different technology components is needed. Hydrogen production by electrolysis is for most approaches one of the key technologies in the value chain. Although water demand is limited, water splitting is an energy intensive process and requires large amounts of electricity. This electricity should be supplied from renewable electricity sources and its deployment and costs will also determine the growth of this type of RESfuels. Besides the costs of (renewable) electricity, the investment costs of the electrolyser contribute significantly to the fuel production costs as well. Novel electrolyser technologies (such as high temperature electrolysis and CO_2/H_2O co-electrolysis) are also under development, and may lead to significant results concerning efficiency in the overall synthetic fuel production scheme.

Besides the two large electrolyser facilities in the Audi e-gas plant and CRI methanol plant, a 6 MW PEM electrolyser is operating in Energiepark Mainz (Germany), and a similar size plant is under construction in Linz (Austria) for the H2Future project. Several smaller scale projects are running or under development (Schmidt 2018). Currently plans for several larger-scale electrolysis facilities (10-100 MW) are being developed. Together these projects seem to initiate a significant boost in the European electrolysis capacity in 2030 and beyond, and it is expected that the costs will reduce considerably.

Table 13: Overview of the development status of synthetic fuel production technology

Development stage / Category	Low (TRL<7)	Medium (TRL 7-8)	High (TRL 9<)
Renewable Electricity			- Solar PV - Wind Onshore - Wind Offshore - Hydropower
Electrolysis	- High temperature electrolysis - Co-electrolysis	- PEM electrolysis	- Alkaline electrolysis
CO_2 capture	- Direct air capture	- Capture from less concentrated point sources	- Capture from highly concentrated point sources
CO_2 conversion	- Co-electrolysis	- Direct CO_2 conversion pathways - RWGS - MTA	- Methanol synthesis from syngas - FT synthetic fuel production from syngas - MTG/MTO

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The CO_2 source for RESfuel production is obtained from point sources based on fossil, geological, or biological carbon or from air via direct air capture. CO2 capture and storage (CCS) technology is currently active at megaton scale, mainly for enhanced oil recovery, but also in the fertiliser industry. The capture from flue gasses with a high CO_2 concentration is preferred for energetic reasons and thus costs. In the early phase, capture from fossil-based heavy industry (as e.g. demonstrated in the STEPWISE project) may avoid some emissions by carbon re-use, but will only be a solution during a transition period. Processes running on biomass, e.g. from biogas upgrading or bio-ethanol plants, are more attractive in the long run as sustainable carbon source. As these sources may become limited, CO_2 extraction from air is needed to deploy sustainable synthetic fuel production at scale. Currently only a few companies are developing direct air capture (DAC) installations, which can deliver around 900 t of CO_2 per year. DAC is currently in the scale-up phase and several companies are seeking for attractive business cases and investors. Carbon Engineering is designing a 1 MtCO2/yr production plant, which will produce CO_2 for underground storage.[20]

CO_2 conversion technology to produce methane, methanol, or hydrocarbon liquids is developed at large scale. In most commercial routes, fossil feedstocks are converted into syngas (mixture of CO, H2, and some CO_2). Via the water-gas shift (WGS), an equilibrium reaction the ratio in this mixture can be optimised for the following chemical conversion reaction. The reverse reaction (RWGS) allows to convert CO_2 and H_2 into a suitable syngas for processes such as methanol and Fischer-Tropsch (FT) synthesis, which are both deployed at large commercial scale. Novel reaction pathways are also investigated and CRI has successfully implemented the direct hydrogenation of CO_2 to produce methanol without first converting CO_2 to syngas. Mobil has also demonstrated that methanol can be converted into several products such as gasoline, kerosene, diesel, olefins, and aromatic compounds. Methanol-to-gasoline (MTG) and methanol-to-olefins (MTO) processes are now implemented in several commercial plants, production of other chemicals from methanol (MTA) has not been commercialised at this large of a scale.

3.3. Advanced biofuel consumption in EU

Derived from the 2019 GAIN report (USDA, 2019), Figure 10 presents the amount of biofuels consumed in Europe broken down into different types. This figure also illustrates the REDII consumption figures. Figure 11 illustrates the share of biofuels in Europe broken down into different types. As shown, the production and consumption of advanced biofuels in Europe relates to hydrogenated vegetable oils (HVO) using used cooking oil and animal fats (referred to as Part B in the graph). Biofuel consumption from lignocellulosic feedstocks were less than 0.2% of total consumption (refers to Part A). In absolute terms, advanced biofuels produced from the feedstocks listed in Part A of the renewable energy directive is around 500 ktoe (<21 PJ).

REDII target for advanced biofuels is set to increase to 3.5% in 2030. This requires around 10000 ktoe. This will require about a hundred advanced biofuel plants with an annual capacity of 200 million litres each (USDA, 2019).

[20] https://carbonengineering.com/news-updates/carbon-engineering-expanding-capacity-of-commercial-dac-plant/

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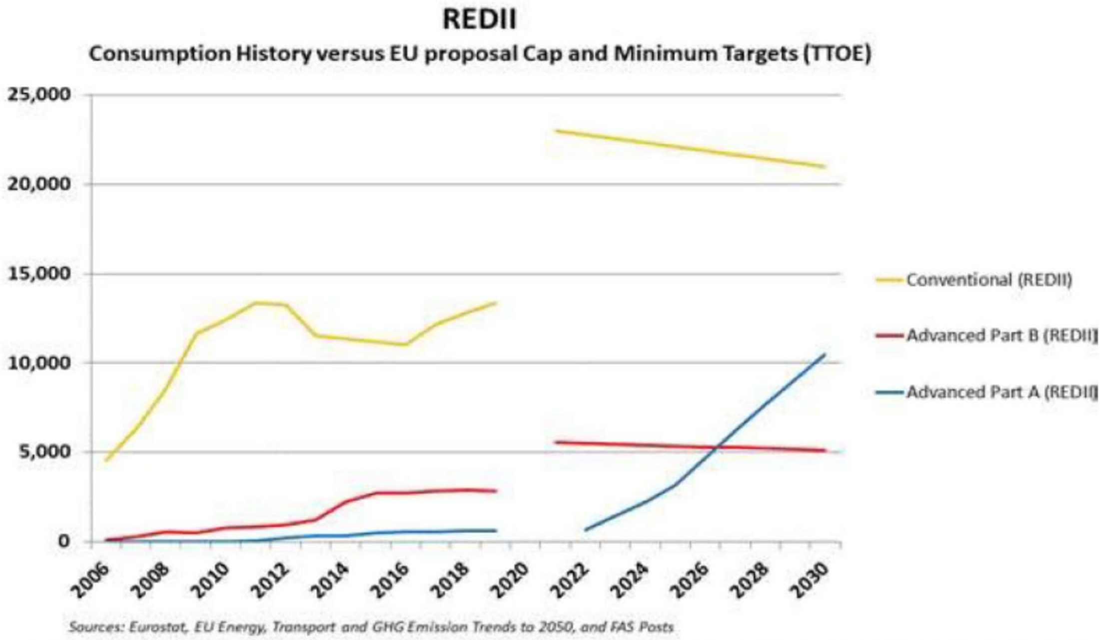

Figure 10: Trends in Conventional and Advanced Biofuels in Europe, installed capacity. Source: Eurostat (derived from USDA, 2019)

* *Part A refers to biofuels produced mainly from lignocellulosic wastes and residues. Part B refers to biofuels produced from used cooking oil and animal fats and residues. Conventional biofuels are the biofuels produced from food crop-based feedstocks.*

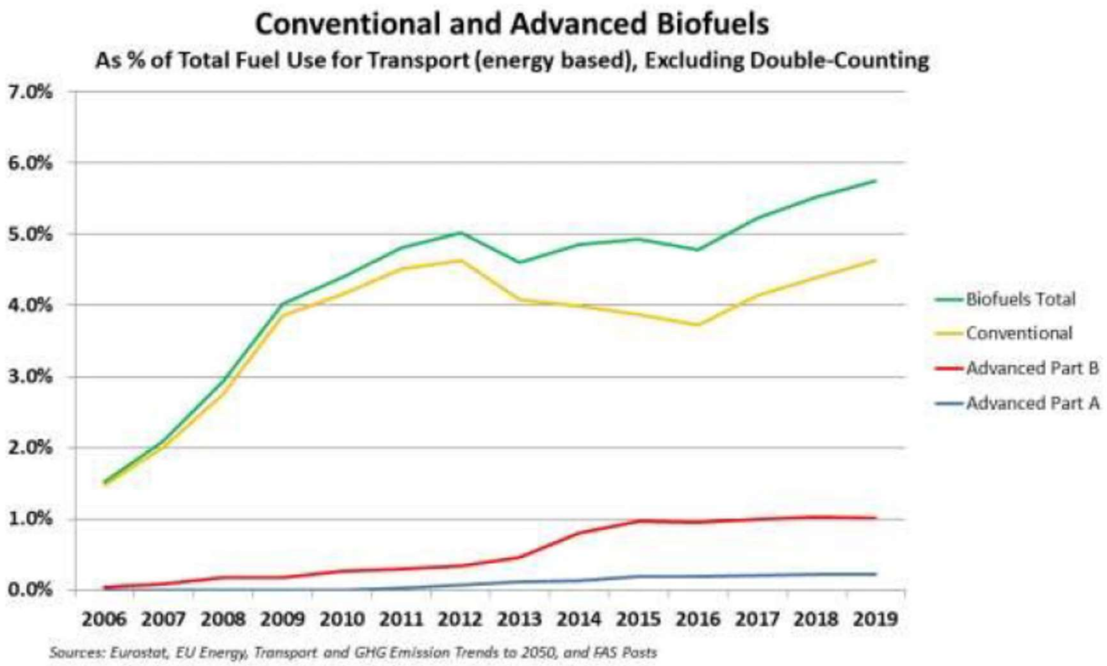

Figure 11: Conventional and Advanced Biofuels consumption as percentage of total fuel use in transport in the EU. Source: Eurostat (derived from USDA, 2019)

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3.4. Investments to RESfuel

Biofuels experienced a growth in new investment from 2004 to 2007, with a strong growth in first-generation biofuels. Investments in first-generation biofuels started to decline from 2008, with the exception of a minor increase in 2009-2011. Figure 12 illustrates the global new investments to biofuels. Investments to advanced biofuels (referred to as 2G Biofuels in Figure 12), starting from 2006, follow a steady path and peaked in 2011-2012 before declining again.

According to the 2019 IRENA report (IRENA, 2019b, IRENA, 2019c) *"The desired shift from 1G biofuels to advanced biofuels was reflected in the Renewable Energy Directive (RED) of 2009 and its revisions of 2015, and the US's Energy Independence and Security Act (EISA) of 2007 in their specific support mechanism for advanced biofuels."* From 2014, we see a decline in the investments in advanced biofuels. As highlighted in the IRENA report *"Barriers affecting investments in advanced biofuels are numerous and reflect the complex nature of the business environment. Not only is the technology immature, reflected in the operational problems of the first-of-its-kind projects and high costs, but the challenges also include an array of environmental, infrastructure-related, social and political issues."*. The investment of selected advanced biofuels plants is introduced in Annex 2.

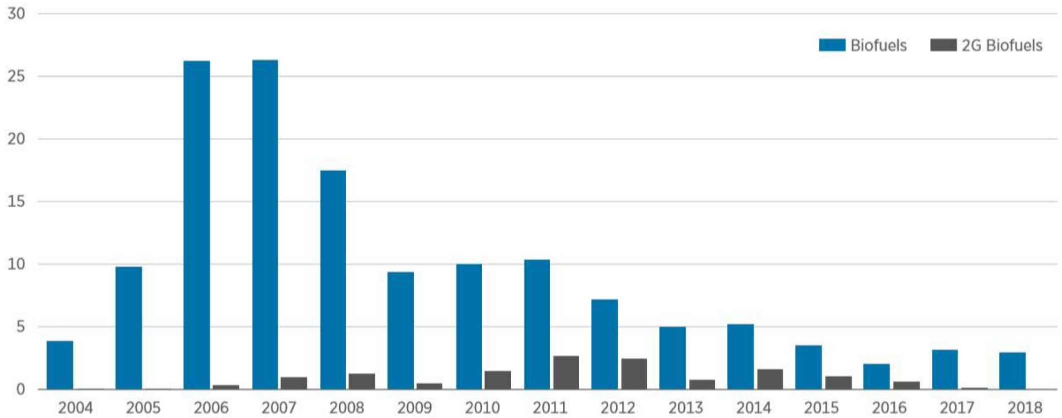

Figure 12: Annual investments in biofuels (USD billion). Source: IRENA, 2019. Note: Second generation (2G) 2018 data not available.

3.5. EU Funding programs

Next to governmental support to biofuels European Commission initiates public co-funding to enable industrial-scale demonstration of advanced biofuels through a variety of programs, such as NER300, Horizon2020 (H2020), European Industrial Bioenergy Initiative (EIBI), ERA-NET+, Bio-Based Industries Joint Undertaking (BBI JU).

Following NER300, a financing instrument to fund innovative low-carbon energy demonstration projects, launched in 2008 under Article 10a(8) of the Emission Trading Directive 2009/29/EC[21], funding was proposed for five advanced biofuel and three bioenergy projects announced to

[21] The first NER300 calls were launched in 2011 and 2012, and the second in 2014.

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receive funding. However, the majority of these proposals were withdrawn. Currently, the operational Verbio project in Germany converts straw into biomethane and with funding from the NER300 programme of up to EUR 22.3 milling during 2014-2019, the Verbio plant capacity is now 16.5 MW (136 GWH/a)[22]. A second NER300 call was in 2014, whereby six of the selected projects were bioenergy projects. Two of them aimed to produce ethanol for the transport sector, in which one of them was withdrawn. The status of these projects, also including the bioenergy related ones, is presented in Table A 6 (see Annex III).

EU's Horizon 2020 framework (2014-2020) programme for research provides funding for advanced biofuels. Figure 13 presents an overview of the H2020 projects related to advanced biofuels and bio-refineries with a TRL level greater than 4. The data refers to the projects that started within the time-frame between 2015-2017 and that are applicable for funding greater than 250 k€.

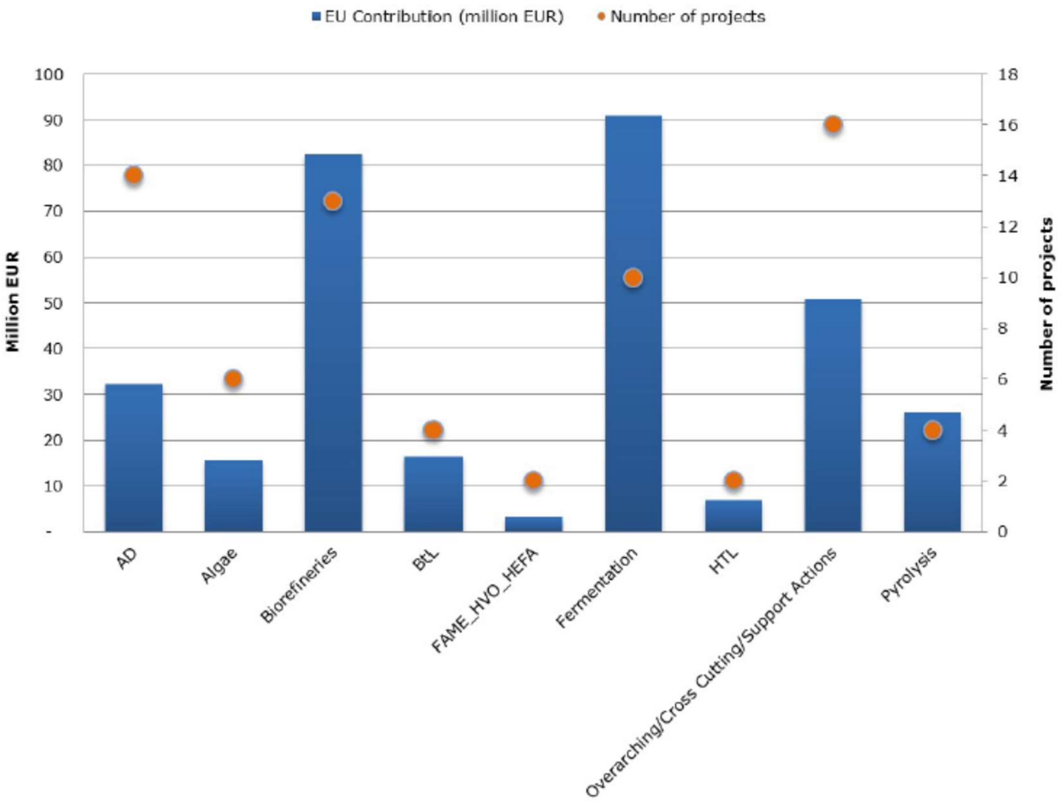

Figure 13: Distribution of EU funded advanced biofuel technologies projects above 250 k€ ((Lonza & O'Connel, 2018).

The European Industrial Bioenergy Initiative (EIBI), one of the industrial initiatives under the SET-Plan[23], aims to have the first commercial plants in operation by 2020 with a focus on advanced biofuels (ETIP, 2019). InnovFin Energy Demo Projects (EDP) Facility enables the EIB to finance innovative FOAK demonstration projects in the field of renewable energy and hydrogen/fuel cells. InnovFin Energy Demonstration Projects provides loans, loan guarantees or equity-type financing (typically between EUR 7.5 million and EUR 75 million) to innovative demonstration

22 https://www.verbio.de/en/products/verbiogas/

23 https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan

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projects in the fields of energy system transformation. This includes but is not limited to renewable energy technologies, smart energy systems, energy storage, carbon capture, and storage or carbon capture and use, helping them to bridge the gap from demonstration to commercialisation.

3.6. Policies promoting RESfuels

An important driver behind policy support towards (advanced) biofuels is the overall goal to comply with the 2015 UNFCCC Paris Agreement, whereby countries are required to present Nationally Determined Contributions (NDCs). For EU28, the decarbonisation of the transport sector is currently promoted through various EU directives, such as the 2009 Renewable Energy Directive (REDI), the 2009 Fuel Quality Directive (FQD), and 2015 ILUC Directive. Different types of policies are applied at different stages of the supply chain, including among others feedstock production, plant construction and fuel supply. Policy instruments also differ between supply and demand side. On the supply side, examples of support include grants and loans. On the demand side, blending mandates (as well as double counting[24]) and tax incentives are typically used to promote advanced biofuels. Table 14 provides a brief summary of key instruments applied in selected EU countries. For sake of comparison, the table also includes policies applied in the US.

Table 14: Overview of policy support measures to promote (advanced) biofuels in selected regions/countries, per June 2020. (Source: ICCT, 2018; UPEI, 2018; ePURE, 2018; GAINS report; 2020)

Region / Country	Sub-mandate for advanced biofuels	Double Counting	(Tradeable) Certificates	Penalty for non-compliance of sub-mandate[25]	Tax incentives to advanced biofuels
Within the EU					
Austria	✓				
Denmark	✓	✓			✓
Germany	✓	✓			✓
Finland		✓			✓
France		✓			✓
Italy	✓	✓	✓	✓	
Netherlands	✓	✓		✓	
Slovakia	✓	✓			
Sweden			✓		
UK	✓	✓	✓	✓	✓
Outside the EU					
US	✓[26]				✓

[24] ... the energy content of promoted biofuels is double counted towards the overall energy in transport target

[25] For details on the Sub-mandates shares, see: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuel%20Mandates%20in%20the%20EU%20by%20Member%20State%20in%202019_Berlin_EU-28_6-27-2019.pdf

[26] Within the US RFS, a 2019 final rule sets the total U.S. renewable fuel volume requirements at 19.92 billion gallons, a 630 million gallon increase in the advanced biofuel target relative to 2018 levels. For advanced biofuels, the quantity is set at 4.92 billion gallons, including 418 million gallons for cellulosic biofuels. Advanced biofuels include fuels such as imported sugarcane ethanol as well as fuels that qualify for the biomass-based diesel (biodiesel and renewable diesel) and cellulosic biofuel targets. In recent years, the majority of advanced biofuel RFS credits have been generated from biomass-based diesel consumption.

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In addition to the table above, some highlights to mention regarding Member States' implementation of national advanced biofuels mandates are (USDA, 2020):

- Denmark has approved a specific target for advanced biofuels, namely 0.9 percent blending mandate by 2020, which excludes used cooking oil (UCO) and animal fats.
- An Italian Decree in December 2017 requires gasoline and diesel to contain at least 0.1 percent of advanced biofuels made of waste and non-food feedstocks as of January 2018, rising to 0.2 percent in 2019, and one percent in 2020.
- In 2018, the Netherlands introduced an obligation for advanced biofuels respectively of 0.6, 0.8 and 1.0 percent. The advanced biofuels must be produced from waste, not including used cooking oil and animal fats.
- In February 2019, Finland approved a law that mandates an advanced biofuel share of 2 percent in 2023, increasing to 10 percent in 2030.
- Mandates for advanced biofuels will also go into effect in countries, such as the UK and the Slovak Republic in 2019 and in Bulgaria and Germany in 2020.

As it can be seen above in Table 14, double counting is permitted in France, Italy, Denmark, the Netherlands, and the UK. Definition and eligible feedstocks vary by MS. For example, the quantity of advanced biofuels that can be double counted in France is strictly limited in order to favour biofuels produced in France (if it was not limited, this measure could lead to an increase in imports of advanced biofuels at the expense of domestic "conventional" biofuels).

REDII, adopted in December 2018, will enter into force in January 2021. REDII mandates member states to require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. Within this target, there is a sub-target for advanced biofuels produced from feedstocks in Part A of Annex IX. These fuels must a minimum of 0.2% of transport energy in 2022, 1% in 2025 and increasing to at least 3.5% by 2030. Advanced biofuels will be double-counted towards both the 3.5% target and towards the 14% target. Several Member States are already preparing for the implementation of this directive.

A bill has been proposed which aims, among others, to extend the second generation biofuel producer tax credit through 2018[27]. Furthermore, additional financial support to biomass feedstock crops for advanced biofuels facilities and production of advanced biofuels available. Loan guarantees are provided where the government commits to paying a company's investment loans if that company is unable to pay them. These loan guarantees are meant for early commercial-stage projects. Loan guarantees supported Project LIBERTY, the country's first commercial scale cellulosic ethanol plant sponsored by POET.

Whilst this section presents an overview of policies supporting the promotion of advanced biofuels in a selection of countries, section 2.5.1 on Good practices in Europe and outside makes a first analysis of Good Practice policies.

3.7. Feedstock cost developments

Feedstock prices next to the capital costs are the dominant cost factor in effecting the advanced biofuel production costs (feedstock costs comprise ~ 40% of the total production cost of bio-

[27] https://ethanolrfa.org/tax/

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fuels). There are currently no established markets to define feedstock prices dedicated to advanced biofuels. The main feedstock used in the existing (lingo)cellulosic ethanol plants are mainly the agricultural residues such as cereal strove and, to a limited degree, straw. In the medium to long term, biofuels from other woody biomass are expected to increase their market uptake as well. Two KPIs are determined as proxy to present the feedstock price developments; straw and wood pellet prices, and their historical price developments are presented below.

Straw price developments

The figure below presents the difference and variability of straw prices in several member states according to Eurostat. Currently the straw price developments mainly relate to demand for straw to be used in food and bedding for cattle (see Figure 14). There are relatively large regional differences. These differences relate to the weather, forage harvest and animal stock density in each country.

The market price for biofuel production will be influenced by the factors such as the ratio of supply and demand and how much is in stock from the demanding sectors and the energy sector's willingness to pay. The cellulosic ethanol operators are expected to supply straw from local farmers with the long-term contracts. In Denmark, for instance, straw has been used to produce heat and electricity since 1980s' and the straw price has been rising since 2007/08 due to the large increase in power plant capacity (Kuhler, 2013).

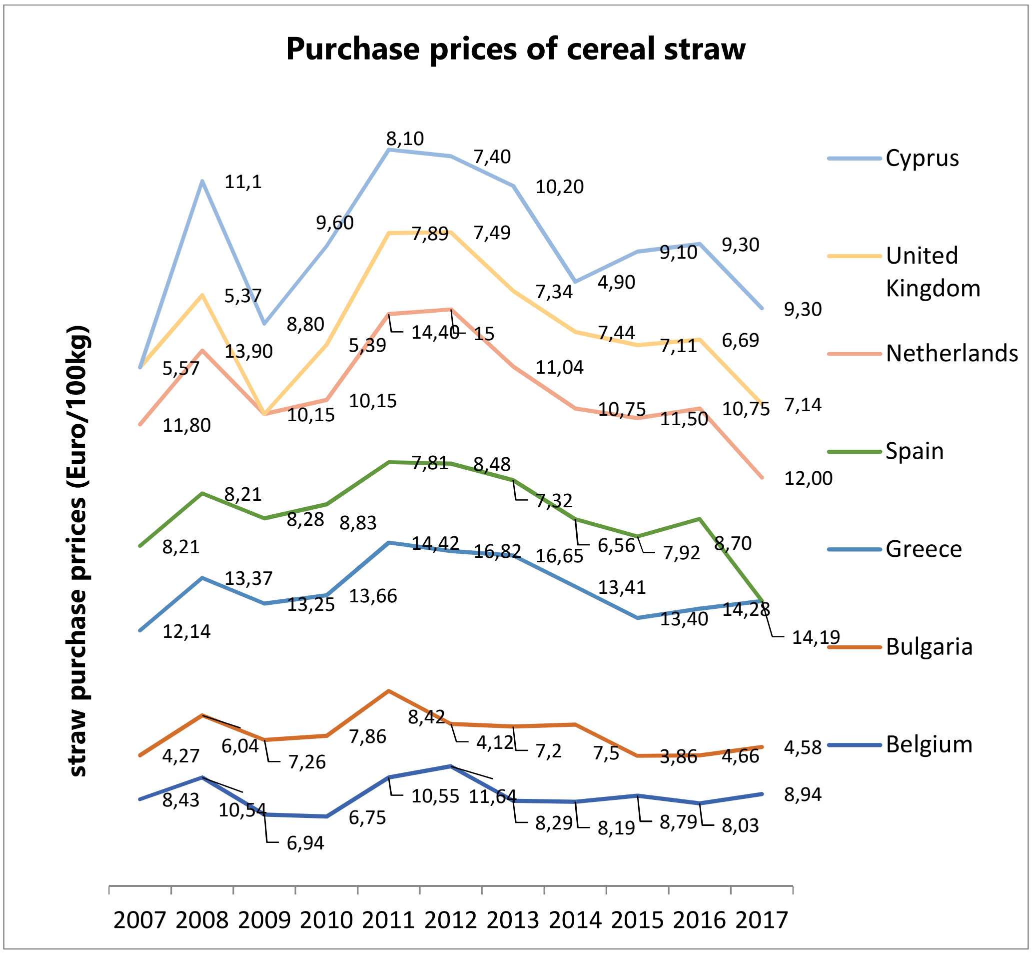

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Figure 14: Purchase prices of cereal straw (Eurostat, 2019) (refers to real purchase prices on farm)

Wood pellet prices

Wood pellet price developments relate to residential and industrial use for energy production. There is currently no market regarding wood pellet use in advanced biofuel plants. Thus, these data should be interpreted carefully. There are two main categories; industrial-grade pellets, aimed for medium- and large-scale application (such as co-firing in coal plants), and residential grade pellets, mainly used in small-scale heating appliances.

Pellet price fluctuations for residential consumers (see Figure 15) in Europe relate to production costs, over or under supply in the market (as occurred in 2016), weather conditions (soft versus cold winters), and external shocks including (dollar) exchange and shipping rate developments (as it is a tradable commodity) (Thraen et al., 2018).

Industrial wood pellet markets are characterised by a few central factors that are crucial for price developments (Thran et al., 2018). These factors are:

- The industrial pellet market is demand driven, which depends on policy schemes including underlying remuneration levels and related regulations
- The wood pellet market is small in comparison. It lacks the liquidity of true commodity markets and it is dominated by a few market actors (Olsson et al., 2016), effecting the spot market prices easily (i.e. the fires in Drax power plant resulted in general price decreases in Europe).
- Exchange rate fluctuations can influence economics of industrial pellet consumers who often purchase pellets in United States Dollars (USD) but receive their revenue (from electricity sales) in their respective local currencies.

Figure 16 illustrates the industrial wood pellet price fluctuations.

The operational advanced biofuel plants are currently very limited to have any impact on the feedstock market. The operational plants resource their feedstock from the nearby locations and the prices are much likely to be low (or in some cases might be negative, i.e. when wastes are used). However, when the market evolves and the demand increases above factors, at least the ones mentioned for the industrial wood pellet markets, are likely to effect the feedstock prices. In case the advanced biofuel plants run on clean wood the existing wood pellet market may expand and also supply to biorefineries next to power and heat markets.

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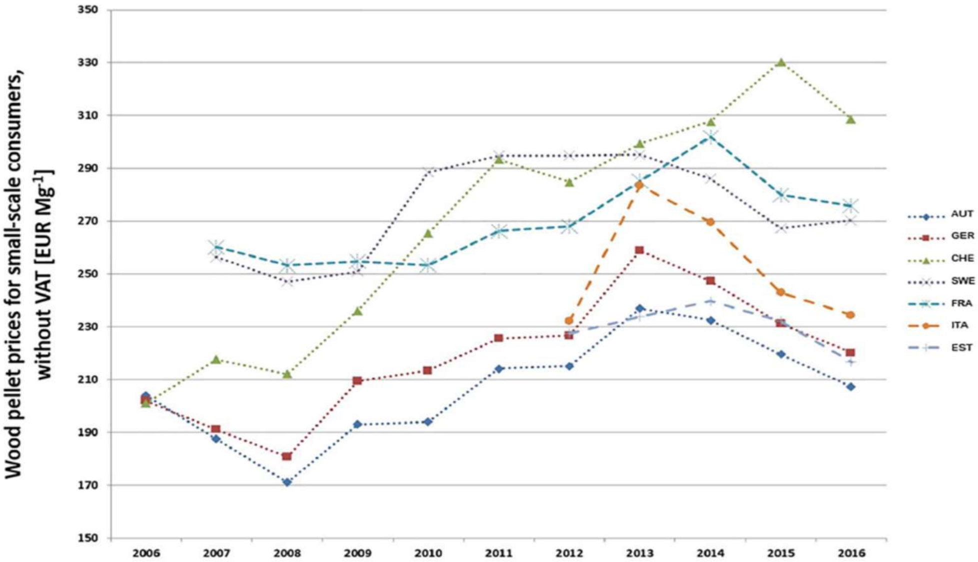

Figure 15: Comparison of wood pellet prices for small scale consumers, delivered either in bulk or in bags (Thraen et al. 2018).

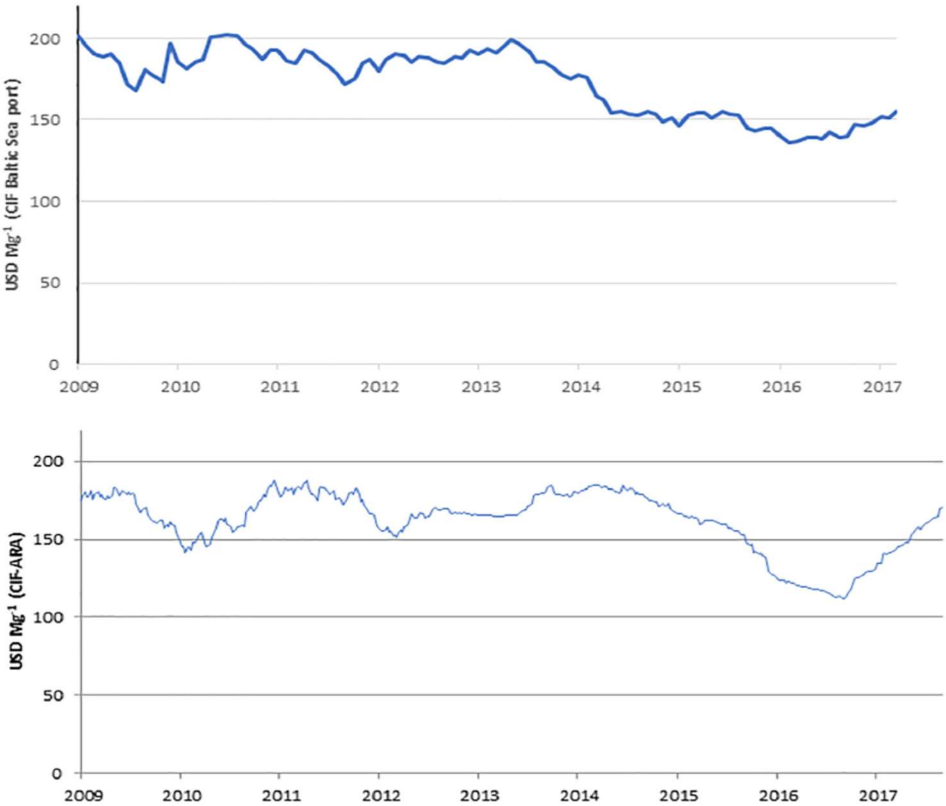

Figure 16: Industrial wood pellet prices 2009–2017 in the Baltic Sea region (upper pane) and the Amsterdam-Rotterdam-Antwerp (ARA) region (lower pane) (Thran et al., 2018).

Note: the effects on ARA prices of the February 2012 Tilbury fire, as well the dampened prices in 2015–mid 2016 as policy uncertainty coincided with significant capacity increase. (The Baltic Sea prices have been converted from EUR MWh−1 to USD Mg−1 using an energy density of 4.7222 MWh Mg−1 and monthly EUR/USD exchange rates from the Swedish Riksbank.) (Argus, 2018; Foex Index, 2018)

4. Conclusions

In summary, the following conclusions (non-exhaustive) can be drawn from the updated presentation of project and market-based KPIs:

- The advanced biofuels industry continues to struggle to reach commercialisation in the EU and in other parts of the world.
- Recent developments show that the US no longer holds the largest installed capacity of ethanol production from lignocellulosic feedstocks. Production of biodiesel using lignocellulosic feedstocks is limited in comparison to lignocellulosic ethanol.
- In recent years, difficult market conditions coupled with high operational costs and financial difficulties companies were facing, have forced the closure of several lignocellulosic ethanol plants. Majority of these plants remain closed.
- There was a small spike in investments in advanced biofuels in the EU following the adoption of REDI in 2009, but barriers affecting investments in advanced biofuels remain numerous, mostly due to the complex nature of the business environment. Not only does the technology remain immature, but the operational problems of FOAK projects persist and costs remain high. Additional challenges include an array of environmental, infrastructure-related, social and political issues.
- The US and Italy were the first two countries to introduce dedicated mandates for advanced biofuels. With the adoption of REDII, there will be an EU-wide obligation for fuel suppliers in Europe to utilise advanced biofuel, starting in 2022. EU Member States are slowly but surely taking steps to implement mandates for advanced biofuels.
- Feedstock prices next to the capital costs are the dominant cost factor in effecting the advanced biofuel production costs. While there are currently no established markets to define feedstock prices once the sector matures, the feedstock prices may follow an increasing trend depending on the buying capacity of the biofuel plants and the market supply of certain feedstock (i.e. straw). Little has developed in this domain since the previous ADVANCEFUEL monitoring report, published in early 2019.
- Project results show that production costs of dedicated energy crops are in the order of 7-25% lower when compared to reference scenarios (before innovation implementation). Costs are reduced by applying innovative approaches such as propagation by seeds and/or by stem segments, planting density increase, economy of scale and learning effects.

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Annex I Overview of operational, planned and idle RESfuel plants

Table A 1 List of operational lignocellulosic ethanol plants. Source: IEA Bioenergy Task 39 database.

Type	Name/place	Feedstock	Technology	Capacity (t/a)
US				
Demo	Renmatix	Lignocellulosics	Fermentation	500
Demo	American Process/Thomaston GP3+ Bio-refinery	Forest residues	HTF	180
Demo	LanzaTech/US Mobile Demo	Woody biomass syngas	Gasification	70
FOAK	Quad-County Corn Processors, Galva	Lignocellulosics	Fermentation	6 000
FOAK	American Process/Alphena Biorefinery	Forest residues	HTF	2 100
CANADA				
Demo	Tembec Chemicals	Lignocellulosics	Gasification	13 000
Demo	Enerkem Alberta Biofuels LP/Westbury, Edmonton	Forest residues	Gasification	4 000
Demo	Iogen Corporation	Lignocellulosics	Fermentation	1 600
Demo	Woodland Biofuels	Organic residues and waste streams	Fermentation	6 000
FOAK	Enerkem Alberta Biofuels LP, Edmonton	Organic residues and waste streams	Gasification	30 000
BRAZIL				
Demo	Cane Technology Center (CTC)	Lignocellulosics	Fermentation	2 400
FOAK	GranBio, San Miguel	Lignocellulosics	Fermentation	62 000
FOAK	Raizen Energia, Costa Pinto	Lignocellulosics	Fermentation	31 600
EUROPE				
Demo	North European Oil Trade Oy/Cellulonix, Finland	Lignocellulosics	Not specified	7 900
Demo	Chempolis Ltd./Chempolis Biorefinery plan, Finland	Lignocellulosics	Fermentation	5 000
Demo	North European Oil Trade Oy/Ethanolix GOT, Sweden	Organic residues and waste	Fermentation	4 000
Demo	Clariant/Sunliquid, Germany	Lignocellulosics	Fermentation	1 000
Demo	SP/EPAP/Biorefinery demo, Sweden	Lignocellulosics	Fermentation	160
Demo	Borregaard AS/BALI Biorefinery, Norway	Lignocellulosics	Fermentation	110
FOAK	Borregaard Industries/ChemCell Ethanol, Norway	Lignocellulosics	Fermentation	15 800
CHINA				
Demo	Anhui BBCA Biochemical	Lignocellulosics	Fermentation	5 000
Demo	Shandong Zesheng Biotech Co.	Lignocellulosics	Fermentation	3 000
Demo	Jilin Fuel Alcohol/Jilin 2	Lignocellulosics	Fermentation	3 000
Demo	COFCO Zhaodong Co.	Agricultural residues	Fermentation	500
Demo	LanzaTech/Asia Mobile Demo Plant	Waste gases (MSW syn-gas)	Fermentation	70
Demo	Longlive Bio-technology Co. Ltd.	Lignocellulosics	Fermentation	60 000
FOAK	Henan Tianguan Group/Henan 2	Lignocellulosics	Fermentation	30 000
FOAK	Henan Tianguan Group/Henan 1	Lignocellulosics	Fermentation	10 000

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Table A 2 List of idle lignocellulosic ethanol plants. Source: IEA Bioenergy Task 39 database.

Type	Name/place	Feedstock	Technology	Capacity (t/a)
US				
Demo	Pacific Ethanol/West Coast Biorefinery	Lignocellulosics	Fermentation	8 000
Demo	BP Biofuels/Jennings demo	Agricultural residues	Fermentation	4 200
Demo	GeoSynFuels	Agricultural residues	Fermentation	4 500
Demo	ZeaChem,	Lignocellulosics	Fermentation	750
FOAK	DuPont/commercial facility, Nevada, Iowa	Agricultural residues	fermentation	82 700
FOAK	Abengoa Biorefinery, Kansas	Agricultural residues	fermentation	75 000
FOAK	POET-DSM Advanced Biofuels, Emmetsburg	Agricultural residues	Fermentation	75 000
CANADA				
Demo	CORE Biofuels	Organic residuals and waste streams	Gasification	53 500
EUROPE				
Demo	Inbicon/Dong Energy, Denmark	Lignocellulosics	Fermentation	4 300
Demo	Abengoa Bioenergy (Babilafuente), Spain	Lignocellulosics	Fermentation	4 000
Demo	Abengoa Bioenergy (Salamanca), Spain	Organic residues and waste	Fermentation	1 200
FOAK	Beta Renewables	Lignocellulosics	Fermentation	40 000

Table A 3 List of lignocellulosic plants in Europe that are under construction and planned. Source: ETIP Bioenergy, 2020. See http://www.etipbioenergy.eu/images/ETIP-B-SABS2_WG2_Current_Status_of_Adv_Biofuels_Demonstrations_in_Europe_Mar2020_final.pdf

Country	TRL	Start-up year	Planned capacity (kt/y)
Under construction			
Romania	TRL 8	2021	50
Austria	TRL 8	2020	30
Planned			
Slovakia	TRL 9		50
Poland	TRL 9		25
Croatia	TRL 8		55
Finland	TRL 8		40
Norway	TRL 8	2024	40
Norway	TRL 8	2024	40
Spain	TRL 8	2020	25
Finland	TRL 6-7	2021	65

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Table A 4 List of operational, planned, and idle synthetic fuel plants in Europe. Sources: Bailera 2017, Schmidt 2018, http://database.scotproject.org/projects, and project websites

Type	Name/place	Feedstocks	Technology	Output	Capacity (t/a)
Demo	CRI George Olah plant, Iceland	H_2O, and electricity and CO_2 from geothermal powerplant	Alkaline electrolyser and methanol synthesis reactor	Methanol	4 000
Demo	Audi e-gas plant, Germany	CO_2 from biogas plant, H_2O, and electricity	Alkaline electrolyser (6 MWe), methanation reactor	Methane	1 900
Pilot	Store & go, Germany	CO_2 from bio-ethanol plant, H_2O, and electricity	Alkaline electrolyser (2 MWe), methanation reactor	Methane	600
Pilot	STEPWISE, Sweden (related to FresMe and MefCO_2)	CO_2 captured from the blast furnace gas (BFG) of a steel plant	CO_2 capture with SEWGS	CO_2 (and H_2)	5 100
Pilot (idle)	Sunfire, Germany	CO_2 from biogas plant, H_2O, and electricity	RWGS with H_2 from solid oxide electrolyser, FT synthesis of synthetic hydrocarbons	Gasoline	16
Pilot (idle)	Soletair, Finland	CO_2 from air, H_2O, and electricity	CO_2 air capture, electrolysis to produce H_2 and either methanation to produce methane by the Sabatier reaction or RWGS and FT to produce liquid fuels	Gasoline	2
Pilot	Sun-to-liquid, Spain	CO_2, H_2O, and sunlight	Solar thermochemical plant (50 kW) producing syngas, which is converted by FT into hydrocarbon fuels.	Kerosene	9
Pilot (planned)	FresMe (related to STEPWISE and MefCO_2)	CO_2 (and H_2) from steel plant, additional H_2 from electrolysis	electrolysis, and methanol synthesis	Methanol	400
Pilot (planned)	MefCO_2, Germany (related to FresMe and STEPWISE)	CO_2 from powerplant, intermittent renewable electricity, and H_2O	electrolysis, and methanol synthesis	Methanol	400
Demo (planned)	Audi e-diesel plant, Switzerland	CO_2 from biogas plant, hydroelectricity, and H_2O	RWGS with H2 from electrolyzer, FT synthesis	Gasoline/Diesel	330
Demo (planned)	Nordic Blue Crude AS with Sunfire, Norway	CO_2 from fertilizer plant, electricity, and H_2O	H_2 production by SOE, RWGS and FT synthesis	Crude synthetic oil	8 000
Demo	Energiepark Mainz, Siemens, Germany	Wind electricity and H_2O	H_2 production by PEM electrolysis (6 MW)	Hydrogen	-
Demo (planned 2019)	H_2Future, Austria	Renewable electricity and H_2O	H_2 production by PEM electrolysis (6 MW)	Hydrogen	-
(planned 2019)	Nouryon, Gasunie, Netherlands	Renewable electricity and H_2O	H_2 production by alkaline electrolysis (20 MW)	Hydrogen	3 000
(planned 2021)	Nouryon, Tata, Netherlands	Renewable electricity and H_2O	H_2 production by alkaline electrolysis (100 MW)	Hydrogen	15 000

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Annex II Overview of investment costs of Advanced Biofuel production plants

Table A 5 Investment costs of Advanced Biofuel production plants. Sources: IEA Bioenergy Task 39 database and various project websites

Plant name/location	Type of main input and output	Output capacity (t_{fuel}/a)	Total investment (M€2018)	Total investment/capacity output€2018/t_{fuel}	Operational since
Fermentation					
Chempolis Biorefinery (Finland)	Lignocellulosic crops to ethanol	5 000	23	4 500	2008
Sunliquid / Clariant (Germany)	Lignocellulosic crops to ethanol	1 000	17	16 900	2012
Project Liberty / POET-DSM Advanced Biofuels (US)	Agricultural residues to ethanol	75 000	259	3 500	2014
Costa Pinto project, Raizen (Brazil)	Lignocellulosic crops to ethanol	32 000	105	3 300	2014
Bioflex 1, GranBio (Brazil)	Lignocellulosic crops to ethanol	65 000	216	3 300	2014
Gasification					
GoBiGas Phase 1 (Sweden)	Lignocellulosic crops to methane	11 200	155	13 900	2014
Enerkem, Edmonton	Municipal waste to ethanol	30 000	111	3 700	2014
Hydrothermal					
Licella (Australia)	Biowaste to bio-oil	350	5	15 500	2011
CO_2 conversion					
CRI George Olah plant, Iceland	CO_2 and electricity	4 000	8	1 900	2012
Audi e-gas plant (Germany)	CO_2 and electricity	1 900	21	10 800	2013

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Annex III Status of bioenergy projects announced to receive NER300 funding

Table A 6 Status of bioenergy projects announced to receive NER300 funding (SETIS, ETIP Bioenergy, 2019).

Category	Project/ Organisation	Country	Fund. €Million	Comment
Projects executed/ongoing				
Advanced biofuels	Ajos BTL	Finland	88.5	Cancelled despite the NER300 grant.
Advanced biofuels	BEST	Italy	28.4	Ongoing-initially operational but shutdown in 2017. Eni's Versalis won the bidding and is in the process of transferring the business[28]
Advanced biofuel	W2B MSW-to-ethanol	Spain	29.2	Ongoing-as of January 2017, the project sponsor is awaiting for the competitive public tender process to be called by the local authorities. However, other sources report that, the company stopped developing bioenergy facilities (in early 2017) and was forced to stall its own European-based biofuel facilities after agreeing a huge bailout in 2016 (Endwaste&bioenergy, 2017). In the IEA database, the project is reported as cancelled in 2016 (IEA Task 39 database, 2018).
Bioenergy	BIO-Bio2G Bio SNG to be injected into the gas grid	Sweden	203.7	Ongoing[29]-basic design or pre-FEED (front-end engineering design) work has been concluded but the work has not started yet. The present project status is that the project is on hold (IEA, task33, 2018).
Bioenergy	TORR torrefaction	Estonia	25	Ongoing-the environmental and construction permitting process is started.
Bioenergy	VERBIO Straw biomethane production	Germany	22.3	Operational
Projects chosen for funding but withdrawn				
Advanced biofuels	CEG Plant Goswinowice	Poland	30.9	2011/2012 call
Advanced biofuels	UPM Stracel BTL	France	170.0	2011/2012 call
Advanced biofuels	Woodspirit	Netherlands	199.0	2011/2012 call
Bioenergy	Gobigas phase 2 SNG production	Sweden	58.8	2011/2012 call
Bioenergy	Pyrogrot pyrolysis oil)	Sweden	31.4	2011/2012 call
Advanced biofuel	MET Cellulosic ethanol	Denmark	39.3	2014 call
Bioenergy	Fast Pyrolysis	Estonia	6.9	2014 call
Bioenergy	CHP Biomass Pyrolysis	Latvia	3.9	2014 call

[28] See https://www.biofuelsdigest.com/bdigest/2018/10/01/enis-versalis-wins-biochemtex-and-beta-renewables-at-auction/

[29] Officially not yet withdrawn but 'unlikely' or 'put on hold', according to interviews and info from NER300.com (Åhmana, et al., 2018).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Transposition of the ILUC Directive

	Crop cap in 2020 unless other wise specified	Sub-target for advanced biofuels in 2020 unless otherwise specified
Austria	7%	0.5%
Belgium	7%	0.1%
Bulgaria*	7%	0.05%
Croatia	7%	0.1% in 2018
Cyprus	No information	No information
Czech Republic*	Not introduced	0.5%
Denmark	7%	0.9%
Estonia	7%	0.5%
Finland	7%	0.5%
France	7%	0.6%**
Germany	6.5%	0.05%
Greece*	7%	0.2%
Hungary	7%	None
Ireland*	7%	0.25%
Italy	7%	0.6% in 2018, 0.8% in 2019 and 0.9% in 2020
Latvia*	Included	0.5%
Lithuania	7%	0.5%
Luxembourg	Not required	***
Malta	7%	0.5%
Netherlands	3% for 2018, 4% for 2019, 5% for 2020	0.6% for 2018, 0.8% for 2019 and 1% for 2020**
Poland	7%	0.1%
Portugal	7%	0.5%
Romania	No information	No information
Slovakia	7%	0.1% for 2019, 0.5% for 2020-2024
Slovenia	No information	No information
Spain	7%	0.1%
Sweden	7%	None
United Kingdom	4% in 2021, 3% in 2026, 2% in 2032	None

** Under legislative process*
*** Double counted*
**** Advanced biofuels which are blended must represent 15% in the biofuels mix after double counting*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º764799.

Annex IV Time framed CAPEX need for TRL level increase of certain technologies (M€)

Results for KPI

Scenario A corresponds to a very small contribution of liquified biomethane (percentages close to zero) with a very small number of plants (6) in the considered time frame where the TRL increase is studied (2020-2050). In the same time frame, an increase of the installed capacity by one order of magnitude cannot be achieved with the selected CAGR. The contribution of 20% of liquified biomethane to the fossil-based equivalent can be succeeded with a CAGR =29.5%, as shown in Scenario B with a CIC of 390,317MW.

Table A 7 KPI calculations for liquified biomethane

TRL	7-8	8-9	9 mature
Year	Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
Scenario A (Conservative greening) (CAGR 8%)			
CIC (MW)	224 (1)	1,230 (6)	1,230 (6)
Specific investment cost (MEuro/MW)	1.86	1.6	1.6
Cumulative Capex (Meuro)	***372***	***2,076***	***2,076***
Scenario B (CAGR 29.5%)			
CIC (MW)	224	**2,134 (10)**	390,317 (1951)
Specific investment cost (MEuro/MW)	1.80	1.54	1.02
Cumulative Capex (Meuro)	*380*	*2,928*	*429,374*

Methanol

Data sources for methanol are obtained from two different studies, from Pacific Northwest National Laboratory (PNNL) (Zhu, et al., 2011), and from VTT (Hannula, et al., 2013). These studies provide detailed information of operating units and mass and energy balances. The learning rate parameters were assigned as discussed in the liquefied biomethane case for the gasification step, while the methanol synthesis step was a considered a mature technology. The initial capacity selected for a starting capacity is considered 200MW and it is characterized by a CAGR of the syngas (using the market size of syngas on global scale) assuming that bio- methanol production will follow the growth rate bio-based syngas. It should be noted that in Table A 8, methanol capacity refers to the current installed capacity of methanol regardless its use as a fuel or chemical. This may lead to an overestimation of CAPEX values of installed capacities to achieve a specific target of biobased methanol contribution in the fossil based methanol when the capacity of the fossil based one as a transportation fuel is overestimated.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Table A 8 Input data for learning curve model for methanol

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Syngas	0.05		0.05		The minimum value of LR, In accordance with D3.5
Methanol	0.05		0.02		Detz et al. 2018
Gasifier (in Gasification Step)	0.15		0.05		Value greater that 10% that is the average according to Detz et al., 2018, In accordance with D3.5
Cumulative installed capacity (CIC)					
Syngas	200	MW		Sweden	Theoretical value as a scale up of the implemented 20 MW
Methanol	57,040	MW		Global	Assuming 90 million tonnes (M. Alvarado, IHS Chem. Week, 2016, 10–11.)
					Using LHV 19.9 MJ/kg
Cumulative annual growth rate (CAGR)					
Syngas	0.11		0.03	Global	Assuming CAGR of syngas totally produced regardeless fossil or bio-based https://www.globenewswire.com/news-release/2019/03/25/1760424/0/en/Global-Syngas-Market-Growth-Trends-and-Forecast-to-2024-Market-is-Expected-to-Grow-at-a-CAGR-of-11-02.html
Methanol	0.07		0.02	Global	Detz et al. 2018

Results for KPI

Scenario A shows that an increase of the installed capacity by one order of magnitude can be achieved with the selected CAGR=14% with CIC =2,050MW and Cumulative CAPEX ranging between 1,980 and 3,834 MEuro. To achieve maturity (TRL 9), CIC = 6,938MW is required which corresponds to a contribution of 3% of biobased methanol to the production of fossil-based methanol for 2050. As shown in Scenario B the contribution of 20% of biobased methanol to the fossil-based equivalent can be succeeded with a CAGR =21.5%, with a Cumulative CAPEX of 36,008-80,337 MEuro.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Table A 9 KPI calculations for methanol

	TRL	7-8	8-9	9 mature
		Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
	Scenario A (Conservative greening) (CAGR 14%)			
VTT (Hannula, et al., 2013)	CIC (MW)	249 (1)	2,050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	2.08	1.75	1.59
	Cumulative Capex (Meuro)	518	3,834	11,875
Indirect gasification (Zhu, et al., 2011)	CIC (MW)	249 (1)	2050 (10)	6938 (35)
	Specific investment cost (MEuro/MW)	1.15	0.86	0.74
	Cumulative Capex (Meuro)	286	1,980	5,792
Direct gasification (Zhu, et al., 2011)	CIC (MW)	249 (1)	2050 (10)	6938 (35)
	Specific investment cost (MEuro/MW)	1.65	1.21	1.03
	Cumulative Capex (Meuro)	411	2,809	8,124
	Scenario B (CAGR 21.5%)			
VTT (Hannula, et al., 2013)	CIC (MW)	284	1934 (10)	53,297 (266)
	Specific investment cost (MEuro/MW)	2.06	1.77	1.42
	Cumulative Capex (Meuro)	583	3,641	80,337
Indirect gasification (Zhu, et al., 2011)	CIC (MW)	284	1934 (10)	53,297 (266)
	Specific investment cost (MEuro/MW)	1.13	0.87	0.61
	Cumulative Capex (Meuro)	320	1,880	36,008
Direct gasification (Zhu, et al., 2011)	CIC (MW)	284	1934 (10)	53,297 (266)
	Specific investment cost (MEuro/MW)	1.62	1.23	0.83
	Cumulative Capex (Meuro)	459	2,663	49,121

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Dimethylether (DME):

For the case of DME in the PNNL report (Zhu, et al., 2011), the processing steps include the previous steps described for methanol synthesis (for direct and indirect cases) and one more step for the synthesis of DME. The study of VTT is based on one-step DME synthesis from syngas, using Haldor Topsøe's fixed-bed reactor design, and the recovery and distillation section for the preparation of fuel-grade dimethyl ether.

For the CIC we use the limiting capacity of 200MW and it is characterized by a CAGR of the syngas (using the market size of syngas on global scale) assuming that bio-DME production will follow the growth rate bio-based syngas. The respective capacity for DME for the year 2018 is also used which refers to the total production of DME regardless its use as fuel or chemical.

Table A 10 Input data for learning curve model of DME

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Syngas	0.15		0.05		Value greater that 10% that is the average according to Detz et al., 2018, In accordance with D3.5
Methanol	0.05		0.02		Detz et al. 2018
DME	0.05		0.02		Detz et al. 2018
Gasification to methanol (bio-methanol)	0.05		0.02		The minimum value of LR, In accordance with D3.5
Gasification to DME (bio-DME)	0.05		0.02		The minimum value of LR, In accordance with D3.5
Cumulative installed capacity (CIC)					
Syngas	200	MW		Sweden	Theoretical value as a scale up of the implemented 20 MW
Methanol	57,040	MW		Global	M. Alvarado, IHS Chem. Week, 2016, 10–11.
DME	7,288	MW		Global	https://www.sciencedirect.com/science/article/abs/pii/S1875510012000650
Cumulative annual growth rate (CAGR)					
Syngas	0.11		0.03	Global	https://www.globenewswire.com/news-release/2019/03/25/1760424/0/en/Global-Syngas-Market-Growth-Trends-and-Forecast-to-2024-Market-is-Expected-to-Grow-at-a-CAGR-of-11-02.html
Methanol	0.07		0.02	Global	Detz et al., 2018
DME	0.07		0.02		Similar to methanol

Results for KPI

Scenario A shows that an increase of the installed capacity by one order of magnitude can be achieved with the selected CAGR=14% with CIC =2,050MW and Cumulative CAPEX ranging between 1,840 and 4,074 MEuro. To achieve maturity (TRL 9), CIC = 6,938MW is required which corresponds to a contribution of 15% of biobased DME to the production of fossil-based DME for 2050. As shown in Scenario B the contribution of 20% of biobased DME to the fossil-based equivalent can be succeeded with a CAGR =15%, with a Cumulative CAPEX of 6,986 -16,086 MEuro.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Table A 11 KPI calculations

	TRL	7-8	8-9	9 mature
		Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
	Scenario A (Conservative greening) (CAGR 14%)			
VTT (Hannula, et al., 2013)	CIC (MW)	249	2,050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	2.25	1.83	1.64
	Cumulative Capex (MEuro)	561	4,074	12,426
Direct gasification (Zhu, et al., 2011)	CIC (MW)	249	2,050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	1.65	1.21	1.03
	Cumulative Capex (MEuro)	412	2,816	8,150
Indirect gasification (Zhu, et al., 2011)	CIC (MW)	249	2,050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	1.06	0.80	0.70
	Cumulative Capex (MEuro)	265	1,840	5,431
	Scenario B (CAGR 15%)			
VTT (Hannula, et al., 2013)	CIC (MW)	254(1)	1939(10)	9175(46)
	Specific investment cost (MEuro/MW)	2.25	1.84	1.61
	Cumulative Capex (MEuro)	571	3,874	16,086
Direct gasification (Zhu, et al., 2011)	CIC (MW)	254(1)	1939(10)	9175(46)
	Specific investment cost (MEuro/MW)	1.65	1.22	1.00
	Cumulative Capex (MEuro)	419	2,682	10,419
Indirect gasification (Zhu, et al., 2011)	CIC (MW)	254(1)	1939(10)	9175(46)
	Specific investment cost (MEuro/MW)	1.06	0.81	0.68
	Cumulative Capex (MEuro)	268	1,753	6,986

FT liquids (Diesel, jet fuel and gasoline))

FT process coproduces diesel with naphtha, jet fuel, and gasoline. In this case the evolution of diesel market is considered is the driving product for that market and that is the product with the higher percentage of production among the other co-products. The initial capacity selected for a starting capacity is considered 200MW and it is characterized by a CAGR of the syngas (using the market size of syngas on global scale) assuming that FT liquids production will follow the growth rate bio-based syngas. The respective capacity for FT process is obtained from the study of Detz et al., 2018. Market demand values were found for syngas (2024) and FT liquids, and these were used for setting CAGR values in Scenarios A and B, following the approach described above

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Table A 12 Input data for learning curve model of FT liquids (through FT synthesis)

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Syngas	0.15		0.05		Value greater that 10% that is the average according to Detz et al., 2019, In accordance with D3.5
FT synthesis plant	0.05		0.02		Detz et al., 2018
Cumulative installed capacity (CIC)					
Syngas	200	MW		Sweden	Theoretical value as a scale up of the implemented 20 MW
FT synthesis plant	40,000	MW		Global	Detz et al., 2018
Cumulative annual growth rate (CAGR)					
Syngas	0.11		0.03	Global	https://www.globenews-wire.com/news-release/2019/03/25/1760424/0/en/Global-Syngas-Market-Growth-Trends-and-Forecast-to-2024-Market-is-Expected-to-Grow-at-a-CAGR-of-11-02.html
FT synthesis plant	0.13		0.05	Global	Detz et al 2018, refers to FT liquids

Results for KPI

Scenario A shows that an increase of the installed capacity by one order of magnitude can be achieved with the selected CAGR=14% with CIC =2,050MW and Cumulative CAPEX ranging between 2,992 and 4,669 MEuro. To achieve maturity (TRL 9), CIC = 6,938MW is required which corresponds to a contribution of 1% of biobased FT liquids to the production of fossil-based FT liquids for 2050. As shown in Scenario B the contribution of 20% of biobased FT liquids to the fossil-based equivalents can be succeeded with a CAGR =26.8%, with a Cumulative CAPEX of 222,217-398,259MEuro.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Table A 13 Results for KPI for diesel (through FT synthesis)

	TRL	7-8	8-9	9 mature
		Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
	Scenario A (Conservative greening) (CAGR 14%)			
Indirect gasification (Zhu et al., 2011)	CIC (MW)	249 (1)	2050 (10)	6937(35)
	Specific investment cost (MEuro/MW)	1.66	1.33	1.18
	Cumulative Capex (Meuro)	417	2,992	9,025
Direct gasification (Zhu et al., 2011))	CIC (MW)	249 (1)	2050 (10)	6937(35)
	Specific investment cost (MEuro/MW)	2.10	1.70	1.51
	Cumulative Capex (Meuro)	523	3,789	11,503
High-temperature gasification -steam/oxygen-fed entrained flow (Swanson, et al., 2010)	CIC (MW)	249 (1)	2050 (10)	6937(35)
	Specific investment cost (MEuro/MW)	2.60	2.08	1.85
	Cumulative Capex (Meuro)	649	4,669	14,105
Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	CIC (MW)	249 (1)	2050 (10)	6937(35)
	Specific investment cost (MEuro/MW)	2.68	2.20	1.97
	Cumulative Capex (Meuro)	668	4,874	14,892
	Scenario B (CAGR 14.3%)			
Indirect gasification Zhu et al., 2011)	CIC (MW)	309 (1)	2182 (10)	208,968 (1045)
	Specific investment cost (MEuro/MW)	1.64	1.38	0.99
	Cumulative Capex (Meuro)	507	3,231	222,217
Direct gasification, (Zhu et al., 2011))	CIC (MW)	309 (1)	2182 (10)	208,968 (1045)
	Specific investment cost (MEuro/MW)	2.08	1.76	1.26
	Cumulative Capex (Meuro)	642	4,097	280,297
High-temperature gasification -steam/oxygen-fed entrained flow (Swanson, et al., 2010)	CIC (MW)	309 (1)	2182 (10)	208,968 (1045)
	Specific investment cost (MEuro/MW)	2.57	2.20	1.66
	Cumulative Capex (Meuro)	792	5,098	365,091
Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	CIC (MW)	309 (1)	2182 (10)	208,968 (1045)
	Specific investment cost (MEuro/MW)	2.66	2.33	1.82
	Cumulative Capex (Meuro)	818	5,345	398,259

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Ethanol

In the thermochemical route, biomass is first converted by gasification, typically above 800 oC, into synthesis gas, which is thereafter conditioned and catalytically converted into ethanol. NREL (Dutta et al., 2010) considers indirect steam gasification for the conversion of woody biomass to ethanol, and the syngas is then, cleaned, conditioned, and converted to mixed alcohols over a solid catalyst. Two more studies were used as sources for the current analysis that is , the study of Valle et al., (2013) that investigates ethanol from biomass via steam–air indirect circulating fluidized bed gasification (iCFBG) and subsequent catalytic synthesis and the study of Perales et al., (2011) that is based on an entrained flow gasification conversion process. The initial capacity selected for a starting capacity is considered 200MW and it is characterized by a CAGR of the syngas (using the market size of syngas on global scale) assuming that liquids (ethanol and mixed alcohols) production will follow the growth rate bio-based syngas. The respective capacity for mixed alcohols synthesis process was based on an assumed capacity of 200 MW Market demand values were found for syngas (2024) and bio-ethanol, and these were used for setting CAGR values in Scenarios A and B, following the approach described above It should be noted that the CAGR refers to the growth rate of bioethanol in general, including first generation production

Table A 14 Input data for learning curve model of ethanol

Input data for LC model					
Technology	**Value**		**Range**	**Region**	**Reference**
Learning rate (LR)					
Gasification step	0.05		0.05		The minimum value of LR, In accordance with D3.5
Gas cleanup (in gasification step)	0.15		0.02		Value greater that 10% that is the average according to Detz et al., 2018, In accordance with D3.5
Alcohol synthesis	0.05		0.02		The minimum value of LR, In accordance with D3.5
Cumulative installed capacity (CIC)					
Gasification step	200	MW			Theoretical value as a scale up of the implemented 20 MW
Alcohol synthesis	200	MW			Assumption
Cumulative annual growth rate (CAGR)					
Gasification step	0.11		0.03	Global	https://www.globenewswire.com/news-release/2019/03/25/1760424/0/en/Global-Syngas-Market-Growth-Trends-and-Forecast-to-2024-Market-is-Expected-to-Grow-at-a-CAGR-of-11-02.html
Alcohol synthesis (Ethanol assumed)	0.06		0.02	Global	Worldwide, commercial aviation is forecast to grow at up to 5% a year and this trend is forecast to continue towards 2050. https://renewablesnow.com/news/ethanol-industry-to-grow-at-cagr-of-6-in-2010-2018-study-70224/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º764799.

Results for KPI

Scenario A corresponds to a with a very small number of plants(3) in the considered time frame where the TRL increase is studied (2020-2050). Thus, an increase of the installed capacity by one order of magnitude cannot be achieved with the selected CAGR in this time frame. In Scenario B the contribution of bioethanol in a 10%w/w gasoline blend is investigated for 2050. Total gasoline capacity (2017) equals to 103,036MW assuming a CAGR=10% (Capacity refers to 3,251,525TJ TJ of road and ship gasoline obtained from https://www.eea.europa.eu/data-and-maps/daviz/transport-energy-consumption-eea-5#tab-chart_2 for final energy consumption per type of fuel in transportation). In this case CAGR of bioethanol should be 25.8% to achieve this target.

Table A 15 Results for KPI for ethanol

	TRL	7-8	8-9	9 mature
		Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
	Scenario A (Conservative greening) (CAGR 14%)			
Duta et al., 2010	CIC (MW)	250(1)	2050 (10)	6938 (31)
	Specific investment cost (MEuro/MW)	2.59	2.27	2.13
	Cumulative Capex (Meuro)	647	4,903	15,548
Valle et al., (2013)	CIC (MW)	250(1)	2050 (10)	6938 (31)
	Specific investment cost (MEuro/MW)	2.81	2.23	1.98
	Cumulative Capex (Meuro)	700	5,008	15,109
Perales et al., 2011	CIC (MW)	250(1)	2050 (10)	6938 (31)
	Specific investment cost (MEuro/MW)	2.18	1.72	1.53
	Cumulative Capex (Meuro)	545	3,881	11,682
	Scenario B (CAGR 24.3%)			
Duta et al., 2010	CIC (MW)	297 (1)	2135 (10)	110,494 (552)
	Specific investment cost (MEuro/MW)	2.59	2.41	2.13
	Cumulative Capex (Meuro)	769	4,526	241,768
Valle et al., (2013)	CIC (MW)	297 (1)	2135 (10)	110,494 (552)
	Specific investment cost (MEuro/MW)	2.81	2.48	1.98
	Cumulative Capex (Meuro)	832	5,554	230,327
Perales et al., 2011	CIC (MW)	297 (1)	2135 (10)	110,494 (552)
	Specific investment cost (MEuro/MW)	2.18	1.92	1.53
	Cumulative Capex (Meuro)	648	4,312	177,919

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Pyrolysis plant

The study refers to fast pyrolysis oil from biomass and the upgrading of that bio-oil as a means for generating infrastructure-ready renewable gasoline and diesel fuels. The fast pyrolysis of biomass is already commercialized on a small scale (15-30MW as described in D3.2), while upgrading bio-oil to transportation fuels has only been demonstrated in the laboratory and at small engineering development scale. Pyrolysis upgrading path is assumed to produce diesel as main product, gasoline and naphtha. Calculations are based on a CIC of the existing capacity that is 185MW (170,424tonnes/year) and considering the CAGR of 10% assuming an average rate of commercial processes as described in Detz et al., 2018. The actual production capacity of diesel fuel is found equal to 291,600 MW (Capacity refers to 9,204,686.26TJ TJ of road and ship diesel) and the respective capacity of gasoline equals 103,036MW (Capacity refers to 3,251,525TJ TJ of road and ship gasoline, obtained from https://www.eea.europa.eu/data-and-maps/daviz/transport-energy-consumption-eea-5#tab-chart_2 for final energy consumption per type of fuel in transportation).

Table A 16 Input data for learning curve model of pyrolysis based liquids (diesel and gasoline)

Input data for LC model					
Technology	**Value**		**Range**	**Region**	**Reference**
Learning rate (LR)					
Pyrolysis	0.05		0.02		Daugard et al., 2014
Hydroprocessing	0.2		0.06		Daugard et al., 2014
Cumulative installed capacity (CIC)					
Pyrolysis	158	MW			Based on data given on D3.2
Hydroprocessing	20	MW			Based on assumption
Cumulative annual growth rate (CAGR)					
Pyrolysis	0.1		0.03	Global	Assumption according to Detz et al. 2018 that refers to most mature technologies have a CAGR between 7% and 13%
Diesel	0.1		0.03	Global	Assumption according to Detz et al. 2018 that refers to most mature technologies have a CAGR between 7% and 13%
Gasoline	0.1		0.03	Global	Assumption according to Detz et al. 2018 that refers to most mature technologies have a CAGR between 7% and 13%

Results for KPI

Scenario A shows that an increase of the installed capacity by one order of magnitude can be achieved with the selected CAGR=14% with CIC =2,050MW and Cumulative CAPEX ranging between 1,622 and 3,409 MEuro. To achieve maturity (TRL 9), CIC = 6,938MW is required which corresponds to a contribution of 0.2% of pyrolysis based liquid fuels (diesel and gasoline) to the production of conventional diesel and gasoline for 2050. As shown in Scenario B the contribution of 20% of biobased pyrolysis liquids to the fossil-based equivalents can be succeeded with a CAGR =32.5%, with a Cumulative CAPEX of 442,558-918,650 MEuro.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

Table A 17 Results of KPI for diesel and gasoline

	TRL	TRL	7-8	8-9
	year	year	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
	Scenario A (Con-servative greening) (CAGR 14%)			
Zhu et al., 2011	CIC (MW)	250 (1)	2050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	0.91	0.72	0.63
	Cumulative Capex (Meuro)	228	1,622	5,581
Zhu et al., 2011	CIC (MW)	250 (1)	2050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	1.79	1.48	1.33
	Cumulative Capex (Meuro)	358	3,188	9,945
Dutta et al., 2015	CIC (MW)	250 (1)	2050 (10)	6,938 (35)
	Specific investment cost (MEuro/MW)	1.86	1.54	1.39
	Cumulative Capex (Meuro)	464	3,409	10,470
	Scenario B *CAGR 32.5%)			
Zhu et al., 2011	CIC (MW)	337 1)	2099 (10)	853,439 (4267)
	Specific investment cost (MEuro/MW)	0.90	0.78	0.48
	Cumulative Capex (Meuro)	303	1,733	442,558
Zhu et al., 2011	CIC (MW)	337 1)	2099 (10)	853,439 (4267)
	Specific investment cost (MEuro/MW)	1.76	1.53	0.97
	Cumulative Capex (Meuro)	592	3,396	883,965
Dutta et al., 2015	CIC (MW)	337 1)	2099 (10)	853,439 (4267)
	Specific investment cost (MEuro/MW)	1.76	1.58	1
	Cumulative Capex (Meuro)	593	3,522	918,650

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

1. Biochemical Pathway

Ethanol

Data for ethanol are based on the study of Humbird et al. (NREL) where ethanol is produced from corn stover through biochemical conversion. Ethanol production is described by one conceptual processing step. Cost decomposition is based on the same study and refers to a simulation study of 161 MW ethanol.

Learning rates for cellulosic ethanol are based on the study of Daugaard et al.2018 and are equal to 0.05, referring to the entire step, whereas from the component analysis of the ethanol production step, two of them where characterized as less mature: the enzymatic hydrolysis and fermentation and enzyme production which are sub-steps with potential of improvements. For the CIC parameter the capacity of the existing ethanol plants in operation is selected (Cost reduction of biofuels report, IEA, 2020). It should be noted that the CAGR refers to the growth rate of bioethanol in general, including first generation production. In this case ethanol is investigated for its contribution as an additive in 10% blend with gasoline. An initial capacity of ethanol plants is assumed equal to 145MW. The CAGR is based on the bioethanol growth rate between the years.

Table A 18 Input data for learning curve model of ethanol production

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Ethanol Step	0.05		0.02		T. Daugaard et al.
Hydrolysis and Fermentation (in Ethanol Step)	0.15		0.05		Value greater that 10% that is the average according to Detz et al., 2019, In accordance with D3.5
Cumulative installed capacity (CIC)					
Ethanol	304	MW	358000	t/a	Cost reduction of biofuels report, IEA (2020)
Cumulative annual growth rate (CAGR)					
Ethanol	0.06,		0.02	Global	Refers to bioethanol market, https://www.marketwatch.com/press-release/cagr-of-5-bioethanol-market-escalating-with-cagr-of-5-by-2026-2019-05-21 and https://renewablesnow.com/news/ethanol-industry-to-grow-at-cagr-of-6-in-2010-2018-study-70224/

Results for KPI

Scenario A corresponds to a with a very small number of plants (3) in the considered time frame where the TRL increase is studied (2020-2050). Thus, an increase of the installed capacity by one order of magnitude cannot be achieved with the selected CAGR in this time frame. In Scenario B the contribution of bioethanol in a 10%w/w gasoline blend is investigated for 2050. Total gasoline capacity (2017) equals to 103,036MW assuming a CAGR=10% (Capacity refers to 3,251,525TJ TJ of road and ship gasoline obtained from https://www.eea.europa.eu/data-and-maps/daviz/transport-energy-consumption-eea-5#tab-chart_2 for final energy consumption per type of fuel in transportation). In this case CAGR of bioethanol should be 25.8% to achieve this target.

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Table A 19 KPI results for ethanol production

TRL	7-8	8-9	9 mature
year	Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
Scenario A (Conservative greening) (CAGR 14%)			
CIC (MW)	156	490(3)	490(3)
Specific investment cost (MEuro/MW)	2.28	2.03	2.03
Cumulative Capex (Meuro)	357	1,067	1,067
Scenario B (CAGR=25.8%)			
CIC (MW)	220 (1)	1450 (10)	117,593
Specific investment cost (MEuro/MW)	2.28	2.20	2.03
Cumulative Capex (Meuro)	503	3,240	242,869

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Ethanol to Jet fuels

Calculations are based on a CIC of the existing capacity that is 145MW (170,424 tonnes/year) and considering the CAGR of bio-ethanol that is 6%. The actual production capacity of jet (aviation) fuels is found equal to 75,929MW (Capacity corresponds to 2,396,089 TJ of aviation kerosene obtained from https://www.eea.europa.eu/data-and-maps/daviz/transport-energy-consumption-eea-5#tab-chart_2 for final energy consumption per type of fuel in transportation)

Table A 20 Input data for learning curve model for jet fuels production through ethanol

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Ethanol Step	0.05		0.02		T. Daugaard et al.
Hydrolysis and Fermentation (in Ethanol Step)	0.15		0.05		Value greater that 10% that is the average according to Detz et al., 2019, In accordance with D3.5
Ethanol to Jet Fuels	0.05		0.02		The minimum value of LR, In accordance with D3.5
Cumulative installed capacity (CIC)					
Ethanol	145	MW	358000	t/a	Adding capacities from http://www.etipbioenergy.eu/value-chains/products-end-use/products/cellulosic-ethanol#best
Jet fuels	75,929	MW			Capacity refers to 2,396,089 TJ of aviation kerosene for 2017 obtained from https://www.eea.europa.eu/data-and-maps/daviz/transport-energy-consumption-eea-5#tab-chart_2 for final energy consumption per type of fuel in transportation
Cumulative annual growth rate (CAGR)					
Ethanol	0.06		0.02	Global	Refers to bioethanol market, https://www.marketwatch.com/press-release/cagr-of-5-bioethanol-market-escalating-with-cagr-of-5-by-2026-2019-05-21 and https://renewablesnow.com/news/ethanol-industry-to-grow-at-cagr-of-6-in-2010-2018-study-70224/
Jetfuels	0.05		0.02	Global	https://www.marketwatch.com/press-release/aviation-fuel-market-2019-global-industry-size-by-leading-manufacturers-growth-rate-demand-status-professional-study-forecast-to-2026-2019-09-05

Results for KPI

Scenario A corresponds to a with a very small number of plants (3) in the considered time frame where the TRL increase is studied (2020-2050). Thus, an increase of the installed capacity by one order of magnitude cannot be achieved with the selected CAGR in this time frame.

As shown in Scenario B the contribution of 20% of biobased jet fuels to the fossil-based equivalents can be succeeded with a CAGR =21.5%, with a Cumulative CAPEX of 102,993 MEuro.

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Table A 21   Results of KPI for Jet fuels

	TRL	7-8	8-9	9 mature
	year	Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
Biomass to jet fuels	**Scenario A (6%)**			
	CIC (MW)	156	490(3)	490(3)
	Specific investment cost (MEuro/MW)	3.67	3.32	3.32
	Cumulative Capex (Meuro)	574	1,727	1,727
Biomass to jet fuels	**Scenario B *CAGR 21.5%)**			
	CIC (MW)	206	1,402 (10)	38641 (266)
	Specific investment cost (MEuro/MW)	3.60	3.12	2.51
	Cumulative Capex (Meuro)	739	4,637	102,993

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Butanol

There are two major ways to ferment biobutanol (here referring to both n-butanol and iso-butanol), i.e. the ABE process using wild bacteria strains for n-butanol, and the process using bacteria or yeasts for iso butanol and n-butanol production.

The current international price of bulk grade butanol is approximately $4 per gallon (liquid fuel) with a worldwide market of 350 million gallons per year which corresponds to a capacity equal to 1,115MW. The conventional chemical processes for butanol synthesis include the oxo process, wherein synthesis gas is reacted with propylene and hydrogenated subsequently to produce butanol (Bankar et al., 2013) with a CAGR =5%.

The initial capacity selected for a starting capacity is considered 200MW and it is characterized by a CAGR of biobutanol.

It should be noted that in Table A 22, butanol capacity refers to the current installed capacity of butanol regardless its use as a fuel or chemical. This may lead to an overestimation of CAPEX values of installed capacities to achieve a specific target of biobased butanol contribution in the fossil based methanol when the capacity of the fossil based one as a transportation fuel is overestimated.

Table A 22 Input data for learning curve model for butanol

Technology	Value		Range	Region	Reference
Learning rate (LR)					
n-butanol					
ABE process	0.05		0.02		In accordance with D3.5
Fermentation (of C5 & C6)	0.15		0.05		Value greater that 10% that is the average according to Detz et al., 2019, In accordance with D3.5
Iso-butanol			0.00		In accordance with D3.5
Saccharification & fermentation	0.15		0.05		In accordance with D3.5
On-site enzyme production	0.15				Value greater that 10% that is the average according to Detz et al., 2019, In accordance with D3.5
Cumulative installed capacity (CIC)					
n-butanol	200	MW			Assumption
Iso-butanol	200	MW			Assumption
Cumulative annual growth rate (CAGR)					
Biobutanol overall	0.0836		0.03	Global	https://www.researchandmarkets.com/reports/4515064/global-bio-butanol-market-growth-trends-and?utm_source=GN&utm_medium=PressRelease&utm_code=9m9jvb&utm_campaign=1230214+-+World+Bio-Butanol+Market+to+Post+a+CAGR+of+8.36%25+During+2019-2024+-+Key+Market+Insights&utm_exec=joca220prd
Butanol (coventional)	0.05				https://www.marketsandmarkets.com/Market-Reports/n-butanol-market-1089.html

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Results for KPI

Scenario A corresponds to a with a very small number of plants (6) in the considered time frame where the TRL increase is studied (2020-2050). Thus, an increase of the installed capacity by one order of magnitude cannot be achieved with the selected CAGR in this time frame. With this specific CAGR =8% Both n-butanol and iso-butanol contribute to 44% of the total butanol production for 2050.

In Scenario B the contribution of biobutanol in a 10%w/w gasoline blend is investigated for 2050. Total gasoline capacity (2017) equals to 103,036MW assuming a CAGR=10% (Capacity refers to 3,251,525TJ TJ of road and ship gasoline obtained from https://www.eea.europa.eu/-data-and-maps/daviz/transport-energy-consumption-eea-5#tab-chart_2 for final energy consumption per type of fuel in transportation). In this case CAGR of biobutanol should be 24.5% to achieve this target.

Table A 23 Results of KPI for butanol

	TRL	7-8	8-9	9 mature
	year	Initial capacity	Estimated number of plants (in parenthesis)	Estimated number of plants (in parenthesis)
	Scenario A (8%)			
n-butanol	CIC (MW)	224	1230 (6)	1230 (6)
	Specific investment cost (MEuro/MW)	3.76	3.23	3.23
	Cumulative Capex (Meuro)	842	4,271	4,271
Iso-butanol	CIC (MW)	224	1230 (6)	1230 (6)
	Specific investment cost (MEuro/MW)	2.47	2.05	2.05
	Cumulative Capex (Meuro)	554	2202	2202
	Scenario B (24.5% CAGR)			
n-butanol	CIC (MW)	297 (1)	2176 (10)	116,327 (582)
	Specific investment cost (MEuro/MW)	3.76	3.57	3.23
	Cumulative Capex (Meuro)	1,119	7,936	384,800
Iso-butanol	CIC (MW)	297 (1)	2176 (10)	116,327 (582)
	Specific investment cost (MEuro/MW)	2.47	2.32	2.05
	Cumulative Capex (Meuro)	736	5,179	245,323

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Annex V Well-to-Weel (WtW) analysis

Table A 24 LCA factors used for estimation of KgCO2eq and MJeq

LCA factors	*IPCC 2007*	*CED*	
	GWP 100a	*CED fossil*	*Renewable, biomass*
	kg CO2-eq	*MJ-eq*	*MJ-eq*
Wood chips, mixed, u=120%, at forest/RER S (m3) (d=188.6kg/m3 dried matter)	5.48	79.52	3799.20
Wood chips, mixed, u=120%, at forest/RER S (kg)	0.03	0.42	20.14
Chemicals inorganic, at plant/GLO (kg)	1.86	20.94	0.29
Heat, natural gas, at industrial furnace >100kW/RER (MJ)	0.07	4.03	0.00
Heat, natural gas, at industrial furnace >100kW/RER (m3)	0.00	0.11	0.00
Electricity, medium voltage, production RER, at grid/RER (kWh)	0.50	6.17	0.25
Water, deionised, at plant/CH (kg)	0.00	0.00	0.01
oxygen, liquid, at plant/RER (kg)	0.41	4.97	0.11
Steam, for chemical processes, at plant/RER (kg)	0.23	3.92	0.00
Ash disposal (kg)	0.01	0.28	
Silica sand, at plant (kg)	0.02	0.30	0.00
Zeolite, powder, at plant	4.20	58.63	0.84
Sodium hydroxide, 50% in H2O, production mix, at plant	1.10	13.26	0.34
nitrogen, liquid, at plant	0.43	5.26	0.12
rape methyl ester, at esterification plant, RER, [kg]	2.62	22.55	47.60
limestone, milled, packed, at plant, CH, [kg]	0.02	0.27	0.25
potassium carbonate, at plant, GLO, [kg]	2.33	30.91	0.47
charcoal, at plant, GLO, [kg]	1.12	1.52	66.78
sulphuric acid, liquid, at plant, RER, [kg]	0.12	1.72	0.04
ammonia, steam reforming, liquid, at plant, RER, [kg]	1.91	38.99	0.07
diammonium phosphate, as N, at regional storehouse, RER, [kg]	2.80	54.07	0.29
sulphur dioxide, liquid, at plant, RER, [kg]	0.42	5.68	0.10
hydrogen, liquid, at plant, RER, [kg]	1.67	67.93	0.14

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