D3.6 Efficient, low-risk ramp-up of liquid biomass conversion technologies - from short time to long term

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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 CO2 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, it will investigate individual barriers and advance 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 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 for ensuring that renewable fuels are truly sustainable fuels. A decision support tools will be created for policy-makers to enable a full value chain assessment of renewable fuels, as well as useful scenarios and 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 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 to 2030 and beyond.

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Executive Summary

This report discusses the implementation of biomass conversion processes within the ADVANCEFUEL scope from short to long term (2020 to 2050) considering technology maturity and providing data on projected capacity growth rates and capital investment costs based on the learning curve methodology. The investigated liquid biofuels and pathways for their production are based on those proposed in the ADVANCEFUEL framework as already analysed in previous project deliverables. CAPEX values typically represent 30% to 45% of the overall production cost, a similar range referring to the feedstock cost while other operating and maintenance costs typically cover 15%-20% of the overall production cost. Considering the high process efficiency and TRL at demonstration scale of the investigated pathways, the scope of CAPEX reduction remains the most important techno-economic aspect. Feedstock costs are equally significant, but it is more a matter of feedstock price than feedstock efficiency for the investigated pathways, the only exception being ethanol from fermentation with respect to the potential for alternative use of hemicellulose and lignin-based by-products.

A scenario based analysis showed that CAPEX reduction in the range of 10-25% could be expected when moving from first to Nth-of-a-kind plants and increasing the installed capacity by two orders of magnitude compared to the tenths or hundreds of MWs installed today in few demonstration and even fewer commercial plants. To reach further CAPEX reduction of 40%, for example, would require one more order of magnitude of cumulative installed capacity increase, reaching the scale of hundreds of GWs or equivalently some hundreds or thousands of large-scale plants. This target may well be interpreted as as an ambitious upper limit of what can be expected in CAPEX reductions.

It should be noted that the CAPEX reduction estimations entail uncertainties with respect to the technical learning potential of these components and especially after which time point (or installed capacity) this can be assumed to attain near zero values. One should not forget that most of the technical learning is allocated in assembling the plants which consist in a large extent from mature technological components. Thus, an update of the methodology parameters should be possible during the time horizon 2020-2050, assuming that more commercial plants of advanced biofuels will be in operation.

Besides the scope for CAPEX reduction, technical and economic factors, barriers and policy mechanisms associated with the scale–up of all investigated technologies are presented. Although CAPEX aspects of conversion technologies appear as significant barriers in this analysis, technical aspects related with catalyst development and utilisation of by-products, policy aspects referring to feedstock premiums and CO_2 taxes, as well as contemporary engine development are other important factors in generating a safe market for investments from private-public partnerships.

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1. Introduction

This deliverable is an extended version of D3.5 where the methodological framework of the learning curve theory was applied to demonstrate the projection of current capital expenditure (CAPEX) values in the time horizon 2020-2050. This approach was demonstrated in D3.5 only for a few selected fuels and pathways while here all advanced biofuels in the scope of the ADVANDEFUEL project are investigated. Considering that the technology readiness level (TRL) of the investigated technologies ranges from 6 to 9 and that the thermodynamic efficiencies and product yields in most of the cases (i.e., the exception being mainly bioethanol routes with respect to utilisation of biomass fractionation by-products such as hemicelluloses, lignin) are close to theoretical limits, the feedstock related cost does not depend so much on potential process optimisation but rather on factors related with the feedstock price. Feedstock price can be affected by many factors exogeneous to the conversion technology itself, such as advances in biomass production (as described in WP2), supporting policies (as described in WP5), competing technologies and future scenarios about the energy mix (as described in WP6). For these reasons, projections of this cost factor and how it can affect the efficient ramp-up of liquid biofuel technologies do not lie within the scope of this deliverable. Instead, the deliverable investigates in detail capital investment factors and their scope for cost reduction, which represents a big part of the financial risk for companies investing in these technologies.

Besides the cost factors mentioned above, the report contains two types of additional information: an inventory analysis of input and output streams for all investigated pathways and identification of technical and economic factors, barriers and policy mechanisms associated with the scale – up of all investigated technologies, extending in this way the preliminary analysis presented in D.3.3 for only a few cases. The inventory data presented here can be utilised for future projections of the operating costs of the conversion technologies, if scenarios for future prices of feedstock, chemical auxiliaries and energy carriers are available. Similarly, quantification of the economic effects of potential policies to remove the technical and economic barriers identified in this deliverable (e.g., easily access to capital, feedstock premiums, increased CO_2 taxes for fossil-based fuels) will help estimate further reduction potential for capital and operating costs.

The rest of this document is organised in the following way. First, an overview of literature sources providing the primary data for the analysis is presented in section 2, along with a summary of the current status in production costs of the investigated biofuels. Then, in section 3, the method for the multi-component technology learning approach is shortly presented (i.e., more details can be found in D3.5); however, the approach for setting the parameters of this method for the various process components in the investigated pathways is presented here in detail. In section 4, the scope for CAPEX reduction from short to long term based on the technical learning methodology is presented for all investigated

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pathways. In section 5 the work of D3.3 is extended by applying the same approach for linking technical and economic factors and the severity of the associated barriers with potential policy mechanisms for all investigated pathways. Section 6 concludes this work as well as WP3.

2. Conversion technologies

2.1 Primary data sources

Thermochemical pathways are investigated starting from lignocellulosic biomass as feedstock (e.g., hybrid poplar wood chips). The feedstock is kept in this generic form (i.e., nearly any wood type) and further of the cost results to the type of feedstock is not considered. The thermochemical pathways include production of liquified biomethane methanol, dimethylether (DME), diesel and kerosene from FT synthesis, and ethanol through gasification, as well as diesel and gasoline from pyrolysis.

Data sources for methanol and DME production are obtained from the studies of Pacific Northwest National Laboratory (PNNL) (Zhu, et al., 2011), and VTT (Hannula, et al., 2013). For FT liquids, data were obtained from the studies of Pacific Northwest National Laboratory (PNNL) (Zhu, et al., 2011), for direct and indirect gasification and from from NREL study (Swanson et al., 2010) for high (steam/oxygen-fed entrained flow) and low temperature (pressurized, steam/oxygen-fed fluidized bed gasifier) gasifiers. The economic assessment of liquified biomethane was based on data from the GoBiGas plant (Thunman et al., 2018) supplemented by data for the gas liquefaction process (Ahlström et al., 2017, Capra et al., 2019). The data for the biomass-to ethanol process refers to a process design where biomass is converted to syngas via indirect steam gasification, and the syngas is cleaned, conditioned, and converted to mixed alcohols. For this pathway, two studies were used as sources, 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.

Pyrolysis based products in the form of inventory tables and cost decomposition were based on the studies of Zhu, et al., (2011). 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 study of Dutta et al., (2015) described two conversion pathways for *in situ* and *ex situ* upgrading of vapors produced from the fast pyrolysis of biomass

Biochemical pathways include ethanol production through dilute-acid pretreatment and enzymatic hydrolysis of corn stover based on the study of Humbird et al. (2011). This pathway is also complemented

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by a jet fuels production step (Geleynse et al., 2018). Data for n- butanol production through ABE fermentation are based on the work of Jang and Choi (2018) and data for iso-butanol production through enzymatic hydrolysis and fermentation are based on the work of Tao et al., (2014).

The data collected from these literature sources are used for the process inventories and include information for the consumption of feedstock, chemicals auxiliaries and energy carriers as well as the process output streams such as the main product and by-products, waste streams, gas emissions streams and power production. These are presented in detail for all investigated pathways in Appendix A.

2.2 Cost data

Capital cost (CAPEX)

The capital cost estimates for the examined pathways are calculated based on Total Installed Cost (TIC), which includes purchased equipment and installation. The costs are estimated in a bottom-up approach, namely the purchased cost of the equipment is calculated and then cost factors are used to determine the installed equipment costs. The indirect costs (non-manufacturing fixed-capital investment costs including engineering, construction, contractors and fees and contingency costs) are estimated as a percentage of total purchased equipment costs. The total project investment (TPI) is the sum of the total installed cost (TIC) plus the total indirect costs. Detailed decomposition of CAPEX values for all pathways and the respective process components can be found in an MS Excel database in the ADVANCEFUEL website.

Considering these costs as representative for the first-of-a-kind (FOAK) plant corresponds to a more optimistic scenario with respect to future cost predictions. To estimate the point when the technology would reach the Nth-of-a-kind (NOAK) plant, several scenarios are developed in the current analysis, which refer to the degree of increase of capacities in short and long term.

Operating cost (OPEX)

The operating costs are divided into variable and fixed operating costs. The variable operating costs include biomass, raw materials and chemicals, such as catalysts, biomass feedstock, fuel consumption, utilities (such as cooling water, boiler water, electricity etc.) and waste disposal. Quantities of raw materials used as feedstock and wastes produced are determined from inventory tables discussed in the previous paragraph and detailed in Appendix A. Fixed operating costs do not depend on the productivity of the plant. These costs include labour and various overhead items, annual operating and maintenance costs, insurance etc. Operating costs are expressed as monetary unit per kg or per kWh of product(s). In Tables 1-7, operating costs are presented as the sum of these two cost categories.

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From the CAPEX and OPEX information in Tables 1-7, it can be inferred that gasification-based pathways have a lower specific investment cost compared to the biochemical ones, whereas the values of indirect gasification are lower than the respective of direct gasification.

Table 1 Total CAPEX and OPEX data for the case of methanol production.

	PNNL (Zhu, et al., 2011)	**PNNL (Zhu, et al., 2011)**	**VTT (Hannula, et al., 2013)**
	Indirect gasification	Direct gasification	Direct gasification
Input Capacity (MW)	437	437	335
Output Capacity (MW)	197	208	184
Total Project Investment (CAPEX)			
MEuro 2018	234	356	390
Euro/kW methanol	1189	1708	2117
OPEX			
Euro/kg (2018)	0.20	0.21	0.25
Euro/MWh	35.2	38.1	45.3

Table 2 Total CAPEX and OPEX data for the case of DME.

	PNNL (Zhu, et al., 2011)	**PNNL (Zhu, et al., 2011)**	**VTT (Hannula, et al., 2013)**
	Indirect gasification	Direct gasification	Direct gasification
Input Capacity (MW)	437	437	335
Output Capacity (MW)	207	194	179
Total Project Investment (CAPEX)			
MEuro 2018	226	354	401
Euro/kW DME	1095	1828	2233
OPEX			
Euro/kg (2018)	0.25	0.26	0.34
Euro/MWh	34.7	35.4	46.8

Table 3 Total CAPEX and OPEX data for the case of liquefied biogas.

	GoBiGas (Thunman et al., 2019, Capra et al., 2019, Ahlström et al., 2017)
	Indirect gasification
Input Capacity (MW)	329
Output Capacity (MW)	200
Total Project Investment (CAPEX)	
MEuro 2018	375
Euro/kW product	1875
OPEX	

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Euro/kg product (2018)	0.53
Euro/MWh product	39

Table 4 Total CAPEX and OPEX data for the case of FT liquid fuels.

	PNNL (Zhu et al., 2011)	PNNL (Zhu et al., 2011)	NREL (Tan et al., 2017)	NREL (Swanson et al., 2010)	NREL (Swanson et al., 2010)
	Indirect gasification	Direct gasification	Indirect gasification	High-T direct EFG	Low-T direct fluidized bed gasification
Input Capacity (MW)	406	406	431	389	389
Output Capacity (MW)	140	161	205	193	150
Total Project Investment (CAPEX)					
MEuro 2018	300	425	452	532	437
Euro/kW product	2142	2639	2206	2754	2919
OPEX					
Euro/kg product (2018)	0.50	0.50	0.50*	0.55	0.67
Euro/MWh product	41	41	42	45	55

*Calculated using an average low heating value of 43 MJ/kg.

Table 5 Total CAPEX and OPEX data for the case of pyrolysis liquid fuels.

	PNNL (Zhu et al., 2011)	NREL & PNNL (Dutta et al., 2015)	NREL & PNNL (Dutta et al., 2015)
	Fast pyrolysis	Fast Pyrolysis, *in situ* upgrading	Fast Pyrolysis, *ex situ* upgrading
Input Capacity (MW)	422 (+113 NG)	431	431
Output Capacity (MW)	356	234	244
Total Project Investment (CAPEX)			
MEuro 2018	263	428	462
Euro/kW product	738	1828	1895
OPEX			
Euro/kg product (2018)	0.40	0.56	0.51
Euro/MWh product	34	48	43

Table 6 Total CAPEX and OPEX data for the case of jet fuels and ethanol production from biochemical pathway.

	Geleynse et al., 2018	NREL (Humbird et al., 2011)
	Ethanol-to-Jet	Ethanol fermentation
Input Capacity (MW)	56 (+ 9.2 NG)	367
Output Capacity (MW)	53	161
Total Project Investment (CAPEX)		
MEuro 2018	23	371

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Euro/kW product	434	2300
OPEX		
Euro/kg product (2018)	0.13	0.37
Euro/MWh product	11*	49

*Calculated using an average low heating value of 43 MJ/kg.

Table 7 Total CAPEX and OPEX data for the case of butanol production.

	NREL (Tao et al., 2014)	NREL (Tao et al., 2014)	Jang and Choi, 2018 (scaled up)
	Isobutanol	ABE fermentation	ABE fermentation
Input Capacity (MW)	381	381	700
Output Capacity (MW)	149	125 (147 ABE)	164 (200 ABE)
Total Project Investment (CAPEX)			
MEuro 2018	376	380	760
Euro/kW butanol	2522	3053	4641
OPEX			
Euro/kg butanol (2018)	0.50	0.43	0.88
Euro/MWh butanol	54	47	96

3. Technology learning

3.1 The Learning curve framework

The learning curve framework was analysed in detail in D3.5 where the single factor approach was described to provide the way that production costs are reduced by a constant fraction for doubling of cumulative production. The multicomponent analysis was also described as an expansion of the first approach where cost reduction is not applied at the process level but independently at each process component. Assuming that the cost of each component decreases over time according to a power law relation as a result of learning, then the technology learning relationship may be expressed as follows (where the index *i* represents a given cost component):

$$C(Q_t) = \sum C(Q_{0i}) \cdot [\frac{Q_t}{Q_0}]^{-b(i)} = C_{01}[\frac{Q_{t1}}{Q_{01}}]^{-b(1)} + C_{02}[\frac{Q_{t2}}{Q_{02}}]^{-b(2)} + \cdots . + C_{0n}[\frac{Q_{tn}}{Q_{0n}}]^{-b(n)} \quad (1)$$

where b(i) is positive learning parameter for component i,

$C(Q_t)$ is the unit cost of production at cumulative production Q_t,

Q_0 is the cumulative production at an arbitrary starting point,

C_{0i} is the cost and Q_{0i} is the cumulative production of component i at an arbitrary starting point.

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3.2 Cost reduction methodology

To apply the multicomponent learning approach, each pathway is divided into a sequence of unit processes which produce the desired product (Fig 1, lower box). Each process is characterized by a particular maturity level expressed by an average learning rate parameter (LR), and the initial cumulative installed capacity (CIC) at a starting year (2018 is assumed in this case). Each process component has its own cumulative annual growth rate (CAGR); however, the annual growth rate of the whole pathway is at the end determined by the biomass processes related limiting step. For instance, in direct gasification producing methanol, air separation and methanol production from syngas are independent technologies with their own learning and growth rate parameters as they are used in many industrial applications, on the basis of which its production costs will decrease independently from the fact that they will be used or not in gasification plants. However, when CAGR will be used to reach specific capacity targets for the specific fuel under investigation, the CAGR of the pathway depends on the estimated growth rate of the biomass technology limiting step (i.e., gasification in this case). Thus, process components using conventional technologies with wider applications than those of biomass utilisation obtain LR and CAGR parameters from existing market trends for the same or equivalent technologies and products (upper box in Figure 1).

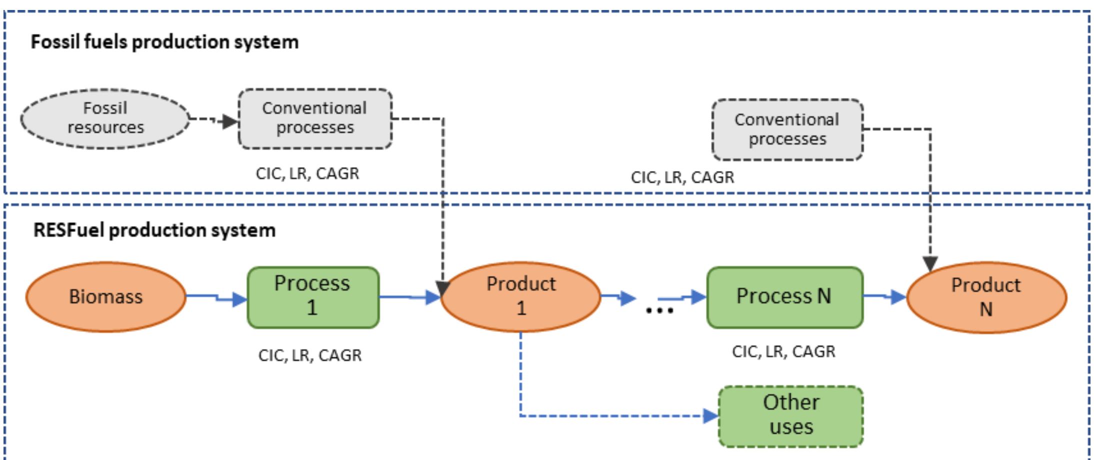

Figure 1 Representation of biobased pathway for the production of liquid biofuels.

Thus, the application of the learning curve theory to assess cost reduction potential through learning by doing is described in Figure 2 and it is composed of 3 steps.

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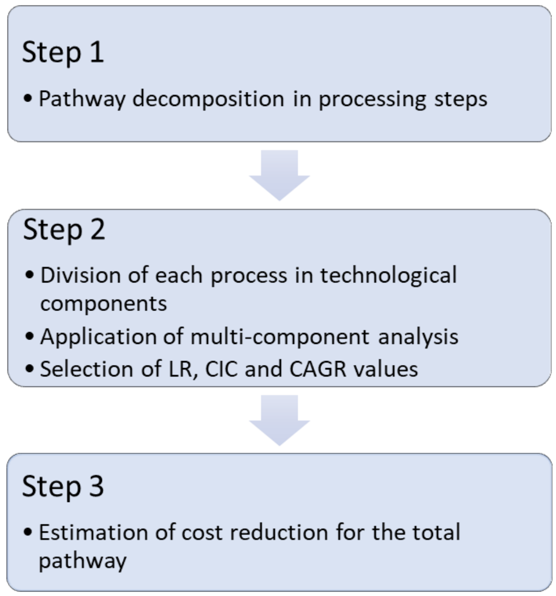

Figure 2 Steps of the cost reduction methodology

Step 1: the technology pathway is divided into process steps resulting in a specific intermediate product (e.g., Syngas, pyrolysis oil, etc.) and each process step is divided into components representing elementary technological steps (e.g., air separation unit used in the direct gasification process step).
Step 2: For each time point (t), defined as one year starting from 2020, the specific investment cost $C(Q_{01})\ [\frac{Q_t}{Q_0}]^{-b(i)}$of each process component (C($Q_{t,i}$) is calculated from the analysis of cost reduction based on the learning curve theory (see also D3.5). C($Q_{t,i}$) depends on the learning rate, LR, where b is obtained from the equation $LR = 1 - 2^{-b}$ and CAGR parameters per process component (i.e., determining the ratio of $CIC_i(t)/CIC_i(t_0)$).

Regarding the selection of LR value for each technological component belonging to a particular process step:

- LR values for each process step is derived by literature (e.g., Detz et al., (2019)). In case of missing values, mature technologies (e.g., conventional steps) are assigned a low LR value of 0.05 and less mature steps a higher value of 0.15.
- If a process step contains a combination of mature and less mature components, then a differentiation of LR values for components within the same process step is possible. For instance, the biomass to syngas process step is considered as a less mature step mainly because of the gasification technology. Thus, a value of 15% is assigned to the gasifier component of this step, while other components such as feedstock handling obtain an LR value of 5%.
- LR values have inherent uncertainties and ranges are suggested that facilitate sensitivity analysis scenarios for further analysis of the results presented herein.

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Cumulative installed capacities (CIC) are defined by considering information for operation by priority as demo or pilot plants in Europe or in global scale or values mentioned in simulation reports.

Cumulative annual growth rate (CAGR) values are generally lacking due to very limited and relatively very recent commercial plants in operation. Thus, the following criteria are employed to select CAGR values:

- If a process step is similar to conventional production (e.g synthesis gas to methanol) values of CAGR for the conventional production is assigned to this process step and all of its components.
- If a value of CAGR is not found for a process step (e.g., biomass-based step), the growth rate in market demand of the corresponding fuel product is considered as a lower limit value in the scenarios described below.
- The CAGR of the intermediate product of a process step can be lower, equal or higher of the respective value of the final product of the pathway (fuel). Higher CAGR values for intermediate products mean that the production volume of the intermediate product is used to cover other uses than this of the final product N. Lower CAGR values mean that other conventional processes exist which cover the demand of final product N. Equal means that the increase of demand in final product N is covered only by the particular technological pathway.

Step 3: By adding the values of all process components, the total specific investment cost of the process step is calculated and consecutively of the whole technological pathway at the time point *t (CAPEX(t))* and therefore also at $CIC_i(t)$. Thus, the specific investment cost of a technology can be expressed as a function of the cumulative installed capacity of any process step. For the next calculations step, it is more convenient to express the specific investment cost of a technology as a function of the CIC of the biomass-based process step ($CAPEX(CIC_i(t)$) which also determines the cumulative installed capacity of the technology under investigation.

The growth rate of advanced biofuels is subject to many uncertainties depending on current conditions for growth rates of fossil-based demand and their future role in the transportation mix. The first scenario, herein mentioned as **baseline scenario**, assumes CAGR values equal to the growth rate of the corresponding market of the fuel, and thus it is a conservative scenario not leading to "greening" of the transportation mix.

Scenario A assumes marginally higher CAGR values 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 with this approach an increase of installed capacity by one order of magnitude may still be achieved in the considered time horizon, 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.

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Scenario B assumes an annual growth of the 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 20% of the production of the respective fossil-based fuel in the end of the time horizon of the ADVANCEFUEL project. The projected amount of fossil-based fuel is calculated based on current market trends. This means that it represents the amount of this fossil-based fuel in a future transportation mix based on the current marginal market conditions (i.e., without considering potential reduction in energy used for transportation in the future and also not significant replacement of fossil-based fuels). Thus 20% production of advanced biofuel of this projected fossil-based quantity can be in agreement with the scenarios of European Commission 2018 that refer to 13%-24% contribution of liquid biofuels in the energy consumption for transportation in 2050 (EUROPEAN COMMISSION, 2018)

Scenario C is based on CAGR that would be necessary to achieve advanced biofuel targets provided by WP6. This calculation is obviously performed only for those fuels that participate in the 2030 or 2050 transportation mix according to the Transport-BIO optimisation scenario of the integrated model of WP6. Since two target values for CIC are considered in Scenario C (i.e., one for 2030 and one for 2050), the CAGR values are adjusted accordingly after 2030. The Transport-BIO scenario of WP6 refers to a large deployment of advanced biofuels; thus, in some cases large installed capacities are assumed already by 2030. The other optimisation scenario in WP6 (Road-ZERO) refers to limited deployment of advanced biofuels, leading to significantly smaller installed capacities and thus limited scope for CAPEX reduction, for instance similar to the results of Scenario A, as far as specific CAPEX (Eur/kW-product) is concerned.

4. Application of learning curve theory to ADVANCEFUEL pathways

This section presents the application of the learning curve methodology for estimation of the scope for CAPEX reduction of the ADVANCEFUEL pathways. For each pathway, the values of the parameters of the learning curve methodology are first presented, organised per process step. Detailed tables with the decomposition of each process step into components and their corresponding learning methodology parameters are available in an MS Excel database in the ADVANCEFUEL website. Ranges of all

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model parameters are included in this database that facilitate sensitivity analysis scenarios and further testing of the robustness of the learning-curve methodology results.

4.1 Thermochemical pathways

Liquified biomethane

In Table 8, the gasification capacity data are based on the GoBiGas demonstration plant and the corresponding scale-up study by Thunman et al. (2018). Liquified biomethanes production considers an additional unit based on the study by Capra et al. (2019). A CIC of 200 MW is considered for the biomethane production step, while for the liquefaction process step the nominal capacity of LNG in the year 2018 is used. Learning rate values are selected as the minimum values found in literature for the mature technological components. For instance, the technologies in the gasification step are all considered mature and attain a learning rate of 0.05, except from the gasifier and the syngas cleaning system that require adjustments and improvements for consistent continuous operation of the plant (Thunman et al., 2018). Market demand values were found for methane (2026) and LNG (2025), and these were used for setting reference CAGR values according to the approach described above.

According to Table 9, baseline scenario and Scenario A correspond to a very small contribution of liquified biomethane (percentages close to zero) with a very small number of plants 3 and 6, respectively, in the considered timeline (2020-2050). On the other hand, Scenario B can be realised with CAGR=26.7% leading to CIC of approximately 390 GW, a little less than 2000 plants in 2050 and a corresponding CAPEX reduction of 45%. Scenario C resembles Scenario B until 2030, after which the growth rate of this technology is significantly reduced. This leads to significantly less plants (i.e., approximately 50) and a corresponding CAPEX reduction of 28%.

Table 8. Parameters of the learning curve model for liquified biogas.

Technology	Value	Unit	Range	Region	Reference
Learning rate (LR)					
Gasification Step	0.05		0.02		The minimum value of LR, In accordance with D3.5
Liquefaction Step	0.05		0.02		The minimum value of LR, In accordance with D3.5
Gasifier (in Gasification Step)	0.15		0.05		Value greater than 10% that is the average according to Detz et al. (2018), In accordance with D3.5
Cumulative installed capacity (CIC)					
Gasification Step	200	MW		Sweden	Based on study for scale up of the GoBiGas plant

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Global nominal liquefaction capacity	570,205	MW			
	370	MTPA		Global	IGU World Gas LNG Report – 2018 Edition, as of March 2018, global nominal liquefaction capacity was 369.4 MTPA, an increase of 32.2 MTPA from the end of 2016. Value was converted to MW using LHV=48.6MJ/kg. (https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html)
Cumulative annual growth rate (CAGR)					
Gasification Step	0.06		0.02	Global	https://www.marketwatch.com/press-release/at-61-cagr-methane-market-size-will-reach-15127-billion-usd-by-2026-industry-share-growth-product-scope-and-top-vendors-research-2019-08-23
Liquefaction Step	0.05		0.02	Global	https://www.techscire-search.com/news/1951-global-lng-market-to-grow-at-cagr-5-until-2025.html

Table 9. Scope of liquified biogas CAPEX reduction.

Scenarios	2018	2020	2030	2050
Baseline Scenario (CAGR=3.9%)				
CIC (MW) (number of plants)	200 (1)	216 (1)	316 (2)	676 (3)
Specific investment cost (MEuro/MW)	1.87	1.86	1.80	1.69
Scenario A (CAGR=5.8%)				
CIC (MW) (number of plants)	200 (1)	224 (1)	395 (2)	1230 (6)
Specific investment cost (MEuro/MW)	1.87	1.86	1.77	1.61
Scenario B (CAGR=26.7%)				
CIC (MW) (number of plants)	200 (1)	321 (2)	3427 (17)	390,317 (1952)
Specific investment cost (MEuro/MW)	1.87	1.80	1.49	1.02
Scenario C (CAGR %)	**36.6%**		**0.8%**	
CIC (MW) (number of plants)	200 (1)	373 (2)	8,461 (42)	9,852 (49)
Specific investment cost (MEuro/MW)	1.87	1.78	1.39	1.35

Methanol

Data sources for methanol are obtained from two different studies, Pacific Northwest National Laboratory (PNNL) (Zhu, et al., 2011), and VTT (Hannula, et al., 2013). The learning rate parameters were assigned as discussed in the liquefied biomethane case for the gasification step, while the methanol syn-

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thesis step was considered as a mature technology. It should be noted that in Table 10, methanol capacity refers to the current installed capacity of methanol regardless of its use as a fuel or chemical. This may underestimate the required growth rates in scenarios B and C and thus also the scope for CAPEX reduction in Table 11.

Baseline scenario, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 2.9 GW, 6.9 GW and 53 GW, respectively. This corresponds to a scope for CAPEX reduction of 20% to 30% for the baseline scenario, 25% to 37% for Scenario A, and 33% to 48% for Scenario C. In all scenarios the technology of indirect gasification shows the biggest potential for CAPEX reduction. Scenario C is not presented in this case since methanol was not part of the optimal mix for transportation fuels in the scenarios considered from WP6.

Table 10. Parameters of the learning curve model for methanol.

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Gasification step	0.05		0.05		The minimum value of LR, in accordance with D3.5
Methanol synthesis	0.05		0.02		Detz et al. (2018)
Gasifier (in Gasification Step)	0.15		0.05		Value greater than 10% that is the average according to Detz et al. (2018), In accordance with D3.5
Cumulative installed capacity (CIC)					
Gasification step	200	MW		Sweden	Based on study for scale up of the GoBiGas plant
Methanol synthesis	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)					
Gasification step	0.11		0.03	Global	Assuming CAGR of syngas totally produced regardless 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 synthesis	0.07		0.02	Global	Detz et al. (2018)

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Table 11. Scope of methanol CAPEX reduction.

	Scenarios	2018	2020	2030	2050
	Baseline Scenario (CAGR=8.8%)				
	CIC (MW) (number of plants)	200 (1)	237 (1)	549 (3)	2,955 (15)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.12	2.08	1.93	1.68
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.19	1.16	1.02	0.81
Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.52	1.66	1.46	1.14
Direct gasification (Zhu, et al., 2011)	**Scenario A (CAGR=11.7%)**				
	CIC (MW) (number of plants)	200(1)	250(1)	756(4)	6938 (35)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.12	2.08	1.89	1.59
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.19	1.15	0.98	0.74
Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.52	1.65	1.39	1.03
	Scenario B (CAGR=19.1%)				
	CIC (MW) (number of plants)	200 (1)	284 (1)	1624 (8)	53,297 (266)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.12	2.06	1.79	1.42
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.19	1.13	0.89	0.61
Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.52	1.62	1.26	0.83

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 gasificat 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. The CIC and CAGR values are set as in the case of methanol, where the respective CIC for DME in 2018 refers to the total production of DME regardless of its use as fuel or chemical (Table 12).

In Table 13, baseline scenario, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 3.0 GW, 6.9 GW and 9.2 GW, respectively. The base line scenario, Scenario A and Scenario B show similar scope for CAPEX reduction, ranging from 24%-33% to 30%-42%. On the other hand, Scenario C results in CIC values of 64 GW in 2050 and a respective CAPEX reduction of 40%-51%. Differently than liquefied biogas whose growth rate phases out after 2030, the one of DME becomes more than double in the period 2030-2050.

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Table 12 Parameters of the learning curve model for DME.

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Gasification step	0.05		0.05		The minimum value of LR, in accordance with D3.5
Methanol synthesis	0.05		0.02		Detz et al. (2018)
DME synthesis	0.05		0.02		Detz et al. 2018
Gasifier (in Gasification Step)	0.15		0.05		Value greater that 10% that is the aver-age according to Detz et al. (2018), In ac-cordance with D3.5
Cumulative installed capacity (CIC)					
Gasification step	200	MW		Sweden	Based on study for scale up of the GoBi-Gas plant
Methanol synthesis	57,040	MW		Global	M. Alvarado, IHS Chem. Week, 2016, 10–11.
DME synthesis	7,288	MW		Global	https://www.sciencedirect.com/sci-ence/arti-cle/abs/pii/S1875510012000650
Cumulative annual growth rate (CAGR)					
Gasification step	0.11		0.03	Global	https://www.globenewswire.com/news-re-lease/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 synthesis	0.07		0.02	Global	Detz et al. (2018)
DME synthesis	0.07		0.02		Similar to methanol

Table 13 Scope of DME CAPEX reduction.

	Scenarios	**2018**	**2020**	**2030**	**2050**
	Baseline Scenario (CAGR=8.8%)				
	CIC (MW) (number of plants)	200 (1)	237 (1)	549 (3)	2955 (15)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.30	2.26	2.07	1.75
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.67	1.46	1.14
Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.09	1.07	0.95	0.76
Direct gasification (Zhu, et al., 2011)	**Scenario A (CAGR=11.7%)**				
	CIC (MW) (number of plants)	200 (1)	250(1)	756 (4)	6938 (35)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.30	2.25	2.01	1.64
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.65	1.40	1.03

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Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.09	1.06	0.91	0.70
	Scenario B (CAGR=12.7%)				
	CIC (MW) (number of plants)	200 (1)	254 (1)	840 (4)	9,175 (46)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.30	2.25	1.99	1.61
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.65	1.38	1.00
Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.09	1.06	0.90	0.68
	Scenario C (CAGR %)	**(CAGR 11.3%)**		**(CAGR 25.1%)**	
	CIC (MW) (number of plants)	200 (1)	248 (1)	725 (4)	63,554 (318)
VTT (Hannula, et al., 2013)	Specific investment cost (MEuro/MW)	2.30	2.25	2.01	1.39
Indirect gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.66	1.40	0.83
Direct gasification (Zhu, et al., 2011)	Specific investment cost (MEuro/MW)	1.09	1.06	0.91	0.58

FT liquids (Diesel, jet fuel and gasoline)

The FT process coproduces diesel with naphtha, jet fuel, and gasoline. In this case the evolution of diesel market is considered as the driving product for that market which is the product with the higher percentage of production among the other co-products. 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 (Table 14).

In Table 15, baseline scenario, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 3.0 GW, 6.9 GW and 209 GW, respectively. Their corresponding scope for CAPEX reduction is 25%, 30% and 40%, respectively. On the other hand, Scenario C results in marginal growth resulting only in 0.6 GW in 2050 and a respective CAPEX reduction of 15%-20%.

Table 14. Parameters of the learning curve model for FT liquids.

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Gasification step	0.05		0.05		The minimum value of LR, in accordance with D3.5
FT synthesis plant	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

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Cumulative installed capacity (CIC)					
Gasification step	200	MW		Sweden	Based on study for scale up of the GoBiGas plant
FT synthesis plant	40,000	MW		Global	Detz et al. (2018)
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
FT synthesis plant	0.13		0.05	Global	Detz et al. (2018), refers to FT liquids

Table 15. Scope for FT liquids CAPEX reduction.

	Scenarios	2018	2020	2030	2050
	Baseline Scenario (CAGR=8.8%)				
	CIC (MW) (number of plants)	200 (1)	237 (1)	549 (3)	2955 (15)
Indirect gasification, Zhu et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.49	1.51	1.25
Direct gasification, (Zhu et al., 2011))	Specific investment cost (MEuro/MW)	2.12	2.08	1.90	1.59
High-temperature gasification -steam/oxygen-fed entrained flow (Swanson, et al., 2010)	Specific investment cost (MEuro/MW)	2.66	2.61	2.35	1.92
Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	Specific investment cost (MEuro/MW)	2.73	2.68	2.44	2.03
	Scenario A (CAGR=11.7%)				
	CIC (MW) (number of plants)	200 (1)	250 (1)	756 (4)	6938 (35)
Indirect gasification, Zhu et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.48	1.48	1.18

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Direct gasification, (Zhu et al., 2011))	Specific investment cost (MEuro/MW)	2.12	2.07	1.85	1.50
High-temperature gasification -steam/oxygen-fed entrained flow (Swanson, et al., 2010)	Specific investment cost (MEuro/MW)	2.66	2.60	2.31	1.85
Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	Specific investment cost (MEuro/MW)	2.73	2.68	2.41	1.97
	Scenario B (CAGR=24.3%)				
	CIC (MW) (number of plants)	200 (1)	309 (2)	2,711 (14)	208,968 (1045)
Indirect gasification, (Zhu et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.64	1.36	1.00
Direct gasification, (Zhu et al., 2011))	Specific investment cost (MEuro/MW)	2.12	2.04	1.70	1.24
High-temperature gasification -steam/oxygen-fed entrained flow (Swanson et al., 2010)	Specific investment cost (MEuro/MW)	2.66	2.57	2.17	1.66
Low-temperature gasification (pressurized, steam/oxygen-fed fluidized bed gasifier) (Swanson, et al., 2010)	Specific investment cost (MEuro/MW)	2.73	2.65	2.30	1.82
	Scenario C (CAGR %)	**0%**		**5.7%**	
	CIC (MW) (number of plants)	200 (1)	200 (1)*	200 (1)*	601 (3)
Indirect gasification, Zhu et al., 2011)	Specific investment cost (MEuro/MW)	1.71	1.70	1.64	1.40
Direct gasification, (Zhu et al., 2011))	Specific investment cost (MEuro/MW)	2.12	2.11	2.06	1.80
High-temperature gasification -steam/oxygen-fed entrained flow (Swanson et al., 2010)	Specific investment cost (MEuro/MW)	2.66	2.64	2.51	2.11
Low-temperature gasification (pressurized,	Specific investment cost (MEuro/MW)	2.73	2.70	2.56	2.17

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steam/oxygen-fed flu-idized bed gasifier) (Swanson et al., 2010)					

*This refers to an even a smaller capacity of 90 MW according to the WP6 scenario.

Ethanol

In the thermochemical route, biomass is first converted by gasification, typically above 800 °C, into synthesis gas, which is thereafter conditioned and catalytically converted into ethanol. NREL considers indirect steam gasification for the conversion of woody biomass to ethanol (Dutta et al., 2010), 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 installed capacity is assumed to be 200 MW. Market demand values were found for syngas (2024) and bioethanol, 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

In Table 17, baseline scenario, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 3.0 GW, 6.9 GW and 110 GW, respectively. Their corresponding scope for CAPEX reduction is 26%, 31% and 43%, respectively, except for the case of Dutta et al. (2010), where lower CAPEX reductions are presented. This is because of a more detailed decomposition of process steps into components in this case, thus reducing the relative importance of the more innovative steps, such as the gasifier technology in the gasification step, which affects the overall scope for CAPEX reduction (i.e., ranging in this case between 16% and 24%, moving from the baseline scenario to Scenario B, respectively). Scenario C is not presented in this case, since ethanol via biomass gasification was not part of the optimal mix for transportation fuels in the scenarios considered from WP6.

Table 16 Parameters of the learning curve model for ethanol via biomass gasification.

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Gasification step	0.05		0.05		The minimum value of LR, in accordance with D3.5
Alcohol synthesis	0.05		0.02		The minimum value of LR, in accordance with D3.5
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)					

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Gasification step	200	MW		Sweden	Based on study for scale up of the GoBi-Gas plant
Alcohol synthesis	200	MW		Global	Assumption for a FOAK plant of similar size to GoBiGas scale-up study.
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	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://renewable-snow.com/news/ethanol-industry-to-grow-at-cagr-of-6-in-2010-2018-study-70224/

Table 17 Scope for ethanol (via biomass gasification) CAPEX reduction.

	Scenarios	**2018**	**2020**	**2030**	**2050**
	Baseline Scenario (CAGR=8.8%)				
	CIC (MW) (number of plants)	200 (1)	237 (1)	549 (3)	2955 (15)
Duta et al., (2010)	Specific investment cost (MEuro/MW)	2.63	2.60	2.45	2.20
Valle et al., (2013)	Specific investment cost (MEuro/MW)	2.88	2.82	2.56	2.13
Perales et al., 2011	Specific investment cost (MEuro/MW)	2.24	2.20	1.98	1.64
	Scenario A (CAGR=11.7%)				
	CIC (MW) (number of plants)	200 (1)	250 (1)	756 (4)	6938 (35)
Duta et al., (2010)	Specific investment cost (MEuro/MW)	2.63	2.59	2.42	2.14
Valle et al., (2013)	Specific investment cost (MEuro/MW)	2.88	2.81	2.48	1.98
Perales et al., 2011	Specific investment cost (MEuro/MW)	2.24	2.18	1.92	1.53
	Scenario B (CAGR=21.8%)				
	CIC (MW) (number of plants)	200 (1)	297 (1)	2,135 (11)	110,494 (552)
Duta et al., (2010)	Specific investment cost (MEuro/MW)	2.63	2.57	2.32	2.01
Valle et al., (2013)	Specific investment cost (MEuro/MW)	2.88	2.75	2.24	1.63
Perales et al., (2011)	Specific investment cost (MEuro/MW)	2.24	2.14	1.74	1.27

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Pyrolysis based liquids (diesel and gasoline)

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 (e.g., 15-30 MW 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. The pyrolysis upgrading path is typically assumed to produce diesel as main product, gasoline and naphtha.

Calculations are based on a CAGR of 10%, assuming an average rate of commercial processes (Table 18) as described in Detz et al. (2018). The overall production capacity of diesel is found equal to 291,600 MW (Capacity refers to 9,205 PJ of road and ship diesel) and the respective capacity of gasoline equals 103,036 MW (Capacity refers to 3,252 PJ of road and ship gasoline, as obtained from European Environmental Agency reports (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 Table 19, baseline scenario, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 2.2 GW, 6.9 GW and 853 GW, respectively. Their corresponding scope for CAPEX reduction is 22%-30%, 26%-33% and 48%, respectively. On the other hand, Scenario C assigns a steep increase in CIC until 2030 followed by a decline in the installed capacity; in such cases no further impact in CAPEX is assumed.

Table 18. Parameters of the learning curve model for pyrolysis-based liquids (diesel and gasoline)

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Pyrolysis	0.05		0.02		Daugard et al. (2014)
Hydroprocessing	0.20		0.06		Daugard et al. (2014)
Cumulative installed capacity (CIC)					
Pyrolysis	200	MW			Based on study for scale up of the GoBiGas plant
Hydroprocessing	200	MW			Assumption for a FOAK plant of similar size to GoBiGas scale-up study.
Cumulative annual growth rate (CAGR)					
Pyrolysis	0.1		0.03	Global	Assumption according to Detz et al. (2018) that refers to most mature technologies having 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 having a CAGR between 7% and 13%

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Technology	Value		Range	Region	Reference
Gasoline	0.1		0.03	Global	Assumption according to Detz et al. (2018) that refers to most mature technologies having a CAGR between 7% and 13%

Table 19. Scope for pyrolysis-based liquids (diesel and gasoline) CAPEX reduction.

	Scenarios	2018	2020	2030	2050
	Baseline Scenario (CAGR=7.8%)				
	CIC (MW) (number of plants)	200 (1)	232 (1)	493 (2)	2212 (11)
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	0.94	0.92	0.82	0.66
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	1.83	1.80	1.65	1.41
Dutta et al. (2015)	Specific investment cost (MEuro/MW)	1.89	1.86	1.72	1.48
	Scenario A (CAGR=11.7%)				
	CIC (MW) (number of plants)	200 (1)	250 (1)	756 (4)	6,938 (35)
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	0.94	0.91	0.80	0.63
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	1.83	1.79	1.62	1.33
Dutta et al. (2015)	Specific investment cost (MEuro/MW)	1.89	1.86	1.68	1.39
	Scenario B (CAGR=29.9%)				
	CIC (MW) (number of plants)	200 (1)	337 (2)	4,596 (23)	853,439 (4,267)
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	0.94	0.90	0.73	0.48
Zhu et al., (2011)	Specific investment cost (MEuro/MW)	1.83	1.76	1.44	0.97
Dutta et al. (2015)	Specific investment cost (MEuro/MW)	1.89	1.82	1.49	1.00
	Scenario C (CAGR %)	**43.6%**		**-1.6%**	
	CIC (MW) (number of plants)	200 (1)	412 (2)	15,359 (77)	11,031 (55)*
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	0.94	0.89	0.69	0.69
Zhu et al. (2011)	Specific investment cost (MEuro/MW)	1.83	1.78	1.33	1.33
Dutta et al. (2015)	Specific investment cost (MEuro/MW)	1.89	1.85	1.37	1.37

*The specific investment cost is assumed to remain constant in the scenarios where CIC is reduced.

4.2 Biochemical Pathways

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

Ethanol

Data for ethanol are based on the study of NREL (Humbird et al., 2011) 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 for a plant with capacity 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 were characterized as less mature: the enzymatic hydrolysis and fermentation and enzyme production which are sub-steps with more significant potential for improvements. For the CIC parameter the capacity of the existing ethanol plants in operation is selected (145 MW according to IEA report, 2020). The CAGR is based on the bioethanol growth rate in general, including first generation ethanol production (Table 20).

In Table 21, baseline scenario and Scenario A are analysed together because the ethanol production is already a "green" pathway, namely the concept of conservative or less conservative greening as part of the overall ethanol market does not apply here. With respect to targeted capacities in Scenario B, ethanol is considered as 10% additive in gasoline. As a result, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 0.5 GW and 117 GW, respectively. Their corresponding scope for CAPEX reduction is rising from 11% to 47%, respectively. On the other hand, Scenario C assigns a steep increase in CIC until 2030, reaching installed capacities of 3.4 GW with CAPEX reduction of 27%, followed by a decline in the installed capacity until no ethanol is assigned to the transportation mix of 2050 according to the scenario taken from WP6.

Table 20. Parameters of the learning curve model for ethanol via fermentation

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Ethanol Step	0.05		0.02		Daugaard et al. (2018)
Hydrolysis and Fermentation (in Ethanol 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)					
Ethanol	145	MW		Global	IEA report (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://renewable-snow.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.°764799.

Table 21. Scope for ethanol (via fermentation) CAPEX reduction

Scenarios	2018	2020	2030	2050
Baseline Scenario/Scenario A (CAGR=3.9%)				
CIC (MW) (number of plants)	145 (1)	156 (1)	229 (2)	490 (3)
Specific investment cost (MEuro/MW)	2.30	2.28	2.19	2.03
Scenario B (CAGR=23.3%)				
CIC (MW) (number of plants)	145 (1)	220 (2)	1788 (12)	117,593 (811)
Specific investment cost (MEuro/MW)	2.30	2.20	1.79	1.23
Scenario C (CAGR %)	**30%**		**0%**	
CIC (MW) (number of plants)	146 (1)	246 (2)	3429 (24)	0 (0)
Specific investment cost (MEuro/MW)	2.30	2.18	1.68	---

Jet fuels production from ethanol

Calculations are based on a CIC of the existing capacity of 145 MW ethanol from fermentation, as explained in the previous paragraph, considering also the CAGR of bioethanol that is 6%. The actual production capacity of jet (aviation) fuels was estimated based on 75,929 MW of aviation kerosene obtained from European Environmental Agency reports (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 22).

In Table 23, baseline scenario and Scenario A are analysed together as it is assumed to follow the baseline growth rate of produced ethanol via fermentation. As a result, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 0.5 GW and 38 GW, respectively. Their corresponding scope for CAPEX reduction is rising from 11% to 37%, respectively. On the other hand, Scenario C assigns a more steep increase in CIC until 2030, reaching installed capacities of 2.8 GW with CAPEX reduction of 21%, followed by a decline in the annual growth rate until a CIC of 33 GW is reached in 2050, resulting in CAPEX reduction of 35% compared to the current CAPEX.

Table 22. Parameters of the learning curve model for jet fuels production via ethanol

Technology	Value		Range	Region	Reference
Learning rate (LR)					
Ethanol Step	0.05		0.02		Daugaard et al. (2018)
Hydrolysis and Fermentation (in Ethanol Step)	0.15		0.05		Value greater that 10% that is the avarage according to Detz et al. (2018), in accordance with D3.5

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Ethanol to Jet Fuels	0.05		0.02		The minimum value of LR, In accordance with D3.5
Cumulative installed capacity (CIC)					
Ethanol step	145	MW			Adding capacities from http://www.etipbioenergy.eu/value-chains/products-end-use/products/cellulosic-ethanol#best
Ethanol to 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 step	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://renewable-snow.com/news/ethanol-industry-to-grow-at-cagr-of-6-in-2010-2018-study-70224/
Ethanol to Jet fuels	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

Table 23. Scope for jet fuels (via ethanol) CAPEX reduction

Scenarios	2018	2020	2030	2050
Baseline Scenario (CAGR=*4%*)				
CIC (MW) (number of plants)	139 (1)	150 (1)	219 (2)	470 (3)
Specific investment cost (MEuro/MW)	2.74	2.72	2.62	2.44
Scenario B (CAGR=*19.2%)*				
CIC (MW) (number of plants)	139 (1)	197 (1)	1,140 (8)	38,030 (274)
Specific investment cost (MEuro/MW)	2.74	2.65	2.27	1.72
Scenario C (CAGR %)	**28.3%**		**13.2%**	
CIC (MW) (number of plants)	139 (1)	229 (2)	2,776 (20)	32,995 (237)
Specific investment cost (MEuro/MW)	2.74	2.68	2.17	1.79

Butanol

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There are two major ways to produce biobutanol via fermentation: the ABE process using wild bacteria strains targeting for n-butanol, and the process using bacteria or yeasts targeting for iso butanol and n-butanol production. The current international market for bulk grade butanol is approximately 350 million gallons per year which corresponds to a capacity equal to 1,115 MW, regardless of its use as fuel or chemical. 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) and has a CAGR of 5%, while the biobutanol has a CAGR of 8.4% (Table 24).
In Table 25, Scenario A and Scenario B show that with the selected CAGR values the cumulative installed capacity in 2050 is 1.2 GW and 116 GW, respectively. Their corresponding scope for CAPEX reduction is similar for n-butanol and iso-butanol, rising from approximately 16% in 2030 to 40% in 2050. Scenario C is not presented in this case, since butanol was not part of the optimal mix for transportation fuels in the scenarios considered from WP6.

Table 24. Parameters of the learning curve model for butanol production via the ABE process

Technology	Value		Range	Region	Reference
Learning rate (LR)					
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 av-arage according to Detz et al. (2019,) in accordance with D3.5
Saccharification & fer-mentation for iso-butanol	0.15		0.05		In accordance with D3.5
On-site enzyme produc-tion	0.15		0.05		Value greater that 10% that is the av-arage according to Detz et al. (2019,) in accordance with D3.5
Cumulative installed ca-pacity (CIC)					
n-butanol	200	MW			Assumption
Iso-butanol	200	MW			Assumption
Cumulative annual growth rate (CAGR)					
Biobutanol	0.08		0.03	Global	https://www.researchandmar-kets.com/reports/4515064/global-bio-butanol-market-growth-trends-and?utm_source=GN&utm_medium=PressRe-lease&utm_code=9m9jvb&utm_cam-paign=1230214+-+World+Bio-Buta-nol+Mar-ket+to+Post+a+CAGR+of+8.36%25+During+2019-2024+-+Key+Market+In-sights&utm_exec=joca220prd
Butanol (conventional)	0.05		0.02	Global	https://www.marketsandmar-kets.com/Market-Reports/n-butanol-market-1089.html

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Table 25. Scope for butanol (via ABE) CAPEX reduction

	Scenarios	2018	2020	2030	2050
	Baseline Scenario (CAGR=5.8%)				
	CIC (MW) (number of plants)	200 (1)	224 (1)	395 (2)	1,230 (6)
n-butanol	Specific investment cost (MEuro/MW)	3.80	3.76	3.57	3.23
Iso-butanol	Specific investment cost (MEuro/MW)	2.51	2.47	2.32	2.05
	Scenario B (CAGR 22%)				
	CIC (MW) (number of plants)	200 (1)	298 (1)	2,177 (11)	116,328 (582)
n-butanol	Specific investment cost (MEuro/MW)	3.80	3.67	3.11	2.26
Iso-butanol	Specific investment cost (MEuro/MW)	2.51	2.42	2.04	1.52

Summary of Technical Learning Results

Applying learning theory for CAPEX reduction is based on parameters related to the cumulative annual growth rate of the corresponding technologies and learning rates of the corresponding technology components and their assembly in production lines. For marginally higher cumulative annual growth rates of advanced biofuels compared to the current market trends of the corresponding fossil fuels (Scenario A, Figure 2), CAPEX reductions from 10-25% can be expected assuming only a handful of plants installed. If higher cumulative installed capacities are reached in 2050 (Scenario B, Figure 3), meeting the goal of 20-25% of transportation fuels consumption to be covered by advanced biofuels, CAPEX reduction up to 40-50% can be expected for the new plants that will be built then.

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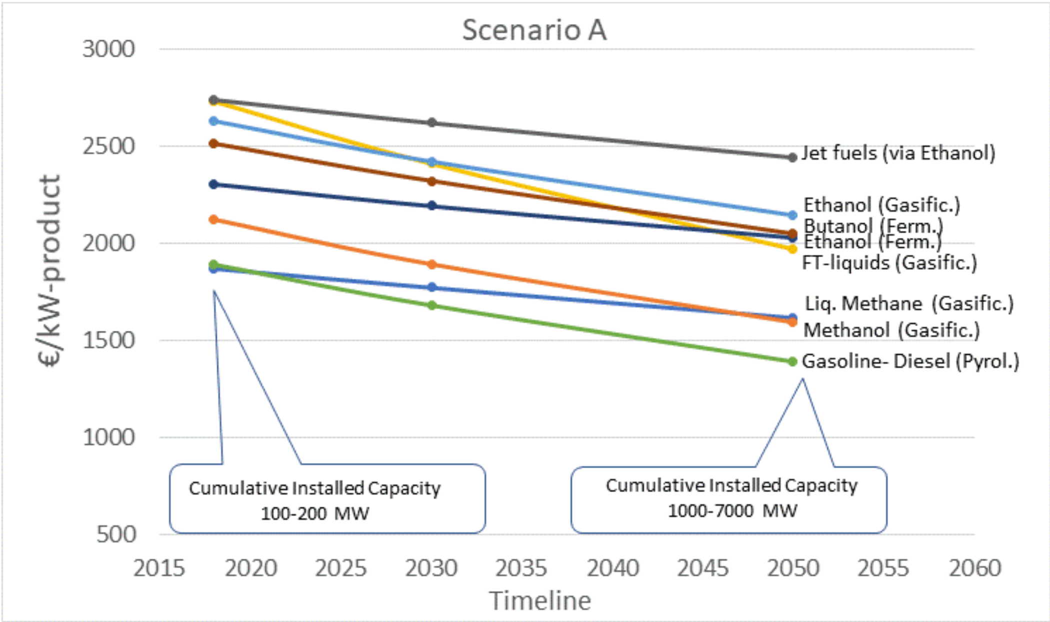

Figure 2 Scope of CAPEX reduction (2020-2050) of advanced biofuels from lignocellulosic biomass for a scenario of capacity annual growth rate marginally higher than the current fuel demands.

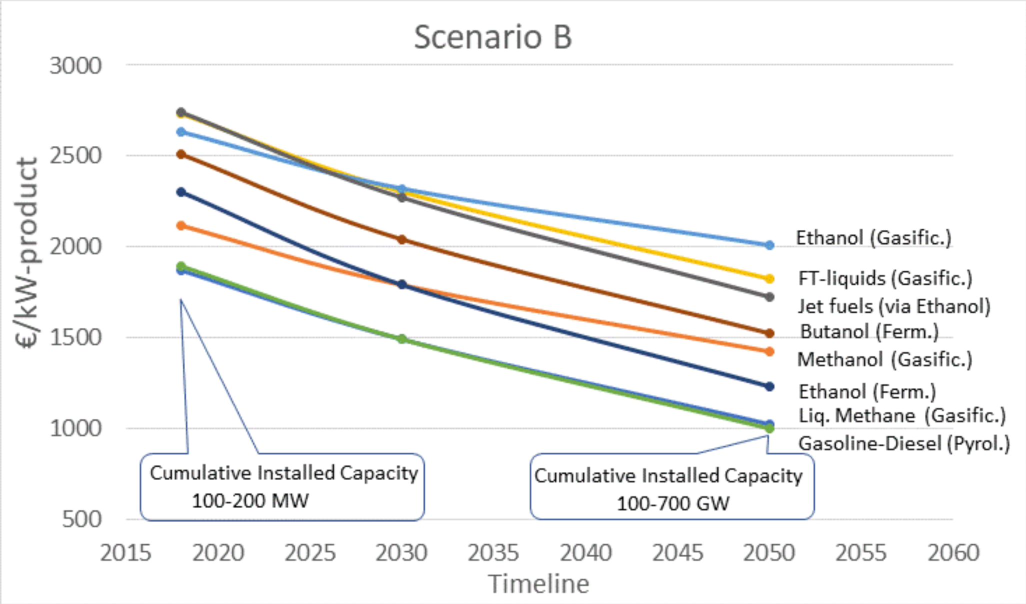

Figure 3 Scope of CAPEX reduction (2020-2050) of advanced biofuels from lignocellulosic biomass for a scenario of capacity annual growth rate meeting the goal of 20-25% transportation fuels consumption to be covered by advanced biofuels in 2050.

It can also be noted that the technical learning approach is strongly influenced by the cumulative installed capacity, at least for the ranges of learning rates assumed in this study. In Figure 3, the lines for all pathways start to attain the inherent curvature of the technical learning mathematical expressions,

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which is not the case of Scenario A (Figure 2), where the behaviour seems to be almost linear. This is because of the much faster CAGR values in Scenario B resulting in substantial cumulative installed capacities in 2050. In this regard, it is important to remember that not all pathways reach similar CIC values in 2050, and thus the results should not be interpreted as a difference arising from the "potential to learn" or the status of the current maturity of the pathway. As an example, methanol and methane production via biomass gasification are both of similar technical maturity, the gasifier technology being the process component with higher technical learning potential. The reason that, in Figure 3, CAPEX of liquefied methane production appears to decrease faster than the methanol one is the very different CAGR values leading to CICs of 390 GW for liquefied gas to 53 GW of methanol. On the other hand, in Scenario A, where the CAGR values of methanol are higher than those of biogas, the opposite trend appears with respect to CAPEX decrease potential.

It should also be noted that extrapolating from the lines in Figure 3 to a time horizon beyond 2050 will not lead to valid conclusions as the parameters of the technical learning approach should be revised. It cannot be expected that technical learning will keep taking place in the same extent after, for instance, some hundreds or thousands of plants are in operation; the lines in Figure 3 are expected to reach an asymptotic behaviour. Most likely, this constant update of learning parameters will already take place in the horizon 2020-2050. There is a parameter in the method updating (i.e., decreasing) the expected CAGR value from its current status. The method can become even more sophisticated by considering gradual or step changes in the learning parameters when a status of NOAK plant is reached to impose asymptotic behaviour faster. For instance, in Scenario B, this status is reached for the investigated pathways quite before 2050.

In general, the trends discussed above apply also for Scenario C (Figure 4), in the sense that the short-term scope of CAPEX reduction with conservative CAGR values is ranging from 5% to 10% (e.g., DME and FT-liquids from gasification, and Jetfuels via ethanol) and for cumulative installed capacities in the range of tenths of GWs is ranging from 30% to 40%. However, for some cases in Scenario C (ethanol from fermentation, gasoline and diesel from pyrolysis liquids and liquefied gas from gasification) targeted installed capacities are already reached in 2030, and after this year either the CAGR values are very low (i.e., the scope for CAPEX reduction attenda already the asymptotic behaviour) or the corresponding pathway is not part of the advanced biofuels mix for transportation in 2050 (e.g., the ethanol case). It should also be noted that for jet fuels via ethanol and DME the curvature of the corresponding CAPEX reduction lines is different than the ones in Scenario B because the lower CAGR values are assumed until 2030 and much higher after this year (i.e., in Scenario B a constant CAGR values is imposed until 2050).

In all cases, it should be noted that building tenths or hundreds of such plants in short-term is rather ambitious if not unrealistic. Thus, the correct interpretation of the results of the afore mentioned scenarios is that the scope for CAPEX reduction of 40-50% can be perhaps realised only with installed

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capacities in the ranges of tenths or hundreds of GWs of operating plants at full scale and it could represent a theoretical target in the time horizon 2030-2050.

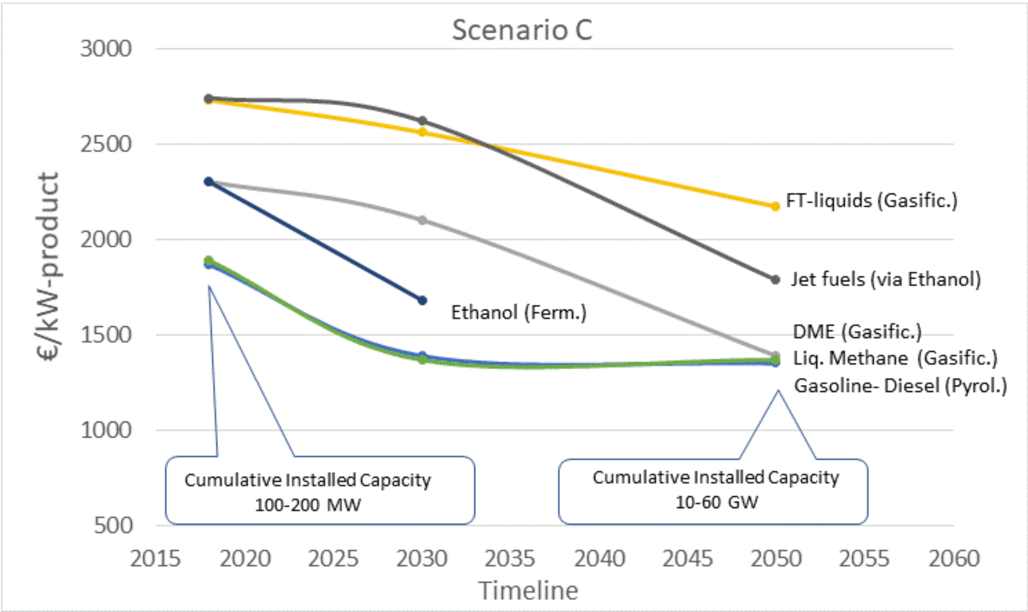

Figure 4 Scope of CAPEX reduction (2020-2050) of advanced biofuels from lignocellulosic biomass for a scenario of capacity annual growth rate meeting the targets obtained from a selected scenario from WP6.

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5. Technical and economic barriers for scaling up

Apart from cost reduction potential that is an important driver for the deployment of advanced biofuels processes, factors which affect the scaling-up and maturity of production technologies were investigated, as an extension of the work in D3.3 to all pathways. The application of this approach for all case studies is provided in Appendix B.

In general, the cost factors introducing uncertainty are mainly those associated with market conditions and regulatory mechanisms (e.g., fossil fuel pricing and CO_2 taxes, biomass price and logistics).

As for the thermochemical processes and especially for the gasification pathways, the analysis shows that the barriers are mostly associated with economic factors. The process efficiency for liquefied biomethane and DME production is high, close to thermodynamical limits, and the processes are certainly technologically ready for large-scale industrial production. Moreover, the technology mostly comprises industrially established process steps, where cost reductions can mainly be expected from learning in assembling the process and reduced costs from reducing high risk premiums of FOAK projects as presented in D3.3 for the case of methanol. For the case of FT liquids, there is a lower biomass to fuel efficiency due to the co/by-products (such as alcohols, acids, ketones, water and CO2 are also produced). This pathway is associated with more technical barriers compared to the other gasification-based ones (such as catalyst deactivation, syngas cleaning etc). For the pyrolysis pathway, the most important constraints are the upgrading steps of bio-oil which are in early development stage (i.e., lab to pilot scale), even though pyrolysis is a well stabled technology. Bio-oil differs from conventional liquid fuels and must therefore overcome both technical and marketing hurdles.

As for the biochemical pathways, barriers of 2nd generation ethanol were analysed in detail in D3.3. Future ethanol plants will depend, among other factors, on technological solutions related to increasing the overall biomass conversion efficiencies (i.e., not only regarding ethanol yields but also with respect to the currently not optimally utilised biomass fractions of lignin and hemicelluloses), and further intensifying the biomass fractionation and fermentation processes (e.g., through advanced continuous operations, higher product concentrations). Thus, the role of research and innovation grants will be more important for this type of plants. Even though the upgrading processes of ethanol to jet fuels are already in commercial scale, the deployment of jet fuels production is constrained from scaling up due to the ethanol production step which minimizes the entire efficiency of the path. Biobutanol constraints are mainly focused on technical reasons and especially to the low efficiency of ABE fermentation which

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produces n-butanol, whereas iso-butanol production is still in pre-commercial stages as no plant has achieved to produce iso-butanol in commercial scale.

The uncertainty in engine development is another important factor. For example, for the case of liquefied bio-methane use, engines of LNG already exist and the infrastructure for storage and supply for liquefied biogas is the same as for LNG, thus making liquefied biogas a drop-in fuel. The challenge is on the infrastructure for the liquefied biogas production, which is currently very limited. Of course, additional challenges exist for ships with no LNG infrastructure where major investments will be required. On the other hand, DME, for example, is not ready to be used in ship engines, and even though it is an excellent diesel fuel, it cannot be considered as a drop-in fuel, since it requires dedicated or modified engines (e.g., retrofitting of diesel engines for DME use is possible and was demonstrated by Volvo Trucks). There are also additional issues with respect to type and size of storage infrastructure (i.e., the fuel tanks resemble propane tanks more than diesel tanks and they require specific seals and material; DME energy content is equivalent to 55% that of diesel, which means that almost double size of fuel tanks is needed). FT liquids such as kerosene could be used in specific mixing blends and this could be a strong potential for the case of BtL fuels. Similarly, ethanol blends with gasoline (e.g., 5% or 10% ethanol) are drop-in fuels. Summarizing, further engine development can increase the scope of drop-in advanced biofuels and their blends, thus having a direct impact on the required installed capacities and production costs.

Capacity building, innovation funds and public-private partnerships will help tackle barriers such as those related to investor risk premium and access to debt financing, whereas cost reductions gained from experience when moving from FOAK to NOAK plants, either for greenfield projects or co-location to existing infrastructures, will also play a role.

6. Conclusions

This report focuses on cost aspects of the ADVANCEFUEL project pathways, especially on CAPEX status and the scope for reduction from short to long term. CAPEX values typically represent 30% to 45% of the overall production cost, a similar range referring to the feedstock cost while other operating and maintenance costs typically cover 15%-20% of the overall production cost. Considering the high process efficiency and TRL at demonstration scale of the investigated pathways, the scope of CAPEX reduction remains the most important improvement from technical perspective in plant economics. Feedstock costs are equally significant, but it is more a matter of feedstock price than feedstock efficiency for the investigated pathways, the only exception being ethanol from fermentation with respect to the potential for alternative use of hemicellulose and lignin-based by-products.

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The scope for CAPEX reduction was investigated by using a multi-component learning curve methodology for short- and long-term implementation of advanced biofuels. A scenario based analysis with respect to estimated cumulative annual growth rates showed that CAPEX reduction in the range of 10-25% could be expected when moving from FOAK to NOAK plants and increasing the installed capacity by two orders of magnitude, for example, compared to the tenths or hundreds of MWs installed today in few demonstration and even fewer commercial plants. To reach further CAPEX reduction of 40%, for example, would require one more order of magnitude of cumulative installed capacity increase, reaching the scale of hundreds of GWs or equivalently some hundreds or thousands of large-scale plants. This target may well be interpreted as a theoretical target for the time horizon 2030-2050 or in other words as an ambitious upper limit of what can be expected in CAPEX reductions.

It should be noted that the CAPEX reduction estimations entail uncertainties beyond the estimated cumulative annual growth rates of the technologies. Two important methodological aspects refer to the degree of available information allowing or not a detailed decomposition of the pathway to process components as well as the technical learning potential of these components and especially after which time point (or installed capacity) this can be assumed to attain near zero values. One should not forget that most of the technical learning is allocated in assembling the plants which consist in a large extent from mature technological components. Thus, a more sophisticated parameterisation of the methodology should be possible during the time horizon 2020-2050, assuming that more commercial plants of advanced biofuels will be in operation.

Besides the scope for CAPEX reduction, technical and economic factors, barriers and policy mechanisms associated with the scale–up of all investigated technologies are presented. Although CAPEX aspects of conversion technologies appear as significant barriers in this analysis, technical aspects related with catalyst development and by-products utilisation, policy aspects referring to feedstock premiums and CO_2 taxes, as well as contemporary engine development are important factors in generating a safe market for investments from private-public partnerships. Similarly, quantification of the economic effects of potential policies to remove the technical and economic barriers identified in this deliverable (e.g., easily access to capital, feedstock premiums, increased CO_2 taxes for fossil-based fuels) will help estimate further reduction potential for capital and operating costs.

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Appendix A

Methanol production

Pacific Northwest National Laboratory, (2011) Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels (Indirect gasification)

Input-output ratios		Unit	
Inputs	Lignocellulosic biomass Dry wood chips	MW	437
	Catalysts	MW methanol/L catalyst	5.00E-03
	Natural gas	MW	0
	Power consumption	MW	31
	Total water demand	m3/hr	219
Outputs	Methanol	MW	197
	Power Generation (Gross)	MW	23
	Wastewater	m3/hr	83
	Ash (Calcium Oxide)	kg/hr	2,590
Efficiency	***biomass to methanol***	***wt.%***	***43%***

Pacific Northwest National Laboratory, (2011) Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels (Direct gasification)

Input-output ratios		Unit	2018
Inputs	Lignocellulosic biomass *Dry wood chips)	MW	437
	Catalysts	kg/h methanol/L catalyst	5E-03
	Natural gas	MW	29
	Power consumption	MW	24
	Total water demand	m3/hr	261
Outputs	Methanol	MW	208

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	Power Generation (Gross)	MW	32
	Wastewater	m3/hr	96
	Ash (Calcium Oxide)	kg/hr	6,414
Efficiency	***biomass to methanol***	***wt.%***	***45%***

VTT, 2013, Liquid transportation fuels via large-scale fluidised- bed gasification of lignocellulosic biomass (Direct gasification)

Input-output ratios		Unit	2018
Inputs	Dry wood chips	MW	335
	Oxygen	kg/hr	19800
	Oxygen	kg/hr	15480
	Power consumption	MW	30
	Steam from auxiliary boiler	kg/hr	19080
Outputs	Methanol	MW	184
	Power Generation (Gross)	MW	33
	District heat (90 °C)	MW	0
Efficiency	***biomass to methanol***	***wt.%***	***45%***

DME production

Pacific Northwest National Laboratory, (2011) Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels, (Indirect gasification)

Input-output ratios		Unit	2018
Inputs	Lignocellulosic biomass Dry wood chips	MW	437
	Catalysts	MW methanol/L catalyst	6E-03
	Natural gas	MW	0
	Power consumption	MW	29
	Total water demand	m3/hr	243
Outputs	DME	MW	207

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	Power Generation (Gross)	MW	29
	Wastewater	m3/hr	97
	Ash (Calcium Oxide)	kg/hr	2,590
Efficiency	***biomass to DME***	***wt.%***	***34%***

Pacific Northwest National Laboratory, (2011) Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels, (Direct gasification)

Input-output ratios		**Unit**	**2018**
Inputs	Lignocellulosic biomass Dry wood chips	MW	437
	Catalysts	MW methanol/L catalyst	6.50E-03
	Natural gas	MW 0	
	Power consumption	MW	20
	Total water demand	m3/hr	280
Outputs	DME	MW	194
	Power Generation (Gross)	MW	29
	Wastewater	m3/hr	109
	Ash (Calcium Oxide)	kg/hr	2590
Efficiency	***biomass to DME***	***wt.%***	***32%***

VTT (2013), Liquid transportation fuels via large-scale fluidised- bed gasification of lignocellulosic biomass

Input-output ratios-mass balance		**Unit**	**2018**
Inputs	Dry wood chips	MW	335
	Oxygen	kg/hr	19800
	Oxygen	kg/hr	15480
	Power consumption	MW	30
	Steam from auxiliary boiler	kg/hr	30600
Outputs	DME	MW	179
	Power Generation (Gross)	MW	36

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	District heat (90 °C)	MW	0
Efficiency	***biomass to DME***	***wt.%***	***34%***

Liquefied biogas

Göteborg Energi, 2019, The GoBiGas Project

Input-output ratios		**Unit**	
Inputs	Wood pellets	dry tonnes/h	62
	Nitrogen	m3/h	40
	Olivine	kg/h	650
	Rapeseed Methyl Ester	kg/h	700
	Limestone	kg/h	1
	Potassium carbonate, 40 % solution	L/h	50
	Active carbon	kg/h	27
	Natural gas	m3/h	1000
	Power consumption	MW	20
	Power consumption	MWh el/MWh LBG.	0.034
	Total water demand	m3/h	50
Outputs	Methane	MW	200
	Bottom ash	kg/h	1500
	Fly ash	kg/h	350
	Wastewater	m3/h	
Efficiency	***Biomass to methane***	***wt.%***	***61%***

FT liquids (Diesel, jet fuel and gasoline)

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Pacific Northwest National Laboratory Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels, (2011) Indirectly-Heated Gasifier

Input-output ratios		Unit	
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2000
	Power consumption	MW	25
	Total water demand	m3/h	205
Outputs	Diesel	m3/h	12
	Naphtha	m3/h	4
	Power Generation (Gross)	MW	47
	Wastewater	m3/h	122
	Ash	kg/h	2590

Pacific Northwest National Laboratory Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels, (2011) Directly-Heated Gasifier

Input-output ratios		Unit	
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2000
	Power consumption	MW	17
	Total water demand	m3/h	265
Outputs	Diesel	m3/h	13
	Naphtha	m3/h	4
	Power Generation (Gross)	MW	41
	Wastewater	m3/h	123
	Ash	kg/h	6414

National Renewable Energy Laboratory Techno-Economic Analysis of Biofuels Production Based on Gasification (2010) Biomass to FT Fuels through High Temperature, Entrained Flow Gasification

Input-output ratios		Unit	
Inputs	Lignocellulosic biomass (corn stover)	dry tonnes/d	2000
	Fischer-Tropsch Catalyst (cobalt)	kg/h	10

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	WGS Catalyst (copper-zinc)	kg/h	0.3
	PSA molsieve 13X	kg/h	2
	Activated carbon	Not specified	
	Zinc oxide	Not specified	
	Natural gas	kg/h	312
	Power consumption	MW	22
	Total water demand	Not specified	
Outputs	Gasoline	kg/h	4700
	Diesel	kg/h	11100
	By-product sulfur	dry kg/h	132
	Power Generation (Gross)	MW	36
	Wastewater	tonnes/h	63
	Slag	kg/h	4750

National Renewable Energy Laboratory Techno-Economic Analysis of Biofuels Production Based on Gasification (2010) Biomass to FT Fuels through Low Temperature, Fluidized Bed Gasification

Input-output ratios		**Unit**	
Inputs	Lignocellulosic biomass (corn stover)	dry tonnes/d	2000
	Fischer-Tropsch Catalyst (cobalt)	kg/h	8
	WGS Catalyst (copper-zinc)	kg/h	0.3
	SMR Catalyst (nickel-aluminium)	kg/h	0.5
	PSA molsieve 13X	kg/h	2
	Activated carbon	Not specified	
	Zinc oxide	Not specified	
	Natural gas	kg/h	231.0
	Power consumption	MW	15
	Total water demand	Not specified	
Outputs	Gasoline	kg/h	3630
	Diesel	kg/h	8580
	By-product sulfur	dry kg/h	29

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Input-output ratios		Unit	
	Power Generation (Gross)	MW	31
	Wastewater	tonnes/h	58
	Ash	kg/h	4960

Ethanol production through gasification

National Renewable Energy Laboratory, (2011), Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol

Input-output ratios		Unit	2018
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2000
	Olivine	kg/h	244
	Magnesium oxide (MgO)	kg/h	3
	Tar reforming catalyst	kg/h	5
	Alcohol synthesis catalyst	kg/h	9
	Caustic (50 wt%)	kg/h	18
	Boiler chemicals	kg/h	1
	Cooling tower chemicals	kg/h	1
	Diesel fuel	kg/h	32
	LO-CAT chemicals	kg/h	1
	DEPG makeup	kg/h	1
	Amine makeup	kg/h	0.1
	Power consumption	MW	64
	Total water demand	tonnes/h	76
Outputs	Ethanol	kg/h	23133
	Mixed higher alcohols	kg/h	2925
	Sulfur	kg/h	18
	Power Generation (Gross)	MW	64
	Wastewater	tonnes/h	24
	Olivine, MgO, catalyst, ash, sulfate	kg/h	1228

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	Alcohol synthesis catalyst	kg/h			11

Reyes Valle et al, (2013) Techno-economic assessment of biomass-to-ethanol by indirect fluidized bed gasification: Impact of reforming technologies and comparison with entrained flow gasification

Input-output ratios		Unit	2018	Unit	2018
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2140	MW (HHV)	500
	Power consumption	MW	54		
Outputs	Ethanol	L/h	18088	MW (HHV)	117
	Other alcohols	MW (HHV)	40		
	Power Generation (Gross)	MW	55		

Reyes Valle et al (2013) Techno-economic assessment of biomass-to-ethanol by indirect fluidized bed gasification: Impact of reforming technologies and comparison with entrained flow gasification

Input-output ratios		Unit	2018	Unit	2018
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2140	MW (HHV)	500
	Power consumption	MW	45		
Outputs	Ethanol	L/h	22162	MW (HHV)	144
	Other alcohols	MW (HHV)	47		
	Power Generation (Gross)	MW	50		

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Pyrolysis based liquids (diesel and gasoline)

Pacific Northwest National Laboratory (2011) Techno-economic Analysis for the Thermochemical Conversion of Biomass to Liquid Fuels, Biomass to Gasoline and Diesel through Fast Pyrolysis

Input-output ratios		Unit	2018	Unit	2018
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2000		
	Natural gas	m3/h	11525	MW	113
	Power consumption	MW	25		
	Total water demand	m3/h	110		
Outputs	Diesel	m3/h	16		
	Naphtha	m3/h	21		
	Power Generation (Gross)	MW	2		
	Wastewater	m3/h	33		
	Wet ash (62.5 % water)	kg/h	4354		

NREL and PNNL (2015) Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels, Biomass to Gasoline and Diesel with in Situ Upgrading of Fast Pyrolysis Vapors

Input-output ratios		Unit	2018	Unit	2018
Inputs	Blended woody biomass	dry tonnes/d	2000		
	Sand makeup	kg/h	0		
	Natural gas	kg/h	24.49		
	Zeolite catalyst	kg/h	156		
	Hydrotreating catalyst	kg/h	7		
	Hydrocracking catalyst	kg/h	1		
	Caustic (50 wt%)	kg/h	132		
	Boiler feed water chemicals	kg/h	1		
	Cooling tower chemicals	kg/h	0.5		
	Diesel fuel	kg/h	32		
	Power consumption	MW	43		
	Total water demand	tonnes/h	20		

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Outputs	Gasoline fuel	kg/h	14454	MW	170
	Diesel fuel	kg/h	5373	MW	64
	Power Generation (Gross)	MW	48		
	Wastewater	tonnes/h	10		
	Solids purge from fluidized bed reactor	kg/h	1159		

NREL and PNNL (2015) Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels, Biomass to Gasoline and Diesel with Ex Situ Upgrading of Fast Pyrolysis Vapors

Input-output ratios		Unit	2018	Unit	2018
Inputs	Blended woody biomass	dry tonnes/d	2000		
	Sand makeup	kg/h	72		
	Natural gas	kg/h	57		
	Zeolite catalyst	kg/h	104		
	Hydrotreating catalyst	kg/h	7		
	Hydrocracking catalyst	kg/h	2		
	Caustic (50 wt%)	kg/h	133		
	Boiler feed water chemicals	kg/h	1		
	Cooling tower chemicals	kg/h	0.5		
	Diesel fuel	kg/h	32		
	Power consumption	MW	41		
	Total water demand	tonnes/h	19		
Outputs	Gasoline fuel	kg/h	9257	MW	110
	Diesel fuel	kg/h	11221	MW	134
	Power Generation (Gross)	MW	44		
	Wastewater	tonnes/h	9		
	Solids purge from fluidized bed reactor	kg/h	1059		

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Ethanol from biochemical pathway

Humbird et al. (NREL) (2011) Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol

Input-output ratios		Unit	2018	Unit	2018
Inputs	Lignocellulosic biomass (corn stover)	dry tonnes/d	2000	MW	367
	Sulfuric acid (93 %)	kg/h	1981		
	Ammonia	kg/h	1166		
	Corn steep liquor	kg/h	1322		
	Diammonium phosphate	kg/h	142		
	Sorbitol	kg/h	44		
	Glucose	kg/h	2418		
	Host nutrients	kg/h	67		
	Sulfur dioxide	kg/h	16		
	Caustic	kg/h	2252		
	Boiler chems	kg/h	<1		
	FGD lime	kg/h	895		
	Cooling tower chems	kg/h	2		
	Power consumption	MW	28		
	Total water demand	tonnes/h	147		
Outputs	Ethanol	tonnes/h	22	MW	161
	Power Generation (Gross)	MW	41		
	WWT brine	kg/h	9929		
	Ash	kg/h	5725		

Ethanol to jet fuels production

Geleynse et al. (2018) The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation

Input-output ratios		Unit	2018	Unit	2018
Inputs	Ethanol	dry tonnes/d	181	MW	56
	Dehydration catalyst	kg/day	9		
	Oligomerization catalyst	kg/day	26		

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	Hydrogenation catalyst	kg/day	4
	Hydrogen	tonnes/day	1
	Natural gas	MW	9
	Power consumption	MW	2
	Refrigeration (-50 C)	MW	2
	Total water demand	tonnes/h	1898
Outputs	Jet fuel	kg/h	3149
	Gasoline	kg/h	450
	Diesel	kg/h	900
	Wastewater	m3/h	3

Biomass to Jet Fuels production

Aggregation of Humbird et al. (NREL) (2011) and Geleynse et al. (2018) for the biomass to jet fuels production

Input-output ratios		**Unit**	**Aggregate**
Inputs	Lignocellulosic biomass (corn stover)	dry tonnes/d	2000
	Sulfuric acid (93 %)	kg/h	1981
	Ammonia	kg/h	1166
	Corn steep liquor	kg/h	1322
	Diammonium phosphate	kg/h	142
	Sorbitol	kg/h	44
	Glucose	kg/h	2418
	Host nutrients	kg/h	67
	Sulfur dioxide	kg/h	16
	Caustic	kg/h	2252
	Boiler chems	kg/h	0
	FGD lime	kg/h	895
	Cooling tower chems	kg/h	2
	Dehydration catalyst	kg/day	24
	Oligomerization catalyst	kg/day	76
	Hydrogenation catalyst	kg/day	12

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	Hydrogen	tonnes/day	3
	Natural gas	MW	26
	Refrigeration (-50 C)	MW	6
	Power consumption	MW	32
	Total water demand	tonnes/h	5586
Outputs	Jet fuel	kg/h	9024
	Gasoline	kg/h	1289
	Diesel	kg/h	2578
	Power Generation (Gross)	MW	41
	Wastewater	m3/h	9
	WWT brine	kg/h	9929
	Ash	kg/h	5725

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Biobutanol

Jang and Choi (2018) Techno-economic analysis of butanol production from lignocellulosic biomass by concentrated acid pretreatment and hydrolysis plus continuous fermentation

Input-output ratios		**Unit**	**2018**	**Unit**	**2018**
Inputs	Lignocellulosic biomass (corn stover)	dry tonnes/d	3614		
	Sulfuric acid (75%)	kg/h	7439		
	SMB make-up resin	L/h	113		
	Nutrients	Not specified			
	NaOH (1 M)	kg/h	489		
	Adsorption column make-up resin	L/h	124		
	Distillation column make-up resin	L/h	1		
	Purification membrane	m2/h	0.2		
	Caustic	kg/h	2639		
	Boiler chemicals	kg/h	2		
	Boiler FGD lime	kg/h	1573		
	Cooling tower chemicals	kg/h	4		
	Nitrogen	L/h	1		
	Power consumption	MW	35		
	Total water demand	kg/h	111921		
Outputs	N-butanol	kg/h	17751	MW	164
	Ethanol	kg/h	2317	MW	17
	Acetone	kg/h	2317	MW	19
	Power Generation (Gross)	MW	49		
	Ash	kg/h	10062		

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

Tao et al (NREL) (2014) Techno-economic analysis and life-cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n-butanol

Input-output ratios		Unit	2018	Unit	2018
Inputs	Lignocellulosic biomass (corn stover)	dry tonnes/d	2000		
	Sulfuric acid	kg/h	1878		
	Ammonia	kg/h	998		
	Corn steep liquor	kg/h	1094		
	Diammonium phosphate	kg/h	134		
	Caustic soda	kg/h	2140		
	Lime	kg/h	864		
	Enzyme loading	kg/h	13089		
	Sugar for enzyme production	kg/h	2225		
	NH3 for enzyme production	kg/h	131		
	CSL for enzyme production	kg/h	131		
	Total water demand	m3/h	148		
Outputs	Isobutanol	L/h	20167	MW	149
	Power Generation (Net)	MW	11		
	Ash	kg/h	5700		

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Appendix B

Analysis of barriers and policies

Table B1 presents a matrix associating technical and economic barriers with the related policy mechanisms that could be applied to overcome these barriers. The analysis of barriers identification and policy mechanisms has been provided in detail, in Deliverable 3.3. In this context, Table 1 presents a representative sample of barriers and it is not exhaustive for all the possible barriers associated with the advanced biofuels production paths. Policy mechanisms belong to three wider categories that is, **regulations** (e.g. quota obligations, product standards, exemption and reduction of taxes, targets for RESfuel shares in production and/or consumption and qualifying criteria for incentives, feed-in-tariffs, subsidy, green procurement etc.), **financing** (e.g. biomass feedstock premiums, capital grants, technology and feedstock related feed in tariffs or premiums, tax incentives, R&D grants for short and long term development etc.) and **information provision mechanisms** (promotion, capacity building, awareness raising etc.) associating them to barriers and by extension to technical and economic factors of conversion technologies.

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Table B8. Association of barriers to policy mechanisms. The "+" symbol indicates the correlation of a barrier with a policy mechanism. It should be noted that one barrier can be correlated with more than one policies and vice versa. (will be completed at the end)

Barriers	**Policy Mechanisms**									
	Capital investment grants	Premiums (e.g. feedstock, conversion efficiency, GHG reduction) and reduced taxation	Regulations (e.g. quota obligations, tax reduction etc.)	R&D grants	Innovation Fund	Tax (or other CO2 penalty) for using fossil fuels to promote biofuels	Labor costs policies	Capacity building	Standardisation	LCA studies and environomic dimensions
Costly auxiliaries or not available in commercial scale (e.g., enzymes, special catalysts) and trade-off among efficiency and cost	+	+			+		+			
High pre-treatment costs, high biomass price, and high logistics costs		+	+		+		+			
Lack of process integration (heat and materials, re-use)	+			+	+			+		
Lack of regulatory framework to promote greening of fossil-fuel infrastructures			+			+	+			
Restricted knowledge/experience in assembling technology components				+	+			+		
Biomass price fluctuations		+	+			+				

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Unknown conditions for efficiency related parameters (e.g. enzymes selection, adjustment of reaction conditions)	+	+		+	+					
Impurities in the feedstock influencing the performance, excessive wear of certain equipment, cellulose washing	+	+		+	+				+	
Low enzymatic hydrolysis performance due to lignin product quality, yeast process inhibitor, many organic waste streams, recirculation of solvents and solvent recovery	+	+		+	+					
Liquids properties not known, difficulties in mixing				+	+				+	
Reactors and separations should be adjusted to scale up conditions	+			+	+					
Lack of systematic framework to assess 2nd generation fuels sustainability			+			+				+

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Liquefied biogas

Table B2: Technical and economic factors, barriers and policy mechanisms for liquefied biomethane production from lignocellulosic biomass gasification.

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	N	Gasification plants can reach, after modifications, theoretical efficiency yields in commercial scale. Conversion efficiency form feedstock to liquefied biomethane is comparably high.[1]	Capital investment grants for higher efficiency technologies should focus on maximum utilisation of resulting by-products (e.g., tars), and reduce loss of carbon atoms to CO_2 emissions (e.g., by innovative CCU pathways).

[1] The syngas production part of the biomethane path, generally reaches the highest feedstock conversion efficiencies, typically in the range of 71.7-83.5% (Anderson et al. 2013). The combination of potential improvements in a gasification plant (measures improving the efficiency including the use of additives (potassium and sulfur), high-temperature preheating of the inlet streams, improved insulation of the reactors, drying of the biomass and electrification as decarbonisation means (power-to-gas)) can increase the cold gas efficiency to 83.5 % LHV-daf, which is technically feasible in a commercial plant. (Alamia et al. 2017).

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Operating capacity	N	Regarding the operating capacity, gasification plants have achieved continuous operation (e.g., the case of GoBiGas).[2]	Capital investment grants with priority to specific technological pathways and conversion efficiencies. This can support increasing the number of demonstration plants to verify the stability of continuous operation and test diversified biomass feedstock.
Co-location with existing infrastructures	M	Co-location of biomass gasification with existing infrastructures with respect to integration of material and energy flows. (e.g. district heating, pulp, paper and saw mills, oil refineries/petrochemical industries) However, other parameters such as economic and regulatory reasons may constrain it.	Premiums and reduced taxation Capacity building
Process design: aspects	M	Issues with product quality, tar fouling in heat exchangers during syngas cleaning, and tar utilisation are solvable but may require innovations, especially if these issues appear in technologies demonstrated only in lower scales.[3]	Regulations and R&D grants

2 The plant has been in continuous operation in a single run since the beginning of December 2017, namely for more than 1,800 hours, with consistent performance. In total, the gasifier has been operated for more than 15,000 hours, since its commissioning in 2014. The plant was operational after an initial period of 6 months. Potassium was added to saturate and stabilise the chemistry that controls the catalytic effect, to assure the quality of the produced gas thereby avoiding any clogging of the product gas cooler. The bed height of the gasifier was lowered so that the fuel could be fed closer to the surface of the bubbling bed in the gasifier, thereby reducing the heat transfer and clogging of the fuel-feeding screw and enabling 1800 h of continuous operation (Thunman et al. 2019).

3 It should be noted that the gas cleaning complexity is very similar to what you have out from steam crackers of naptha or old coal gasifiers aiming for providing the petrochemical industry with building blocks; so large-scale plants can use the solutions previously applied to this kind of processes.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Scale-up aspects	M	Serious technical scale up issues from demonstration to full scale do not exist, other than biomass availability and logistic constraints (i.e., the theoretical economic optimum in terms of capacity may not be reached because of biomass logistics issues) No large biomass gasification plants have ever been built, however their economic performance can be assessed with some certainty on the basis of the operation of demonstration plants.	R&D grants and Innovation Fund
Economic			
Market conditions	S	Competition with other uses of biomass and development of alternative fuels for the transportation and power sector will play an important role for the enviro-economic assessment of bio-methane production via biomass gasification. Biomethane is considered as a suitable alternative to fossil natural gas for two main applications: direct injection into natural gas grid and use in transport.	All policies mentioned below affect market conditions Labor costs policies for this kind of plants
Capital investment and production costs	S	Biomass price, logistics and production costs are high; capital costs are also high, especially when no collocation is assumed or retrofitting of existing plants. In particular, the investment cost for handling and preparation of the feedstock (including drying) is considerable because of the low energy density and high moisture content of the fresh biomass.	Sufficient tax (or other CO_2 penalty) for using fossil fuels Feedstock premiums for low cost residual and waste biomass types

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		As mentioned in the scale-up aspects, there is an inherent trade-off between the economy of scale and the logistics of biomass for the plant. Ships running on LNG fuel also have higher capital cost for the system installation, and thus not a practical fuel for conventional low-cost shipping[4].	
Uncertainties of production cost	S	For first-of-its-kind plant the biggest uncertainty is in getting high enough availability, thus assuring redundancy that avoid unplanned stops in the production is a must.5 Temporal and geographical uncertainties pertaining to the estimated production costs are timing of the investment, the location of the installation and price of feedstock. The price of LNG is strongly influenced by transportation costs as this accounts for a large share of the overall costs. While large-scale liquefaction of natural gas is an established technology, small-scale liquefaction of biomethane is a recent concept and as such, cost reduction and efficiency improvements will occur over time[6]	Feedstock premiums towards a common framework in EU countries (a challenging task)
Investor risk premium		High investment risk premium is expected due to unstable regulatory framework for investment and market prices of RESfuels.	Capital grants and Innovation funds

[4] IEA Bioenergy, 2017, Biofuels for the marine shipping sector

[5] For newly built processes it is a big challenge to reach high availability as fast as possible after commissioning.

[6] Kesieme et al., 2019, Biofuel as an alternative shipping fuel: technological, environmental and economic assessment, Sustainable Energy Fuels

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
	M	Because the technology is still at the level of first of its kind plants (at least for the biomass to syngas part) uncertainty for investments increases. The GoBiGas plant was built by Göteborg Energi, which is an energy company owned by the municipality of Gothenburg and was supported by the Swedish Energy Agency.	Capacity building and training for investors and industry on the needs of this sector
Access to debt financing	M	This will mainly be a barrier for companies with high debt-to-equity financing ratios. On the other hand, for larger companies with a diversified business portfolio and low debt-to-equity financing ratios, as well as for public-private partnerships this will not be a significant barrier. The presently low interest rates also help overcome this barrier.	Development of green bonds or loans for green projects. The new EU innovation fund. Public Private partnerships and Joint Ventures
Commercially available process components	M	Only one component is considered less mature, namely the gasifier. The rest of the process components of the technology have already reached the nth-of-its kind installation and learning will only be related to the assembly of these parts into a new system.	Training, capacity building, and certification.
End-use market development (or engine development)	S	Biomethane fuel characteristics and suitability in marine engines. LBG (Liquefied Bio-Gas) has high energy density, but needs to be stored in cryogenic tanks. A new fuel infrastructure may be needed (terminals, bunker, new storage facilities and engines on board).	Standardisation (e.g., implementation of European standards allowing the use of methane in high concentrations)

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		Gaseous fuels such bio-methane will require a different type of fuel handling system, fuel tanks and gas burning engines that are not currently in use on most ships. More fuel space for an equivalent quantity of energy is needed for fuel storage on board. This will imply that LNG as a fuel will not be suitable for all ship types. As LNG is also a relatively new marine fuel, access to fueling stations is still limited, and there are also needs for proper LNG storage facilities at ports to facilitate use of this technology. Spark-ignited gas engines using the Otto-cycle operating only on LNG or dual-fuel diesel engines where both LNG and other fuels can be used. The engine efficiency is of the same order of magnitude as that for medium speed diesel engines. A few small ships have also been recently built with LNG engines, and were introduced on the marine market since 2010. To switch from LNG to LBG investments and technological development are needed to introduce their biogas at central LNG terminals within Europe.	R&D grants for engine development (e.g., dedicated to methane powertrains) Social perception related to the toxicity of methanol Introduction of tax incentives for using biomethane in fuels. Comprehensive LCA studies are essential for comparing alternatives.[8] Increasing the LBG refueling infrastructure

[8] Comprehensive LCA based approach would be required for an in-depth comparison of the environmental impact of biofuels used in internal combustion engines (ICVs) and electric vehicles (EVs). Yet, both these depend on the system boundaries and how the surrounding system develops over time. Thus, the environmental impact of production of batteries and operating of the EVs will depend on how the electricity mix develops (i.e., its associated GHG emissions). The IC and batteries operating life time and the potential for recycling their materials after their end of use, particularly when it comes to rare meals in batteries, should also be considered. Finally, biomass use will be linked to other environmental goals such as biodiversity which may also be subject to discussion and therefore need to be analysed. Considering the urgency of mitigating carbon emissions, it is likely that both EVs and biofuel fired IC vehicles are needed, but with different penetration over time.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		At present, the utilisation of LNG is negligible in both ship and Heavy Duty Vehicles (HDV) transport[7].	
Enviro-economic aspects	M	Sustainability goals in RED II do not clearly include CO_2 emission targets per sector, and CO2 taxation in the future is uncertain. From an emissions perspective, LNG is a suitable fuel for low carbon shipping due to lower CO2 emissions than distillate and residual fuels as well as the elimination of SOx and PM emissions (IEA, 2017). It contains very little sulphur and can hold more energy per tonne than MDO. However, LNG and associated methane gas leaks do not contribute to solving the fossil fuel dependency nor the climate change related issues. The overall (well to wheels/WTW) GHG performance range from -12% to +9%, depending on the mode of transport. The GHG savings range from -7% to +6% compared to diesel in cars. In heavy duty, the range is -2% to +5% compared to best in class diesel trucks and depending on fuel engine technology. In shipping, the figures are -12% to +9% compared to marine gas oil (MGO) and they are highly dependent on methane slip (Transport and Environment, 2018)[9]	Regulations Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors.

[7] BMVI, 2014, LNG as an alternative fuel for the operation of ships and heavy duty vehicles

[9] https://www.transportenvironment.org/sites/te/files/publications/2018_10_TE_CNG_and_LNG_for_vehicles_and_ships_the_facts_EN.pdf

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Dimethyl Ether – DME

Table B3: Technical and economic factors, barriers and policy mechanisms for DME production from lignocellulosic biomass gasification.

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	N	Gasification plants can reach, after modifications, theoretical efficiency yields in commercial scale. Conversion efficiency form feedstock to biomethanol is comparably high.[10]	Capital investment grants for higher efficiency technologies should focus on maximum utilisation of resulting by-products (e.g., tars), and reduce loss of carbon atoms to CO_2 emissions (e.g., by innovative CCU pathways).
Operating capacity	N	Regarding the operating capacity, gasification plants have achieved continuous operation (e.g., the case of GoBiGas).[11]	Capital investment grants with priority to specific technological pathways and conversion efficiencies. This can

[10] As for the syngas production part of the DME path, it generally reaches the highest feedstock conversion efficiencies, typically in the range of 71.7-83.5% (Anderson et al. 2013). The combination of potential improvements in a gasification plant (measures improving the efficiency including the use of additives (potassium and sulfur), high-temperature preheating of the inlet streams, improved insulation of the reactors, drying of the biomass and electrification as decarbonisation means (power-to-gas)) can increase the cold gas efficiency to 83.5 % LHV-daf, which is technically feasible in a commercial plant. (Alamia et al. 2017).
Energy efficiencies for biomass to MeOH/DME synthesis were found to be 56-58% and 51-53%, respectively, taking LHV as reference. This efficiency is enhanced to 87 to 88% (LHV) if district heating is also counted as one of the products. (Sikarvar et al. 2017)

[11] The plant has been in continuous operation in a single run since the beginning of December 2017, namely for more than 1,800 hours, with consistent performance. In total, the gasifier has been operated for more than 15,000 hours, since its commissioning in 2014. The plant was operational after an initial period of 6 months. Potassium was added to saturate and stabilise the chemistry that controls the catalytic effect, to assure the quality of the produced gas thereby avoiding any clogging of the product gas cooler. The bed height of the gasifier was lowered so that the fuel could be fed closer to the surface of the bubbling bed in the gasifier, thereby reducing the heat transfer and clogging of the fuel-feeding screw and enabling 1800 h of continuous operation (Thunman et al. 2019).

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
			support increasing the number of demonstration plants to verify the stability of continuous operation and test diversified biomass feedstock.
Co-location with existing infrastructures	M	Co-location of biomass gasification with existing infrastructures with respect to integration of material and energy flows. (e.g. district heating, pulp, paper and saw mills, oil refineries/petrochemical industries) However, other parameters such as economic and regulatory reasons may constrain it. Syngas produced during gasification can also be converted to dimethyl ether (DME) by methanol dehydration or methane via the Sabatier process. For the production of DME, methanol is currently, for the main part produced	Premiums and reduced taxation Capacity building
Process design: aspects	M	Issues with product quality, tar fouling in heat exchangers during syngas cleaning, and tar utilisation are solvable but may require innovations, especially if these issues appear in technologies demonstrated only in lower scales.[12]	Regulations and R&D grants
Scale-up aspects		Serious technical scale up issues from demonstration to full scale do not exist, other than biomass availability and	R&D grants and Innovation Fund

[12] It should be noted that the gas cleaning complexity is very similar to what you have out from steam crackers of naptha or old coal gasifiers aiming for providing the petrochemical industry with building blocks; so large-scale plants can use the solutions previously applied to this kind of processes.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
	M	logistic constraints (i.e., the theoretical economic optimum in terms of capacity may not be reached because of biomass logistics issues) No large biomass gasification plants have ever been built, however their economic performance can be assessed with some certainty on the basis of the operation of demonstration plants.	
Economic			
Market conditions	S	Competition with other uses of biomass and development of alternative fuels for the transportation and power sector will play an important role for the enviro-economic assessment of DME production via biomass gasification.	All policies mentioned below affect market conditions Labor costs policies for this kind of plants
Capital investment and production costs	S	Biomass price, logistics and production costs are high; capital costs are also high, especially when no collocation is assumed or retrofitting of existing plants. In particular, the investment cost for handling and preparation of the feedstock (including drying) is considerable because of the low energy density and high moisture content of the fresh biomass. As mentioned in the scale-up aspects, there is an inherent trade-off between the economy of scale and the logistics of biomass for the plant.	Sufficient tax (or other CO_2 penalty) for using fossil fuels Feedstock premiums for low cost residual and waste biomass types

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Uncertainties of production cost	S	For first-of-its-kind plant the biggest uncertainty is in getting high enough availability, thus assuring redundancy that avoid unplanned stops in the production is a must.[13] Temporal and geographical uncertainties pertaining to the estimated production costs are timing of the investment, the location of the installation and price of feedstock.	Feedstock premiums towards a common framework in EU countries (a challenging task)
Investor risk premium	M	High investment risk premium is expected due to unstable regulatory framework for investment and market prices of RESfules. Because the technology is still at the level of first of its kind plants (at least for the biomass to syngas part) uncertainty for investments increases. The GoBiGas plant was built by Göteborg Energi, which is an energy company owned by the municipality of Gothenburg and was supported by the Swedish Energy Agency.	Capital grants and Innovation funds Capacity building and training for investors and industry on the needs of this sector
Access to debt financing	M	This will mainly be a barrier for companies with high debt-to-equity financing ratios. On the other hand, for larger companies with a diversified business portfolio and low debt-to-equity financing ratios, as well as for public-private partnerships this will not be a significant	Development of green bonds or loans for green projects. The new EU innovation fund. Public Private partnerships and Joint Ventures

[13] For newly built processes it is a big challenge to reach high availability as fast as possible after commissioning.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		barrier. The presently low interest rates also help overcome this barrier.	
Commercially available process components	M	Only one component is considered less mature, namely the gasifier. The rest of the process components of the technology have already reached the nth-of-its kind installation and learning will only be related to the assembly of these parts into a new system.	Training, capacity building, and certification.
End-use market development (or engine development)	M	Alternative fuels to diesel and LNG such as dimethyl ether (DME) and water-in-diesel emulsions (WiDE) have also been explored, but are not yet produced at large scale or traded on the commodity market (IEA Bioenergy, 2017). The totally different fuel injection system is required for DME than for diesel due to its gaseous nature. Mild pressure is needed to keep DME in liquid form. However, retrofitting of diesel engines for DME use is possible and was demonstrated by Volvo Trucks. DME can be applied as a neat fuel and it is commonly considered for light/heavy road transportation, but there is not yet any commercial biofuel production for shipping vessels, due to the low production capacity and the insufficient transport infrastructure (IEA Bioenergy, 2017).	R&D grants for engine development (e.g., dedicated to DME powertrains) Introduction of tax incentives for using bioDME in fuels. Comprehensive LCA studies are essential for comparing alternatives. Increasing the DME refueling infrastructure
Enviro-economic aspects	M	Sustainability goals in RED II do not clearly include CO_2 emission targets per sector, and CO_2 taxation in the future is uncertain.	Regulations Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors.

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Butanol

Butanol is an attractive renewable liquid transportation biofuel which is preferable to ethanol in terms of fuel properties such as high calorific value, low freezing point, high hydrophobicity, low flammability, and corrosiveness. Additionally, butanol is amenable to pipeline distribution and it can be used with or without blending with gasoline in existing vehicles without any modification. Production of butanol is supported by governments around the globe including the United States (US), which mandates an annual production of 16 billion gal of cellulosic biofuels out of total 36 billion gal of renewable biofuels by 2022. [14]

Butanol was traditionally produced by ABE fermentation - the anaerobic conversion of carbohydrates by strains of Clostridium into acetone, butanol and ethanol. However, there are many barriers regarding this technology that make ABE butanol competitive on a commercial scale with butanol produced synthetically and almost all ABE production ceased as the petrochemical industry evolved. However, there is now increasing interest in use of biobutanol as a transport fuel. 85% Butanol/gasoline blends can be used in unmodified petrol engines. It can be transported in existing gasoline pipelines and produces more power per litre than ethanol. Biobutanol can be produced from cereal crops, sugar cane and sugar beet, etc, but can also be produced from cellulosic raw materials.[15]

Table B4: Technical and economic factors, barriers and policy mechanisms for butanol production from lignocellulosic ABE process.

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	S	In conventional ABE fermentations, n-butanol yield is low, typically approximately 15 wt% and rarely in excess of 25 wt. (Ling Tao, Xin He)	Technology and/or innovation premiums[16]

[14] Baral et al., (2016), Techno-Economic Analysis of Cellulosic Butanol Production from Corn Stover through Acetone−Butanol−Ethanol Fermentation, Energy Fuels

[15] https://www.etipbioenergy.eu/value-chains/products-end-use/products/biobutanol

[16] Technology or innovation premiums aim at stimulating the capacity for innovation of companies engaged in research and development.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Operating capacity	M	For iso-butanol Gevo commenced production at the world's first commercial-scale 18 MGPY biobutanol plant, developed by conversion of the former Agri-Energy corn ethanol plant in Luverne (https://www.etipbioenergy.eu/value-chains/products-end-use/products/biobutanol). Efforts for commercial operation have been reported and a number of technical challenges have been overcome (e.g. improved batch turnaround times, avoidance of infections, etc) in the first months of operation, and the company was on target to produce 50,000 to 100,000 gallons per month of isobutanol by the end of 2014 [Source: Gevo]. The company reports that is getting close to the efficiency required for fully commercial operation. Various companies such as Cobalt, Green Biologics, GranBio, Microvi, Optinol and Rhodia are all examples of companies working to commercialize n-butanol production[17].	Capital investment grants with banding for increasing the number of demonstration and commercial plants to verify the stability of continuous operation R&D grants
Co-location with existing infrastructures	M	Several of these companies intend to retrofit existing sugar or corn mills for butanol fermentation and recovery. China is foreseeing to retrofit its existing conventional starch-based refineries to use cheaper cellulosic materials as feedstock for butanol production. Retrofit of old refineries and pulp and paper industry may be a way of acceleration f butanol production especially in developed countries (Brazil, USA) [18]	Premiums and reduced taxation Capacity building

[17] IEA Bioenergy, (2014), The potential and challenges of Drop-in biofuels

[18] Sarangi et al., Recent Advancements in Biofuels and Bioenergy Utilization, Springer Nature Singapore Pte Ltd. 2018

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Process design: aspects	S	Acetone and ethanol are produced as co-products limiting the yield of butanol and increasing the complexity of product separation (e.g. liquid-liquid extraction), which can be very energy-intensive. The main problem associated with the ABE fermentation by bacteria is the self-inhibition of the process due to n-butanol toxicity to the culture. Mentioned toxicity of solvent to the culture and nutrient depletion during long time fermentation processes are two main factors caused premature termination of the fermentation. Apart from the low butanol yield, its separation becomes difficult and expensive process, unlike ethanol. Another limitation that builds up is the selection of biomass along with pretreatment process. Whatever the pretreatment process may be, detoxification is very crucial for removal of inhibitors generated during this processes	Regulations and R&D grants
Scale-up aspects	S	Advanced fermentation technologies are being developed by the expert groups to resolve problems such as low cell density, viability, and solvent sensitivity by modulations in the methods of carbon feeding, mode of culture, and in situ removal and recovery of solvents.[19]	R&D grants and Innovation Fund
Economic			

[19] Sukumaran et al., (2011), Chapter 25 - Butanol Fuel from Biomass: Revisiting ABE Fermentation, Biofuels: Alternative Feedstocks and Conversion Processes

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Market conditions	S	Comparing with methanol and ethanol n-butanol is a more complex alcohol, possessing several advantageous characteristics: higher heating value, lower volatility, less ignition problems, higher viscosity and is safer for distribution. Moreover, n-butanol can be blended with petrol at any ratio. Furthermore, using butanol as a fuel enables reduction of NOx There is increasing interest in use of biobutanol as a transport fuel. 85% Butanol/gasoline blends can be used in unmodified petrol engines.	All policies mentioned below affect market conditions
Capital investment and production costs	S	The low n-butanol yield and n-butanol concentration could make n-butanol production by ABE fermentation more expensive than from petroleum. Due to low crude oil prices, commercial n-butanol operations from sugar-based raw materials ended in the 1980s. Although lignocellulosic biomass can be used as a cheap source of substrates for ABE fermentation, the main challenge of using lignocellulosic biomass as feedstock is the additional costs of sugar production compared to molasses or starches Apart from other technical challenging issues associated with ABE fermentation common to all feedstocks, butanol toxicity and low recovery can hinder its commercial production, which significantly increases the cost of recovery and separation (Ezeji et al. 2007) and therefore the production cost. Although the sustainable production of butanol from renewable biomass is gaining momentum in the biofuel sector (Jung et al. 2013; Gao et al. 2014), the cost of the	Feedstock premiums for low cost residual and waste biomass types

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		substrate only accounts for 60% of the overall production cost. Hence, low cost and year-round availability are the key issues for the successful development of the biotechnological route.	
Uncertainties of production cost	S	Lignocellulosic biomass is regarded as the suitable substrate for conversion into biobutanol through ABE fermentation, The feedstock seasonality, the intense pretreatment requirement and requirement of expensive hydrolytic enzymes, are factors which cause the increase of the price of butanol and hinder its commercialization (Shafiei et al. 2011, 2013, 2014; Boonsombuti et al.)	Feedstock premiums towards a common framework in EU countries (a challenging task)
Investor risk premium	M	Moderate to high investment risk premium (e.g., lower than the gasification- based fuels because of experience from the operation and logistics of the starch based plants). It shares, however, with all RESfuels the unstable regulatory framework for investment and market prices.	Capital grants and Innovation funds Capacity building and training for investors and industry on the needs of this sector
Access to debt financing	M	Companies with experience in starch based plants, old refineries, pulp & paper industry are expected to have substantial know-how in access to debt-financing. Still, larger companies with a diversified business portfolio and low debt to equity financing as well as public-private partnerships will overcome this barrier more easily. The presently low interest rates also help overcome this barrier.	Public Private partnerships and Joint Ventures
Commercially available process components	N	There is experience from ABE and fermentation processes	Training, capacity building, and certification.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
End-use market development (or engine development)	M	Neither ethanol nor butanol are currently considered suitable for direct blending with conventional jet fuel (Hileman & Stratton, in press; ALFA-BIRD, 2012; Hileman et al., 2009). However, there is now increasing interest in use of biobutanol as a transport fuel. Compared to conventional gasoline, n-butanol's anti-knock index is in the same range and thus will not cause a negative impact on engine knock. N-butanol's high heat of evaporation provides additional charge cooling to prevent engine knock when used in gasoline direct-injection engines. This allows better engine spark timing at high loads and thus improves engine thermal efficiency[20]. In general, isobutanol is a better butanol isomer than n-butanol for spark-ignition engines. Isobutanol has significantly higher RON than n-butanol. Isobutanol ASTM D7862standards for blends of butanol with gasoline at 1 - 12.5 % vol in automotive spark ignition engines[21].	Standardisation (e.g., implementation of European standards allowing the use of butanol in high concentrations) R&D grants Introduction of tax incentives for using biobutanol in fuels. Comprehensive LCA studies are essential for comparing alternatives. Increasing the butanol refueling infrastructure
Enviro-economic aspects	M	Sustainability goals in RED II do not clearly include CO2 emission targets per sector, and CO2 taxation in the future is uncertain.	Regulations

[20] Ling Tao, Xin He, Eric C. D. Tan, Min Zhang and Andy Aden, Comparative techno-economic analysis and reviews of n-butanol production from corn grain and corn stover, Biofuels, Bioprod. Bioref. 8:342–361 (2014)
[21] https://www.etipbioenergy.eu/value-chains/products-end-use/products/biobutanol

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		Tests of passenger car exhaust emissions tested over the New European Driving Cycle transient cycle showed that adding 10% n-butanol to gasoline caused a significant decrease in particulate matter and smoke emissions, had no effect on NOx and carbon dioxide (CO_2) emissions, and resulted in higher CO and HC emissions. At high blending levels, oxygenated compounds could account for more than half of the total hydrocarbon emissions (Tao et al., 2013).	Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors.

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Pyrolysis upgrading pathways processes (and production of diesel and gasoline (or naphtha))

Table B5: Technical and economic factors, barriers and policy mechanisms for pyrolysis pathways for advanced biofuels

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	N	Fast pyrolysis is the most feasible way to convert biomass into liquid fuels and give highest yield to liquid fuel products and retains most of the energy from feedstock. The liquid product, known as bio-oil, is obtained in yields up to 75% by weight on a dry feed basis[22] Catalytic fast pyrolysis combines the fast pyrolysis of biomass with the catalytic transformation of the primary pyrolysis vapors to more desirable and less oxygenated liquid fuels. These liquid fuels can readily be upgraded to transportable liquid while simultaneously increasing energy density.[23]	Capital investment grants for higher efficiency technologies should focus on maximum utilisation of resulting by-products (e.g., tars), and reduce loss of carbon atoms to CO_2 emissions (e.g., by innovative CCU pathways).
Operating capacity	N	At present, there is a number of commercial and semi-commercial plants running in EU and outside EU, producing bio-oil for CHP applications, but upgrading the bio-oil to transport fuels has not been fully demonstrated yet and many of the upgrading processes can be defined at an early stage of development (IRENA, 2016).	Capital investment grants with priority to specific technological pathways and conversion efficiencies. This can support increasing the number of demonstration plants

[22] PNNL, 2009, Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case

[23] Bhutto, A., Qureshi, K., Abro, R., Harijan, K., Zhao, Z., Bazmi, A., Abbas T., and Yu, G., Progress in the production of biomass-to-liquid biofuels to decarbonize the transport sector – prospects and challenges, RSC Adv., 2016,6, 32140–32170

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
			to verify the stability of continuous operation and test diversified biomass feedstock.
Co-location with existing infrastructures	M	Bio-oil is poorly suited for direct blending in oil refineries. Catalysts are affected from O2 and H2O content. The upgrading step uses standard refining processes, and it may therefore be possible to co-process pyrolysis oil in existing oil refineries. Co-location eliminates the need for a Pressure Swing Adsorption (PSA) unit in the hydrotreating section if the upgrading unit off-gas can be sent to refinery hydrogen generation. In return, the upgrading unit receives refinery hydrogen at a lower cost. All final processing of the stable oil to fuels occurs in the refinery.	Premiums and reduced taxation Capacity building
Process design: aspects	M	Key parameters affecting the yield of bio-oil are temperature, heating rate, residence time, and particle size Catalyst improvements are also a major opportunity in the upgrading step. Bio-oils contain large amounts of water and oxygenated compounds as well as char particles. They also have drawbacks as combustion fuels such as low energy density, ignition difficulties, high viscosity and instability as well as low pH and high particulate.	Regulations and R&D grants
Scale-up aspects		Upgrading capacity for pyrolysis oil will at first instance largely use existing refinery infrastructure.	R&D grants and Innovation Fund

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
	M	The low H/C ratio in the bio-oils imposes a relatively low limit on the hydrocarbon yield and, in addition, the technical feasibility is not yet completely proven. Catalyst deactivation raises many concerns for both routes, although the coking problem with zeolites can in principle be overcome by a conventional FCC arrangement with continuous catalyst regeneration by oxidation of the coke. The processing costs are high and the products are not competitive with fossil fuels. A projected typical yield of aromatics suitable for gasoline blending from biomass is about 20 wt % or 45% in energy terms.[24]	
Economic			
Market conditions	S	To overcome the commercialization hurdles resulting from the heterogeneity of bio-oils, a set of standards has recently been approved by ASTM. The ASTM D7544 fast pyrolysis oil burner fuel standard was approved in 2010 for Grade G and in 2012 for Grade D bio-oils. (IEA Bioenergy, 2019) These standards qualify pyrolysis oils as burner fuels and they provide benchmark-type minimum requirements upon which applications and trading of bio-oils can be based. A constant and better quality bio-oil available at an attractive price is necessary for commercial, large-scale applications.	All policies mentioned below affect market conditions Labor costs policies for this kind of plants

[24] Czernik S., Overview of Applications of Biomass Fast Pyrolysis Oil, Energy & Fuels 2004, 18, 590-598

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Capital investment and production costs	S	As capital costs for upgrading bio-oils are high it would be synergistically beneficial if existing oil refinery equipment could be used to process these biomass derived liquids. The processes used to upgrade bio-oils resemble those used to upgrade vegetable oils to drop-in biofuels, although pyrolysis liquids are significantly more challenging a feedstock to upgrade than are vegetable oils (VOs) (IEA Bioenergy, 2019)	Sufficient tax (or other CO_2 penalty) for using fossil fuels Feedstock premiums for low cost residual and waste biomass types
Uncertainties of production cost	S	For first-of-its-kind plant the biggest uncertainty is in getting high enough availability, thus assuring redundancy that avoid unplanned stops in the production is a must[25] Temporal and geographical uncertainties pertaining to the estimated production costs are timing of the investment, the location of the installation and price of feedstock. Although pyrolysis has great potential as a low cost liquid fuel, it also has some disadvantages due to the relatively high oxygen content of bio-oils. In "petroleum-like" drop-in biofuels the oxygen has to be removed and this is the primary objective of technologies that try to upgrade bio-oils to transport fuels. Depending on the upgrading efficiency of pyrolysis oils and the price trends of petroleum, bio-oil could become competitive in the near future (IEA Bioenergy, 2014).	Feedstock premiums towards a common framework in EU countries (a challenging task)

25 For newly built processes it is a big challenge to reach high availability as fast as possible after commissioning.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Investor risk premium	M	High investment risk premium is expected due to unstable regulatory framework for investment and market prices of RESfuels. Because the technology is still at the level of first of its kind plants (at least for the biomass to bio-oil part) uncertainty for investments increases.	Capital grants and Innovation funds Capacity building and training for investors and industry on the needs of this sector
Access to debt financing	M	This will mainly be a barrier for companies with high debt-to-equity financing ratios. On the other hand, for larger companies with a diversified business portfolio and low debt-to-equity financing ratios, as well as for public-private partnerships this will not be a significant barrier. The presently low interest rates also help overcome this barrier.	Development of green bonds or loans for green projects. The new EU innovation fund. Public Private partnerships and Joint Ventures
Commercially available process components	M	Upgrading steps are in pre-commercial stages	Training, capacity building, and certification.
End-use market development (or engine development)	M	Bio-oil differs from conventional liquid fuels and must therefore overcome both technical and marketing hurdles prior to its acceptance in the market. To standardize bio-oil quality in the liquid fuels market, specifications are needed. Green Diesel from upgraded pyrolysis bio-oil could potentially be used as a drop-in substitution for fossil diesel in road-transportation, and MGO in marine applications. Additionally, from the lighter fractions of the hydro-	Standardisation (e.g., implementation of European standards allowing the use pyrolysis-based fuels i.e diesel & gasoline in high concentrations)

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Factor	**Barrier (Severe (S), Moderate (M), None (N))**	**Explication**	**Policy mechanisms to overcome barriers**
		treated pyrolysis oil (HPO), a potential substitution for fossil gasoline could be produced.	Introduction of tax incentives for using pyrolysis based fuels. Comprehensive LCA studies are essential for comparing alternatives. Increasing the refueling infrastructure
Enviro-economic aspects	M	Sustainability goals in RED II do not clearly include CO2 emission targets per sector, and CO2 taxation in the future is uncertain.	Regulations Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors.

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FT synthesis liquid fuels

Table B6: Technical and economic factors, barriers and policy mechanisms for FT liquids

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	M	Selectivity to required diesel, jet or gasoline fractions are typically limited to less than 40%. Significant amounts of unwanted olefins, alcohols, acids, ketones, water and CO_2 are also produced.	Capital investment grants for higher efficiency technologies should focus on maximum utilisation of resulting by-products (e.g., tars), and reduce loss of carbon atoms to CO2 emissions (e.g., by innovative CCU pathways).
Operating capacity	M	Commercial biomass-to-liquid (BTL) process has not been completely established.	Capital investment grants with priority to specific technological pathways and conversion efficiencies. This can support increasing the number of demonstration plants to verify the stability of continuous operation and test diversified biomass feedstock.
Co-location with existing infrastructures	M	Co-processing Fischer-Tropsch waxes at existing crude oil refineries (e.g. as developed at the company OMV) is a potential innovation opportunity. This achieves greater economies of scale and efficiencies than can be found at small-scale facilities.	Premiums and reduced taxation Capacity building

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		However, extremely limited volumes of Fischer-Tropsch waxes from biomass are available and this opportunity depends on logistics, and the availability and willingness of existing refineries to co-process. [26] Plant capex savings could amount to 15% but use of third party equipment would probably come with additional costs. Co-gasification of biomass and coal has been broadly investigated by researchers (Collot et al., 1999; Aigner et al., 2011; Taba et al., 2012), because it creates opportunities in industries for biofuels production.	
Process design: aspects	M	Cleaning of syngas is necessary as FT is sensitive to impurities, but requires high capital investments and subsequent steps of cooling and re-heating (Ail and Dasappa, 2016). Fischer-Tropsch synthesis can use syngas derived from any source including biomass, coal or natural gas and it can produce precursors for a wide range of drop-in chemicals and fuel. As long as the syngas is treated and conditioned properly and there is a good H_2/CO ratio, functional and chemical equivalence can be achieved between the syngas derived from these disparate feedstocks (IEA bioenergy, Drop-in biofuels, 2019) Although with a biomass feedstock it is more difficult to achieve the same level of syngas purity as with natural	Regulations and R&D grants

[26] IRENA (2016) Innovation Outlook, Advanced liquid Biofuels

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		gas, a near chemical equivalence can be reached. Scale-up is possible based on the know-how and facilities of existing natural gas and coal gasification FTS plants. (IEA, bioenergy, Drop-in biofuels, 2019) Fischer-Tropsch catalysts need a tightly specified carbon monoxide to hydrogen ratio, which can require a water gas reaction after syngas clean-up. This adds to costs and loss of yield because CO2 is emitted to produce hydrogen. (IEA, bioenergy, Drop-in biofuels 2019) The Fischer-Tropsch reactor design influences the catalyst lifetime and reaction rate.	
Scale-up aspects	M	Demonstration plants have been established to scale down the Fischer-Tropsch process to a size appropriate to a supply chain based on biomass. FT is an established technology, and many components of the system are already proven in coal-to-liquid or gas-to-liquid plants. What remains unproven is the BtL at a commercial scale due to technical barriers as identified by Sims et al. (2010).	R&D grants and Innovation Fund
Economic			
Market conditions	S	Competition of biomass-based products with fossil-based equivalents, no tax for fossil fuels and high production costs	All policies mentioned below affect market conditions Labor costs policies for this kind of plants

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Capital investment and production costs	S	High capital cost due to the multistage character of the process. Production costs are even higher as the optimum scale of operation requires feedstock on an economic price whereas transportation costs are also an important factor. Hence, the economy of scale is decreased compared to a large coal or gas-based operation. Running and maintenance costs are also comparatively high.[27]	Sufficient tax (or other CO_2 penalty) for using fossil fuels Feedstock premiums for low cost residual and waste biomass types
Uncertainties of production cost	S	The cost of gasification-derived biofuels can be estimated quite accurately since the processes are based on established industrial and pilot processes. A study of ISU/ConocoPhillips/NREL (Swanson et al., 2010) has estimated the cost of gasoline produced from FT conversion of biomass syngas (IEA Bioenergy, 2014) For first-of-its-kind plant the biggest uncertainty is in getting high enough availability, thus assuring redundancy that avoid unplanned stops in the production is a must.[28] Temporal and geographical uncertainties pertaining to the estimated production costs are timing of the investment, the location of the installation and price of feedstock.	Feedstock premiums towards a common framework in EU countries (a challenging task)

27 https://www.etipbioenergy.eu/value-chains/products-end-use/products/ft-liquids

28 For newly built processes it is a big challenge to reach high availability as fast as possible after commissioning.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		Large scales are required to benefit from economies of scale both for the gasifier as well as the catalytic equipment, but this is often problematic for biomass installations due to biomass supply logistics.	
Investor risk premium	M	High investment risk premium is expected due to unstable regulatory framework for investment and market prices of RESfuels. Because the technology is still at the level of first of its kind plants (at least for the biomass to syngas part) uncertainty for investments increases.	Capital grants and Innovation funds Capacity building and training for investors and industry on the needs of this sector
Access to debt financing	M	This will mainly be a barrier for companies with high debt-to-equity financing ratios. On the other hand, for larger companies with a diversified business portfolio and low debt-to-equity financing ratios, as well as for public-private partnerships this will not be a significant barrier. The presently low interest rates also help overcome this barrier.	Development of green bonds or loans for green projects. The new EU innovation fund. Public Private partnerships and Joint Ventures
Commercially available process components	M	This is an established technology, and many components of the system are already proven and operational for decades in coal-to-liquid or gas-to-liquid plants. The aggregated part, BtL process, remains unproven at a commercial scale due to technical barriers as identified by Sims et al. (2010) which still need to be overcome.[29]	Training, capacity building, and certification.

[29] M. Padella, A. O'Connell, M. Prussi, E. Flitris, L. Lonza, Sustainable Advanced Biofuels Technology Development Report 2018, EUR 29908 EN, European Commission, Luxembourg, 2019, ISBN 978-92-76-12431-3, doi:10.2760/95648, JRC118317

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

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		Application of the process to biomass is however relatively novel, and has yet to be fully optimised. Gasification technologies require development, especially regarding feedstock handling and logistics (Maniatis, Weitz & Zschocke, 2013; Güell et al., 2012). Fischer-Tropsch processes require less extensive adaptation, due to the compositional similarity of syngas produced from biomass and fossil fuels. [30]	
End-use market development (or engine development)	M	Coal, natural gas, biomass derived FT-SPK can be used in blends of up to 50% with conventional jet fuel for commercial flights[30,31]. Green Diesel could potentially be used as a drop-in substitution for fossil diesel in road transportation and MGO in marine applications. Potential substitution for fossil gasoline could also be applied.	Standardisation (e.g., implementation of European standards allowing the use of FT based fuels in high concentrations) Introduction of tax incentives for using RESfuels. Comprehensive LCA studies are essential for comparing alternatives. Increasing the refueling infrastructure

[30] Rebecca Mawhood, Adriana Rodriguez Cobas, Raphael Slade; (2014), Biojet fuel supply Chain Development and Flight Operations (Renjet) Establishing a European renewable jet fuel supply chain: the technoeconomic potential of biomass conversion technologie, Imperial, College London
[31] CAO-UNDP-GEF, 2017, Sustainable Aviation Fuels Guide

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Enviro-economic aspects	M	Sustainability goals in RED II do not clearly include CO_2 emission targets per sector, and CO_2 taxation in the future is uncertain. The environmental and socio-economic impacts of large scale BTL projects are not known with certainty as there is not an industrial plant currently on operation (Dimitriou et al., 2018)[32]. The renewable nature of feedstock of BTL plants is related with reduced GHG emissions. The development of industries for biomass growing, collecting and transporting close to the conversion plant (e.g. miscanthus) could significantly enhance the local economy The composition of FT-SPK offers certain advantages over conventional jet fuel. These are due to the higher specific energy (per unit mass) of neat FT-SPK than petroleum jet due to its paraffinic structure and low aromatic content. This therefore, reduces the weight of fuel required to fly a specific distance, and the energy consumption per unit of payload. The fuel also generates fewer particular matter emissions due to its structure and carbon content. (Mawhood et al., 2014)	Regulations Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors.

[32] Ioanna Dimitriou, Harry Goldingay, Anthony V. Bridgwater, (2018) Techno-economic and uncertainty analysis of Biomass to Liquid (BTL) systems for transport fuel production, Renewable and Sustainable Energy Reviews Volume 88, Pages 160-175

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

Jet fuels from ethanol through biochemical pathway

Table B7: Technical and economic factors, barriers and policy mechanisms for jet fuels

Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	S	The three upgrading steps (alcohol dehydration, olefin oligomerization, and hydrogenation are already used in at commercial scales and are considered mature technologies. The restriction in process efficiency is related to the ethanol production steps. (i.e. Relatively low conversion efficiencies 15%-25% on mass basis (or, 25%-40% on energy basis) are reported in a few running demonstration and commercial scale plants as described in D3.3) (Tao et al., 2017)	Technology and/or innovation premiums[33]
Operating capacity	M	Technologies to convert alcohols to jet fuels are at the laboratory and pilot stages of implementation. No details of operational dedicated pilot plants were identified in the literature. (Tao et al., 2017; EIT, 2014) Regarding the ethanol production step A potential technology barrier is obtaining a long-term stable process with biocatalysts like enzymes and yeast.	R&D grants and Innovation funds for 2nd generation ethanol from forest waste. Capital investment grants with banding for increasing the number of demonstration and commercial plants to verify the stability of continuous operation and test diversified biomass feedstock

[33] Technology or innovation premiums aim at stimulating the capacity for innovation of companies engaged in research and development.

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Co-location with existing infrastructures	M	As fuel conversion technologies mature, it may possible to integrate (Alcohol to Jet fuels) ATJ processes with a wide range of industrial processes that produce alcohol by-products or have the potential to do so (IATA, 2012a). Lanzatech's retrofit solution for steel mills is one such example. Retrofitting existing ethanol facilities also reduces capital cost (Staples et al., 2014). Another approach to ATJ commercialization is the addition of alcohol upgrading to conventional ethanol production (e.g. the case of Byogy in Brazil) A cellulosic ATJ biorefinery may benefit from the availability of lignin residuals from saccharification and fermentation, but this depends on the price of hydrogen from other sources such as natural gas.	Premiums and reduced taxation Capacity building
Process design: aspects	S	The general ATJ concept is not specific to the type of alcohol fed to catalytic upgrading to hydrocarbons. Other aspects attributed mainly to the ethanol production steps as reported in D3.3. A wide variety of technical challenges exist in the different steps of bioethanol processing from pretreatment to the final separation of the ethanol–water mixture. These include: - Improvement of micro-organisms and enzymes. - Use of C5 sugars, either for fermentation or upgrading to valuable co-products. - Use of lignin as value-adding energy carrier or material feedstock.	R&D grants

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		Feedstock handling and processing in cellulosic plants.	
Scale-up aspects	S	One advantage with dehydration, oligomerization, and hydrotreating process steps is that they have been demonstrated on a commercially relevant scale and the risk of scale-up is expected to be reduced. However, the development and demonstration of the integrated process on biomass-derived intermediates is necessary (Byogy Renewables 2011). Particular challenges relate to the inherent difficulties of managing microorganisms in an industrial fermentation process, such as the rate of conversion of feedstocks to alcohols (which is low compared to chemical refineries), and the sensitivity of microorganisms to impurities (including by-products generated in situ) (Güell et al., 2012). (described in D3.3)	R&D grants and Innovation Fund
Economic			
Market conditions	S	The maximum use of ethanol is 10%-15% for the majority of gasoline vehicles, which creates a blend wall that makes it difficult to achieve further market penetration of ethanol as a blend stock for gasoline. Therefore, upgrading ethanol to jet fuel blend stock presents a potential pathway for developing drop-in or fungible fuels for the jet fuel market. [34] Newly developed fermentation technologies may improve the availability of many cost-competitive alcohols or alco-	All policies mentioned below affect market conditions

[34] NREL, 2016, Review of Biojet Fuel Conversion Technologies

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		hol mixtures in the near future and may achieve more favorable economics when used to provide alcohol for ATJ conversion. Non-upgraded ethanol and butanol are considered to be suitable for use in ground transportation. The safety concerns and operational limitations highlighted for non-upgraded use in aviation do not apply to road vehicles, and both have a high octane rating which is a desirable characteristic for automotive fuels. The potential to use these alcohols in ground applications without the need for expensive upgrading processes suggests that their commercial value may be higher as an automotive fuel than an aviation fuel, particularly in the case of butanol (Mawhood et al., 2014)	
Capital investment and production costs	S	The cost of alcohol production is considered to be the greatest barrier to commercialisation of ATJ fuels at present (Güell et al., 2012). A study of Geleynse is reported that at an average alcohol price, the production of alcohol feedstock for ATJ upgrading is estimated to contribute approximately 80% of the production cost for jetfuel blendstock at the refinery. Improvements to alcohol production to generate low- cost alcohols is a key to improving the viability of ATJ. In the catalytic upgrading process, capital expenses have a significant impact on economics. Reduction in equipment and facilities costs, potentially through integration with ex-	Feedstock premiums for low cost biomass, tax in fossil fuels

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		isting industrial facilities and infrastructure, offers the largest area for reduction in risk for the installation of an ATJ conversion unit. A supply of hydrogen is required for hydrogenation and is an additional source of production cost. Depending on the nature of the plant as a whole, a facility may purchase hydrogen or produce it on site through a number of possible methods, including use of a biomass feedstock	
Uncertainties of production cost	S	To evaluate the overall ATJ conversion pathway and estimate its commercial feasibility, the economics of the fuel upgrading processes such as dehydration, oligomerization, dimerization, and hydrogenation also have to be considered. Because these processes are still under development, more research efforts are required to complete this target goal.	Feedstock premiums towards a common framework in EU countries (a challenging task)
Investor risk premium	M	Moderate to high investment risk premium (e.g., lower than the gasification- based fuels because of experience from the operation and logistics of the 1st generation plants). It shares, however, with all RESfuels the unstable regulatory framework for investment and market prices. Moreover, there is already market for ethanol as transportation fuel, so access will be easier.	Capital grants and Innovation funds Capacity building and training for investors and industry on the needs of this sector
Access to debt financing	M	Companies with experience in 1st generation plants (either for co-allocation with 1st generation or for greenfield 2nd generation ethanol projects) are expected to have substantial know-how in access to debt-financing. Still, larger companies with a diversified business portfolio and low debt to	Public Private partnerships and Joint Ventures Public Private partnerships and Joint Ventures

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
		equity financing as well as public-private partnerships will overcome this barrier more easily. The presently low interest rates also help overcome this barrier.	
Commercially available process components	N	The process includes alcohol dehydration, oligomerization, and hydrogenation. One advantage with dehydration, oligomerization, and hydrotreating process steps is that they have been demonstrated on a commercially relevant scale and the risk of scale-up is expected to be reduced. However, the development and demonstration of the integrated process on biomass-derived intermediates is necessary (NREL, 2016).	Training, capacity building, and certification.
End-use market development (or engine development)	M	Recent qualification of ATJ fuel from ethanol as an approved feedstock in ASTM standards (revised ASTM D7566 Annex A5) indicates momentum toward further developments in the near future[35]. Bio-jet can be used in blends up to 50%.[36]	R&D grants (e.g., related to the dedicated to ATJ-SPK production) Introduction of tax incentives for using ATJ-SPK fuels Increasing the ethanol and the upgrading infrastructure Comprehensive LCA studies are essential for comparing alternatives.

35 https://www.lanzatech.com/2018/04/03/jet-fuel-derived-ethanol-now-eligible-commercial-flights/

36 IRENA, 2017, Biofuels for aviation

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Factor	Barrier (Severe (S), Moderate (M), None (N))	Explication	Policy mechanisms to overcome barriers
Enviro-economic aspects	M	Sustainability goals in RED II do not clearly include CO_2 emission targets per sector, and CO_2 taxation in the future is uncertain.	Regulations Targeted investments and R&D in value chains for the enviro-economic optimal transportation sectors.

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