Ramp up of lignocellulosic ethanol in Europe to 2030

Final Report

E4tech (UK) Ltd for the co-sponsors of the
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List of abbreviations

CHP	Combined Heat and Power
EC	European Commission
EU	European Union
ICLE	International Conference on Lignocellulosic Ethanol
ICCT	International Council on Clean Transportation
MS	Member state (EU)
MSW	Municipal Solid Waste
RED II	Renewable Energy Directive II (Post-2020 policy for renewable energy in the EU)
TRL	Technology Readiness Level
US(A)	United States (of America)

Units

EUR	Euro
GJ	Gigajoule
K	Thousand
l	Litres
M	Million
t	tonnes
toe	tonne of oil equivalent
USD	US Dollar

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Disclaimer

Whilst this report has been prepared with the input of the co-sponsors of the 6th International Conference on Lignocellulosic Ethanol (Beta Renewables, DuPont, ePURE, Leaf, Novozymes, Shell, St1), the figures and results do not necessarily represent the individual views of each sponsor. The reader is also reminded that the ramp up rate in this study assumes a favourable policy environment which supports the development of the industry.

Any figures for which no specific source is mentioned are original work by E4tech.

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Executive Summary

The cellulosic ethanol industry is at a critical development stage; there are technology developers who are taking stock of the lessons learnt during the development of their first plants, and several more are constructing or planning their first plant. In addition, the European Commission has proposed a 3.6% sub-target for all advanced biofuels, including lignocellulosic ethanol, in road and rail transport energy in 2030. This makes it a pertinent time to consider where the European industry is today and where it could be in 2030.

This study develops two deployment scenarios for the EU based on detailed bottom up assumptions on the number of technology developers, plant development timelines, plant capacity, utilisation rates, the rate at which new projects can be initiated, and takes into consideration the availability of project finance. It also considers at what cost cellulosic ethanol could be produced.

An important caveat on the results of this study is that it is assumed that a favourable policy environment extending beyond 2030 exists for cellulosic ethanol, which would make the ramp up to 2030 viable. Furthermore, it should be recognised that the scenarios selected do not present a limit on what could be achieved in this industry. For example, higher levels of production could be achieved if project timelines could be compressed further, plant deployed are larger and the use of ethanol further incentivised.

The two scenarios see total EU production capacity for cellulosic ethanol increase from 31 million litres in 2017 (at one main commercial scale plant) to 2.75 billion litres in 2030 (from 46 plants, each with a capacity of 50-76 million litres/yr)[1] in the central scenario, and 3.8 billion litres (from 64 plants) in the more ambitious scenario. Depending on EU energy demand in 2030, this could equate to a 4-5.6% blend of cellulosic ethanol in gasoline, by volume, in 2030[2], and 0.6-0.8% of road and rail transport energy demand in 2030[3].

Production costs for cellulosic ethanol are projected to be 745-965 EUR/tonne in 2030[4] (down from 945-1,010 EUR/tonne in 2017). Since this will not yet be competitive with expected fossil fuel prices, support in the form of a strong long-term policy environment will be needed in order for either of the modelled deployment scenarios to be realised.

To 2030, the feedstock used in many plants in Europe is likely to be agricultural residues and forestry residues, but many plants may also consider supplementing their feedstock supply with energy crops

[1] Such a ramp up is comparable with the increase in the level of production of corn ethanol in the 1980s and early 1990s in the US, prior to the period of significant ramp up in the 2000s.

[2] Assumes 25% of the projected 2030 energy demand in road and rail transport (see next footnote) will be required by gasoline vehicles, an assumption modelled bottom-up from expected evolution of the vehicle parc in the 2013 E4tech Autofuel study. Available at: http://www.e4tech.com/wp-content/uploads/2015/06/EU_Auto-Fuel-report.pdf

[3] 2030 energy demand in EU road and rail transport is estimated at 231,151ktoe (excludes aviation, inland navigation and the UK's energy demand).
Source: E3MLab & IIASA (2016), "Technical report on Member State results of the EUCO policy scenarios", *European Commission*. Available at https://ec.europa.eu/energy/sites/ener/files/documents/20161219_-_technical_report_on_euco_scenarios_primes.pdf

[4] The range depends on the assumptions taken on feedstock cost, opex and capex, and assuming all other variables such as the price of raw materials are kept equal.

(and to a lesser extent MSW, due to its different handling and composition). As project developers initially focus on countries with low feedstock prices (<60 EUR/dry tonne, including transport) and low labour costs, plants will most likely be located largely in Central and Eastern European countries. The number of plants projected in both scenarios is considered viable at this assumed feedstock price, based on the best available evidence on feedstock prices in different countries. However, the high production cost scenario assumes a higher feedstock price (of 90 EUR/tonne), which increases the number of countries that could potentially sustain cellulosic ethanol plants.

Finally, the outlook to 2030 is only the start of the story for this industry. The period to 2030 has the potential to lay the foundation for significantly higher levels of deployment in the years beyond.

1 Introduction

This study has been commissioned by the co-sponsors of the 6th International Conference on Lignocellulosic Ethanol (BetaRenewables, DuPont, ePURE, Leaf, Novozymes, Shell, St1) to provide an overview of the current status of the lignocellulosic ethanol industry (hereafter cellulosic ethanol), how it could realistically ramp up by 2030 in the EU, and the resulting costs.

Two scenarios are proposed; a central scenario and a more ambitious scenario. They do not represent a limit on what could be achieved by 2030, as more ambitious assumptions could be taken on parameters such as development timelines and plant size for example.

Critical to the robustness of this report is the detailed input on production costs and deployment potential from the key leading cellulosic ethanol technology developers who have sponsored this study. Using this information, a ramp up potential has been developed from the bottom up, based on the number of plants that could be built. As such, this study complements other studies that have developed a technical potential for cellulosic ethanol based on feedstock availability (e.g. the Wasted study)[5].

This study only focuses on the supply of cellulosic ethanol, and what could realistically be supplied in Europe, assuming there is adequate demand for the fuel. It excludes other advanced fuels, such as advanced biodiesel. The focus in this study is on domestic EU production – imports are not modelled but are expected to play a role. Whether the right policy framework is in place to incentivise the level of production and the extent to which cellulosic ethanol will compete with or be complemented by other biofuels are outside the scope of this study.

The feedstocks considered by this study are agricultural residues, energy crops, forestry biomass and the biological fraction of Municipal Solid Waste (MSW). It should also be noted that the technology focus of this study is only cellulosic ethanol produced by purely biological routes (i.e. routes involving gasification and syngas fermentation for example are not considered).

This report starts with a summary of the global status of the cellulosic ethanol industry in chapter 2, which describes the major plants currently in operation or planning. This provides the starting point for the ramp up rate. Chapter 3 looks at current costs and how these costs may come down by 2030. Chapter 4 then describes the two scenarios for the ramp up rate of cellulosic ethanol production in Europe and discusses the different parameters and key assumptions taken. Chapter 5 provides a sense check on the scenarios by comparing them with the ramp up rate achieved in an analogous industry. Chapter 6 considers whether there is likely to be sufficient feedstock to meet the modelled scenarios and Chapter 7 briefly discusses the role of imports. Chapter 8 provides some concluding considerations on the results of the study and highlights key dependencies.

2 Global status of the cellulosic ethanol industry

Table 1 provides an overview of the commercial scale cellulosic ethanol plants across the world, that are either in operation, commissioning, under construction or in the advanced stages of planning.

[5] For example, Malins, Searle et al. (2014) Wasted: Europe's Untapped Resource. Available online at: https://europeanclimate.org/wp-content/uploads/2014/02/WASTED-final.pdf

Table 1: Commercial scale cellulosic ethanol plants[6]

Partners	Location	Feedstock	Start-up year	Production capacity (ML/yr)	Tech status	Project status
Beta Renewables	Italy	Rice straw, wheat straw, *Arundo donax*, wood chips	2012	31	1st commercial	Operational
DuPont	USA	Corn stover	2016	114	1st commercial	Operational (commissioning phase)
Granbio (Novozymes, DSM, Beta Renewables, Grupo Carlos Lyra, BNB, BNDES)	Brazil	Sugarcane bagasse, straw	2014	82	1st commercial	Operational (commissioning phase)
POET-DSM Advanced Fuels	USA	Corn stover	2014	76	1st commercial	Operational (commissioning phase)
Raizen (Cosan, Shell, Iogen)	Brazil	Sugarcane bagasse, straw	2015	40	1st commercial	Operational (commissioning phase)
Borregaard[7]	Norway	Spent sulphite liquor from wood processing	1938	20	Commercial	Operational
Sekab[8]	Sweden	Spent sulphite liquor from wood processing	2004	18	Commercial	Operational
Beta Renewables, Energochemica	Slovakia	Wheat straw, switchgrass, rapeseed straw, corn stover	2017	70	Commercial	Under construction
Enviral, Clariant	Slovakia	Wheat straw	2019	63	1st Commercial	Construction due to commence 2017
Beta Renewables	USA	Miscanthus, switchgrass	2018	75	Commercial	Planned
St1 (Vikem Skog, SA)	Norway	Sawdust	2020	50	Commercial	Planned
St1 (NEB, NEOT, UPM, KaVo)	Finland	Sawdust, recycled wood	2020	50	Commercial	Planned
St1 (NEB, NEOT, UPM, KaVo)	Finland	Sawdust, recycled wood	2020	50	Commercial	Planned

[6] One further cellulosic ethanol plant was suspended in the commissioning phase (the 95Ml former Abengoa plant in the US) due to acquisition by new owners (Synata Bio). It is understood that this plant will be instead focus on producing chemicals rather than fuels in the future, and so is excluded from this table.
[7] Borregaard has produced lignin based products (lignins and lignosulfonates) at this plant since 1938, where it also produces lignocellulosic ethanol as a by-product. Although the plant is not optimised for ethanol production, it does produce lignocellulosic ethanol at commercial scale.
[8] Sekab has a similar plant to the Borregaard plant, which produces ethanol as a by-product of lignin processing. The ethanol produced is largely used for chemical production.

There are a number of plants that are in earlier stages of planning and so are not listed in Table 1. In India, the government has asked state oil companies to set up cellulosic ethanol plants at 12 locations[9] and further policy support is expected that will drive much higher ethanol blends than the very low blend levels realised at present[10]. This is driving investment in plants such as the four announced by Chempolis, the Hindustan Petroleum Company, the Indian Oil Corporation and BPCL-Kochi[11]. There is a similar positive emerging story for second generation biofuel plants in China, with five proposed plants; one by DuPont, one by Anhui M&G Guozhen Green Refinery CO, one by COFCO and two by the Henan Tianguan Group.

Whilst the Table 1 focuses on commercial scale plants, there are also a number of notable demonstration scale plants that are either in operation or commissioning. These include St1's 10Ml plant in Finland based on sawdust, Clariant's 1.3Ml plant in Germany based on wheat straw, corn stover and bagasse and Praj's 1Ml plant in India based on rice and wheat straw, cotton stalk, bagasse, cane trash, corn cobs and corn stover.

There are a number of corn ethanol plants in the US that are starting to produce ethanol from the corn kernel fibre as well as the corn kernel. Since the ethanol plants are not wholly based on cellulosic feedstocks, they are also excluded from Table 1. However, the ethanol produced from the corn kernel fibre is supported as a source of cellulosic ethanol in the US.

The current status of the cellulosic ethanol industry can be summarised as follows:

- The technology (i.e. hydrolysis and fermentation) is currently at Technology Readiness Level (TRL) 7-8[12]. None of the plants currently in commissioning or operation have reached initial intended design levels of production. Some are re-working designs to accommodate lessons learned, whilst others understand how to overcome existing issues but have taken the economic decision not to reach nameplate capacity for the existing plants. Following this learning process, it is expected that in the next 1-2 years, the industry will be at TRL 8 (with technical issues in plants today at TRL 7 having been solved).
- There are currently around seven major technology developers globally, focusing on commercial cellulosic ethanol production.
- Four technology developers currently have large commercial scale plants in operation or in the commissioning phase based on agricultural residues.
- Two technology developers have an established plant based on spent sulphite liquor, although at these plants the cellulosic ethanol is a by-product of high grade lignin and pulp production.
- Commercial scale plants in the commissioning phase are expected to reach a high utilisation rate (e.g. 90%).
- There are at least six large-scale plants under construction or in advanced stages of planning.
- Due to an increasingly supportive policy environment, a number of plants in India and China have been announced.

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[9] https://uk.reuters.com/article/india-energy-biofuels/india-set-to-unveil-new-biofuel-policy-in-bid-to-cut-oil-gas-coal-imports-minister-idUKL4N1KW2WJ
[10] http://www.biofuelsdigest.com/bdigest/2016/10/13/cellulosics-india-goes-huge/
[11] http://www.biofuelsdigest.com/bdigest/2016/09/26/bpcl-to-invest-75-million-in-2g-ethanol-plant-in-kochi/
[12] TRL 7 assumes a demonstration plant working in an operational environment at pre-commercial scale. TRL 8 assumes a first of a kind commercial scale system in which technical issues have been solved.

- All technology developers are likely to have several plants which are in planning stages but have not yet been publicly announced.
- The feedstocks typically used depend on the geographic region: In Europe, the feedstock focus is typically straw and (in Northern Europe) wood-based feedstocks; in the US, corn stover; in South America, bagasse and straw; in China, straw; in India, rice straw, cotton stalk and bamboo. Many technology developers are testing energy crops in their pilot and demonstration plants, but these are not the feedstock of focus for plants in the immediate future- though they are being considered as part of a feedstock portfolio for existing and planned plants.

3 Cost reduction potential

With only a handful of commercial scale cellulosic ethanol plants in operation, the production costs for cellulosic ethanol have the potential to decrease considerably. This chapter outlines current costs and explores how these might reduce to 2030. It should be noted that in order for the deployment modelled in this study to take place, a premium for advanced biofuels compared to fossil fuels will be required, though the extent will depend on the price of oil. For 2017 and 2030, a range of costs is provided (low-high), which is considered to be representative of the range of current and future costs. However, should project developers find they are able to build larger plants (a decision which is largely dependent on the local availability of low cost feedstock), this will likely result in greater economies of scale and lower production costs than proposed here.

3.1 Current costs

Current levelised costs for cellulosic ethanol are in the range 1,470-1,580 EUR/toe (i.e. 940-1,010 EUR/tonne or 0.75-0.80 EUR/litre). Assumptions leading to this figure are:

- Plants currently being built have an output of 32 mtoe ethanol (i.e. 50kt or 63m litres), with an expected eventual utilisation rate of 95%[13]
- Total plant capex is ~160-200M EUR, including an onsite CHP to provide all electricity and steam required and a waste water treatment plant
- Plant consumables (chemicals, enzymes, yeast) are estimated at ~ 13M EUR/yr
- No revenues from the sale of excess electricity are included
- Feedstock is assumed to be purchased at 60 EUR/dry tonne[14]
- The average yield of ethanol is assumed to be 262 litres/t dry biomass (or 4.8 tonnes biomass/tonne ethanol).
- Depreciation of the plant is assumed over 15 years

Capex represents around 25% of the cost, and opex 75% (and around 40% of the opex is feedstock cost). Our assessment of current costs is based on input from several of the major cellulosic ethanol technology developers, and has been validated with publically available literature[15].

[13] This excludes 35 days of maintenance time.
[14] This includes 50km transport. Supply chains in Denmark for agricultural residues have been successfully established at this price point.
[15] For example, IRENA (2016) "Innovation Outlook: Advanced liquid biofuels". Available at www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf [Accessed 23/08/2017]

It should be noted that the production cost of ethanol produced at plants being built today will come down over time, assuming process modifications are made (e.g. more optimised enzymes) that will result in improved ethanol yields. The reduction in cost for a particular plant over time is not presented here but it is worth remembering that these costs do have the potential to come down.

3.2 Future costs

Figure 1 shows the cost reduction potential per tonne of ethanol assumed over the period 2017 to 2030 in a low and high cost scenario.

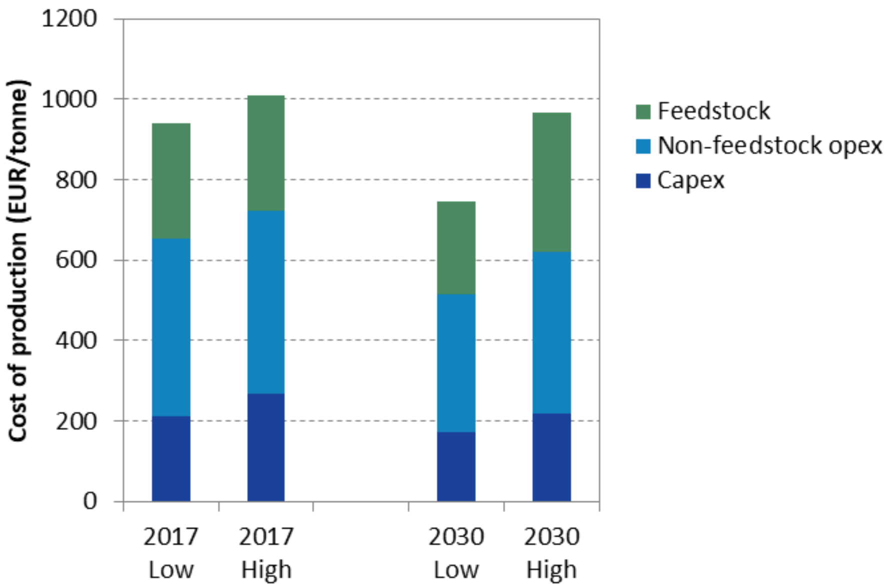

Figure 1: Cost reduction potential over time

Note: the low scenario uses low opex, low capex and low feedstock costs. The high scenario uses high opex, high capex and high feedstock costs. Feedstock costs do not vary between the low and high scenarios in 2017.

Future cellulosic ethanol production costs are projected to be 1,160-1,500 EUR/toe (i.e. 745-970 EUR/tonne or 0.59-0.77 EUR/litre). Current first generation ethanol prices have averaged 552.5 EUR/tonne over the last six months[16]. The breakdown between capex and opex is similar to 2017 (25%: 75%), with feedstock representing 40-45% of the opex cost.

Feedstock costs in both scenarios in 2017 are considered to be 60 EUR/dry tonne, as it is assumed for the first plants that project developers will target locations with very low feedstock costs. In 2030, feedstock costs are considered to remain at 60 EUR/tonne in the low scenario and increase to 90 EUR/tonne in the high scenario. The 2030 low scenario reflects a situation where there remain a significant number of areas of "low hanging fruit" in terms of locations with low cost feedstock. The 2030 high scenario reflects a situation where there is greater competing demand for feedstock, and the locations with low cost feedstock have been exhausted.

[16] The Rotterdam Fuel Ethanol FOB T2 price average over the six month period from April 10 2017 to October 9 2017, according to FO Lichts Interactive data, available online www.agra-net.com/agra/world-ethanol-and-biofuels-report/

A number of factors contribute to the reduction in non-feedstock opex and capex costs:

- Capex and opex costs are assumed to decrease (assuming all else, e.g. materials costs, remains equal), as a result of:
    - *Opex*: Reductions in quantity and cost of consumables (chemicals, yeast, biocatalysts)
    - *Opex*: Lower labour costs for operation (i.e. the plant becomes more efficient and more automated over time)
    - *Capex*: Lower equipment costs (due to higher volumes of production, prefabrication, robotic welding, etc.)
    - *Capex*: Lower labour costs associated with engineering and installation – this is expected to reduce as plants are replicated
- The output of a typical plant in Europe in 2030 is expected to be 38 mtoe ethanol (i.e. 60kt or 76M litres), although it could be bigger if a greater density of feedstock is available in the immediate proximity of the plant. A scaling factor of 0.68 (based on the experience of technology developers) is applied to reflect cost reductions with increasing scale. However, this has little impact on the cost reductions modelled here, as a large increase in the size of plants in Europe (beyond the size of plants in planning at present) is not modelled.
- By 2030, the average yield of ethanol from feedstocks is assumed to be 328 litres/t dry biomass (or 3.8 tonnes biomass/tonne ethanol). This assumption is based on the technology improvements expected by technology developers over this time period.

The cost reductions imply a learning rate of 0.97 for the capex and for ex-feedstock opex[17], based on EU deployment alone.

As noted for plants being built today, the ethanol production costs from plants being built in 2030 will also come down over time, as using more optimised enzymes result in improved ethanol yields. The reduction in cost over time for particular plants is not presented here, but is worth remembering that these costs have the potential to come down further.

3.3 Plausibility of cost reduction

3.3.1 Non-feedstock opex and operational improvements

In this study, non-feedstock opex is modelled to reduce by ~10-20% between 2017 and 2030[18]. For comparison, US corn ethanol non-feedstock opex reduced by 45% between 1983 and 2005[19]. The opportunities for cost reductions for cellulosic ethanol are largely focused on a reduction in the cost and consumption of consumables (bio-catalysts, yeast, chemicals) and labour costs. Whilst there are some similarities with cost reductions experienced by corn ethanol, the overall cost reduction is not as strong, as much of the cost reduction for corn ethanol was due to a reduction in energy consumption, with efforts driven by macroeconomic changes and policy signals. It is likely that many of the lessons learnt from the corn ethanol industry relating to energy efficiency will be incorporated

[17] i.e. a 3% reduction cost for every doubling of installed capacity

[18] The range is due to differing assumptions in the low and high future costs as to the extent to which maintenance costs can be reduced over time and the extent to which the contribution of consumables can be reduced.

[19] Hettinga *et al*. (2009) "Understanding the reductions in US corn ethanol production costs: An experience curve approach", *Energy Policy*, vol. 37, no. 1, pp. 190-203. doi.org/10.1016/j.enpol.2008.08.002

into new cellulosic ethanol plants. Together with the longer development period considered for corn ethanol in the US, this largely explains the more conservative assumptions for cost reduction taken in this study.

3.3.2 Capex

In this study, the capex is expected to reduce from ~240 EUR/tonne in 2017 to ~200 EUR/tonne in 2030 (i.e. a ~20% reduction). The rationale for this reduction is lower equipment cost and a reduction in the required labour, as outlined in section 3.2. For comparison, Hettinga *et al*. (2009) estimate that over the period 1983-2005, capital charges reduced for corn ethanol by 88%, taking into account both technological progress and a scaling up effect. The reduction potential assumed here is more conservative as it assumes a much lower increase in scale by 2030 and also that some components for cellulosic ethanol plants will be the same as those used in corn ethanol plants, and therefore already benefitting from the technological developments and cost reductions in the corn ethanol industry.

3.3.3 Feedstock

The types of feedstocks that will be used in these plants have regional prices, since they are typically traded locally due to their low density. Price therefore depends on the level of production locally, and the level of competition from competing uses locally.

It should be noted that whilst the assumptions around feedstock price (and indeed ethanol production cost) do not directly drive the ramp up rate in this model, they are an important check as to how realistic the ramp up rate is and what the cost of ramping up the industry could be.

The feedstock price of 60 EUR/tonne used for both the low and high production costs in 2017 and the low production costs for 2030 is at the lower end of the range of prices that will be seen by most people buying these feedstocks in Europe. S2Biom[20] identified that in Central and Eastern European Countries (such as Bulgaria, Croatia, Poland, Romania), it should be possible to source feedstocks at this price in 2030 (including transport costs). This feedstock price is also believed to be achievable based on the experience of the straw market in Denmark[21] and feedback from developers who have undertaken feasibility studies for European projects. However, there are other countries in Europe with large straw potentials but where feedstock prices (and labour costs) are likely to be higher, e.g. France (~63 EUR/dry tonne straw including transport) and Germany (~109 EUR/tonne straw)[22].

The lower end of the price range is used for the current price, since project developers will focus their first few plants in locations where they can get feedstocks at these prices. To 2030, two situations are modelled, one where developers continue to be able to source feedstock at prices of <60 EUR/tonne, such as in the Central and Eastern European countries mentioned above. In the high cost scenario, feedstock prices are anticipated to be higher, at 90 EUR/tonne. Considering a higher feedstock price in the high scenario increases the number of countries that are likely to be able to

[20] www.s2biom.eu/en/publications-reports/s2biom.html (note transport costs have been added to the prices in the S2Biom study)
[21] The MEC project in Holsterbro, Denmark, has reached an average < 60 EUR/t wheat straw price over the last few years, as a result of a wheat straw auction in Denmark
[22] Based on S2Biom, with 50km transport cost added

deploy cellulosic ethanol plants but still have relatively low labour costs, such as the Czech Republic and Slovakia. The high scenario reflects a situation in which in practice it is found that there are fewer locations where low feedstock prices can be realised (i.e. the low hanging fruit are all taken), potentially because of new competing uses for the feedstock such as the use of woody and agricultural residues in power plants. Feedstock availability is discussed in more detail in section 6.

It is important to note that although agricultural and forestry residues are the primary feedstocks being considered for many plants, wood waste and energy crops may also be sourced at the price ranges discussed and are likely to be a part of the feedstock supply strategy of many projects, in order to complement supply and mitigate against seasonal feedstock price spikes.

3.3.4 Overall costs

The costs estimated in this study range from ~1,525 EUR/toe in 2017 (975 EUR/tonne) to 1,160-1,510 EUR/toe in 2030 (745-965 EUR/tonne). This is in line with IRENA (2016)[23], which estimated current production costs to be in the range 35-60 USD/GJ (1,246-2,186 EUR/toe), dropping to 27-48 USD/GJ (1,007-1,831 EUR/toe) by 2030 - roughly a 20% reduction in cost. However, further reductions in costs are possible to 2030 and beyond 2030 as a result of larger scales, accelerated learning and technological improvements (e.g. yields and reductions in costs for certain inputs e.g. enzymes).

4 Production potential in the EU to 2030

Two scenarios have been developed in this study; a central scenario and a more ambitious scenario. Both scenarios are possible, provided the right supportive policy environment is in place. The more ambitious scenario reflects an accelerated and greater level of activity, but should not be seen as a limit on what could be achieved by the industry by 2030. Even more optimistic scenarios could potentially be realised, for example if larger plants are built.

The current starting point for both scenarios is the plants which are currently in operation, under construction or which have entered the project development phase in the EU (see Chapter 2 for details). There is currently one commercial scale[24] plant producing cellulosic ethanol in the EU. This is the Beta Renewables plant in Crescentino, which has used a number of feedstocks, including rice straw, wheat straw, *Arundo donax*, and wood chips. For 2018 and beyond, the growth is modelled based on the development timelines, plant sizes and the number of projects being initiated each year.

As mentioned previously, an important prerequisite for both scenarios presented here is that adequate policy conditions are in place, namely an enforceable blending mandate for advanced biofuels, based on Annex IX A feedstocks. Given the production costs outlined in Chapter 3, any uncertainty about the lack of ongoing demand for the product will not result in the level of ramp up outlined here. As this is a supply-focused study, the demand for (cellulosic) ethanol is not explicitly considered here. However, a strong demand for cellulosic ethanol is an integral assumption for this

[23] E4tech & TUHH (2016), "Innovation Outlook: Advanced Liquid Biofuels", IRENA. Available at www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf

[24] For the purpose of this study, plants producing at above 25Ml/yr are considered to be producing at commercial scale

study. Without strong drivers for demand to and beyond 2030, it is unlikely that the production scenarios presented will be realised.

4.1 Central scenario

The results of the central scenario are shown in Figure 2 and summarised below, while assumptions are discussed in more detail in Section 4.3.

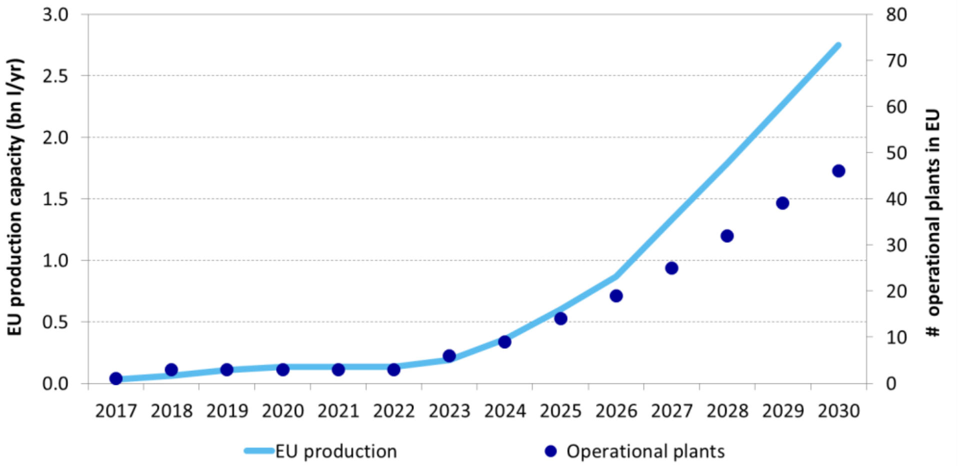

Figure 2: Production capacity of cellulosic ethanol in the central scenario in the EU (left) and number of plants to 2030 (right)
Note: Plant size increases over time

The central scenario sees a ramp up in Europe from one plant producing at commercial scale in 2017 to 46 plants in 2030. From 2022 to 2025, 3-4 plants come online per year across Europe, but from 2025 to 2030, the rate increases to an average of 6-7 new plants commencing production annually. There are multiple reasons for this increased rate over time, most notably a shorter project development timeline together with a greater maturity of the industry and an increased rate of investment so that new projects can be developed concurrently. These parameters are discussed in more detail in Section 4.3.

The total EU production capacity for cellulosic ethanol therefore increases from 31 million litres in 2017 to **2.75 billion litres in 2030**. 31Ml represents around 0.01% of road and rail transport demand today and 2.75bn litres represent an estimated 0.6% in 2030[25]. Depending on gasoline consumption levels in 2030, this could equate to a 4% blend of cellulosic ethanol in gasoline, by volume, in 2030 or

[25] 2030 energy demand in EU road and rail transport is estimated at 231,151ktoe (excludes aviation and inland navigation, as well as UK demand). *Source*: E3MLab & IIASA (2016), "Technical report on Member State results of the EUCO policy scenarios", *European Commission*. Available at https://ec.europa.eu/energy/sites/ener/files/documents/20161219_-_technical_report_on_euco_scenarios_primes.pdf

2.4% by energy[26]. For context, total first generation bioethanol consumption in the EU in 2015 was 0.8% of road and rail energy demand and represented 3.3% ethanol in gasoline by energy[27].

A commercial scale (50-76Ml) plant in 2030 will require around 190-230 kt (dry) of feedstock per annum, depending on the yield assumed. In total, ~10 Mt of feedstock would therefore be required annually to support the number of plants in the central scenario in 2030.

4.2 More ambitious scenario

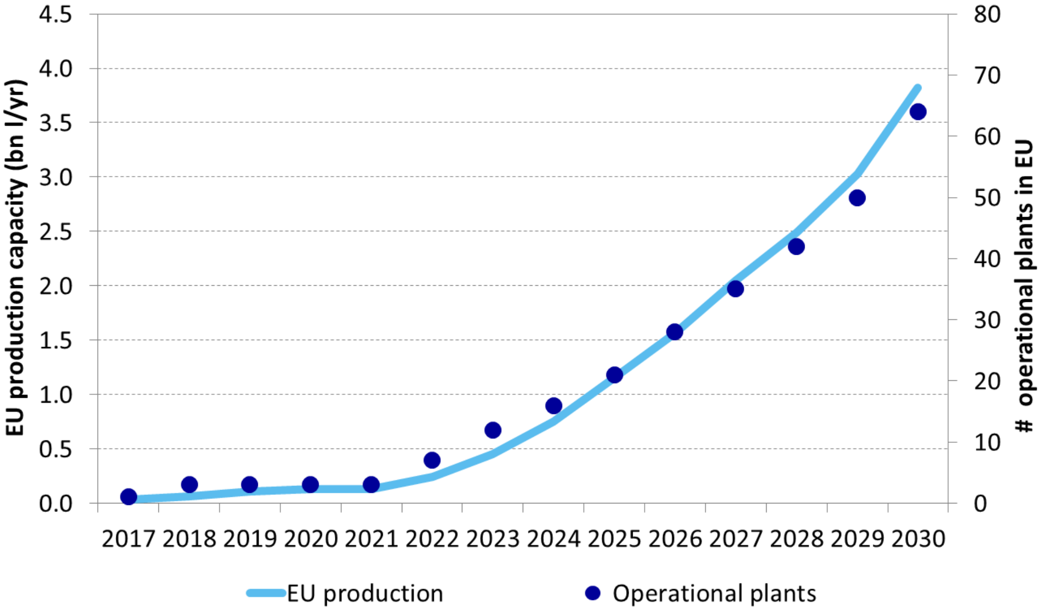

Figure 3: Production capacity of cellulosic ethanol in the more ambitious scenario in the EU (left) and number of plants to 2030 (right)
Note: Plant size increases over time

As shown in Figure 3, the more ambitious scenario sees a ramp up in Europe from one plant producing at commercial scale in 2017 to 64 plants in 2030. From 2022 to 2025, 4-5 plants come online per year across Europe, but from 2025 to 2030 the rate increases to an average of 8-9 new plants commencing production annually. Compared with the central scenario, the main differences are shorter development timelines and an assumption that more plants can be developed concurrently. These parameters are discussed in more detail in Section 4.3. As in the central scenario, the plant sizes modelled are 76 million litres for plants using agricultural residues and 50 million litres using woody residues. In total, ~14 Mt of feedstock would be required annually to support the number of plants in the more ambitious scenario by 2030.

The total EU production capacity for cellulosic ethanol therefore increases from 31 million litres in 2017 to **3.8 billion litres in 2030**. 3.8bn litres represent an estimated 0.84% of projected road and rail

[26] Assumes 25% of the above 2030 energy demand in road and rail transport will be required by gasoline vehicles, an assumption modelled bottom-up from expected evolution of the vehicle parc in the 2013 E4tech Autofuel study. However, this is only a projection and gasoline demand could be lower if more aggressive assumptions are taken about modal shift and the penetration of electric vehicles for example. Available at: http://www.e4tech.com/wp-content/uploads/2015/06/EU_Auto-Fuel-report.pdf

[27] European Commission (2017), "Country datasheets - August 2017 update". Available at https://ec.europa.eu/energy/en/data-analysis/country

energy demand in 2030[28]. Depending on gasoline consumption levels in 2030, this could equate to a ~5.6% blend of cellulosic ethanol in gasoline, by volume, in 2030 or 3.4% by energy[29].

4.3 Parameters affecting the scenarios

The scenarios described above are based on a number of assumptions related to various parameters. These are described in more detail in the following sections.

4.3.1 Development timeline

Based on evidence collected from existing projects and interviews undertaken during the study, Table 2 provides the development timelines for first, second and subsequent (to 2030) commercial scale plants that have been used in the development of the two scenarios. These development timelines are grounded in what has been achieved to date and could reasonably be expected to be achieved in the coming years. Beyond 2030, development timelines would be expected to shorten further with the benefit of experience and a lower level of risk facilitating financing for projects to be put in place more easily.

	1st plant	2nd plant	Subsequent plants to 2030
Project planning & financing	2.5 - 3 years	2 - 2.5 years	2 years
Design, permitting & construction	3 - 4 years	2.5 - 3 years	2 - 3.25 years
Commissioning	1.5 - 2 years	8 months - 1 year	6 - 8 months

Table 2: Development timelines for commercial scale plants in the central (upper end of the range) and more ambitious (lower end of the range) scenarios

The initial stages of a project can take a number of years, as they include engineering design, gaining planning permission and other permitting, contracting feedstock and setting up feedstock supply chains, and critically, reaching financial close. The risk involved at this stage, even with proven technologies, is high, and is often the point at which projects fail. As seen with the first commercial plants built globally, the commissioning stage can also take time, during which product output will be well below nominal capacity, and is still an at-risk step without guaranteed success. In order to reflect the amount of time it has taken for the first-of-a-kind plants to progress through the commissioning phase, we have assumed a longer than average commissioning period (for this kind of industrial facility) of two years (during which time the utilisation rate is assumed to be 50% of full capacity). Longer commissioning phases have, for example, resulted from difficulties experienced with solids handling.

For second and subsequent plants, project development and commissioning time is expected to reduce significantly. After a period of continuous operation of the first commercial plant and as

[28] The same assumptions were taken about road and rail transport energy demand in 2030 as in the central scenario.
[29] The same assumptions were taken about the gasoline consumption levels as in the central scenario.

confidence in the technology and related supply chains and markets become more established, projects are perceived as less risky by investors and the time taken to financial close reduces.

4.3.2 Rate of project initiation

The rate of project initiation is a critical parameter in the development of the scenarios. In developing a project initiation rate for the two scenarios, the following considerations have been taken into account:

- Around seven technology developers are expected to be likely to be operating in the EU in the period to 2030, based on current or planned activity.
    - As outlined in chapter 2, there are a number of developers operating or constructing commercial scale plants globally, and it is assumed that these developers will continue to licence their technology for further commercial scale plants.
    - Only developers with existing operating demonstration plants are assumed to develop commercial projects in Europe by 2030. It is considered unlikely that new technology developers would have multiple commercial scale plants operating by 2030.
    - Consolidation of, or shrinkage in, the number of technology developers could impact the rate of growth in production. However, if demand were strong enough, it is anticipated that this could be compensated by growth of the remaining developers.
- In the early years, there may be a constraint around the familiarity with the technology, availability and resources of engineering, procurement & construction (EPC) companies with expertise in biofuels[30], limiting the number of plants that can be developed concurrently.
- A further constraint could also be the ready availability of key equipment. Sudden increase in demand (including globally) could result in significant lead times which then expand development timelines.
- The second commercial scale plants are likely to begin project development at the end of the first commercial scale plant project development cycle (i.e. once financial close is reached and construction is ready to begin).
- After the second plants, it is assumed that the project development for the next plants will not wait until financial close and construction has begun for prior projects, but that multiple projects can run in parallel. This is due to increased access to funding as the perceived level of risk by investors starts to come down
- Based on evidence collected during the study, some more risk adverse funders will require at least 2-4 years of successful operational data of a first commercial scale plant before being willing to invest in a similar or larger scale plant. As such, the number of financiers willing to invest in projects is likely to increase as the industry becomes more mature, increasing the rate of project initiation over time.

[30] Examples include Fluor, KBR, Technip, Jacobs, and SNC-Lavalin, along with smaller companies such as Tebodin and North European Bio Tech (which is co-owned by St1)

Taking into consideration these different factors which influence the number of projects per year, from 2025, the central scenario effectively sees each technology developer starting one successful project development cycle each year (as with any industry, there may be several project development cycles that are unsuccessful). This equates to seven successful projects being initiated across the industry each year. The more ambitious scenario has double the number of successful cycles starting each year, resulting in 14 successful projects being commenced across the EU each year from 2025. However, taking into account the timeline from project initiation to a fully commissioned plant, even in the more ambitious scenario it takes 4.5 years for the 14 successful plants initiated in 2025 to begin producing at full scale. This indicates that the period to 2030 is likely to represent a phase just prior to a big increase in production capacity.

4.3.3 Plant output

There are a number of commercial scale plants already in operation or under construction globally, ranging in scale from 31 million litres to 114 million litres per annum. However, both scenarios consider a **maximum plant size** of 50 - 76 million litres, depending on the feedstock (with wood based plants at the smaller end of the range and agricultural residue based plants at the higher end of the range). Where a first commercial scale plant is operating, under construction or planned, the announced capacity has been used in the scenarios. Where no first commercial scale plant is under development or there are no public announcements, the first commercial scale plant is assumed to be 76 million litres for plants based on agricultural residues and 50 million litres for plants based on woody residues. Approximately 25% of the plants modelled are considered to be based on woody residues.

Although larger plants are possible and are being built outside the EU (for example DuPont's US plant), it is anticipated that a commercial scale of 50– 76 million litres is likely based on access to nearby feedstocks in the EU. This is a view supported by interviews with project and technology developers undertaken during the study and reflects the sizes of plants that are being considered by project developers in the EU for these different types of feedstocks in the coming years. However, this is an area of uncertainty and if larger plants were built without impacting on the number of plants that were built, this would result in higher levels of production than that proposed in the two scenarios modelled here.

In considering the contribution of existing commercially relevant plants to current production the current **utilisation rate** has been used, where available. Where not known, first commercial scale plants are assumed to have an estimated utilisation of 80-85%, while 2nd and next commercial scale plants have a utilisation rate of 90-95%. This utilisation rate excludes maintenance time (~35 days/yr). For comparison, the average utilisation rate for corn ethanol plants in the US in 2017 is 97%.While this has fluctuated over time it has remained consistently above ~90% (USDA bioenergy statistics[31]). This parameter was therefore considered unlikely to vary significantly and so does not change between the two scenarios.

[31] USDA (2017), "Table 11--Fuel ethanol production facilities capacity and utilization rates, by state". Available at www.ers.usda.gov/data-products/us-bioenergy-statistics/

5 Comparison with the ramp up rate of an analogous industry

In order to take a view on whether the proposed scenarios are credible, the historic rate of ramp up in production of corn ethanol in the US, when it was at a comparable stage of development, has been considered.

The use of ethanol in gasoline in the US began in the late 1970s, as an octane replacement for lead. However, Congress at this time also believed that tax incentives for alternative fuels were required to generate a viable domestic fuel ethanol industry, which was desirable due to the high oil prices and consistent with a national policy of promoting energy self-sufficiency[32]. In 1984, the Deficit Reduction Act raised the tax credit for fuel ethanol to $0.6/gallon (from $0.5/gallon in 1983). Fuel ethanol production started to increase significantly from 1981 (see Figure 4) when only ~0.3bn litres was produced. Production increased steadily through the 1990s. By the late 1990s, its use was encouraged as a replacement for MTBE which was discovered to be causing groundwater contamination. In 2001, there was a sharp up-turn in production, prompted by concerns about energy security (precipitated by the 9-11 terrorist attacks), and then further supported by the introduction of supporting legislation (such as the renewable fuel standard, tax credits and state subsidies[33]) and a high oil price.

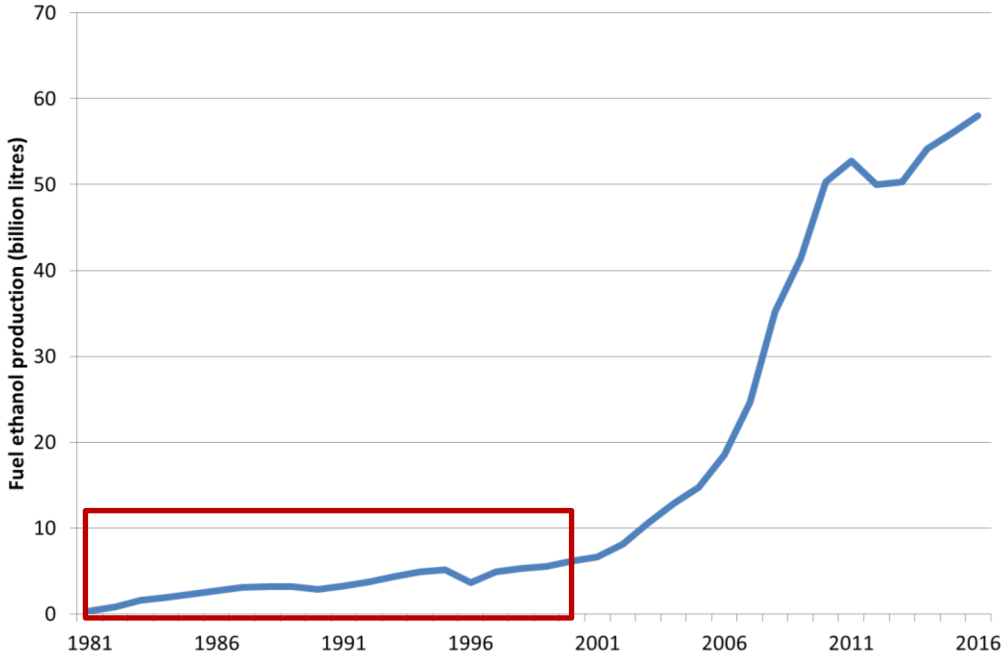

Figure 4: Ramp up in fuel ethanol production in the US from 1981.
Source: US EIA[34]. Red box highlights the period in which a comparable growth rate is realised in the two scenarios

[32] As outlined here: Joint Committee on Taxation (1984). General explanation of the revenue provisions of the Deficit Reduction Act of 1984. Available online at: http://www.jct.gov/jcs-41-84.pdf. See Section IX.C (p1078).
[33] Tyner, W.E. (2008), "The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects", *BioScience*, vol. 58, no. 7, pp. 646-653. doi.org/10.1641/B580718
[34] Available online www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.03#/?f=A&start=1981&end=2016&charted=7-18

The modelled increase in cellulosic ethanol production in the 2020s in the central scenario is largely comparable with the increase in output realised in the corn ethanol industry in the US in the 1980s (on average 0.25bn l/y). Similarly, the growth in production in the more ambitious scenario is largely comparable with the growth realised in the US corn ethanol industry in the 1990s (on average 0.35bn l/y). This period in US corn ethanol history provides a good comparison for the scenarios, since it reflects the rise of a nascent ethanol industry with government support (in the form of tax credits).

The upturn in the corn ethanol industry post-2001 also provides an indication of how the cellulosic industry could potentially flourish with sustained support in the post-2030 period. In the short period between 2005 and 2011, 123 new ethanol plants began operating in the US (see Figure 5).

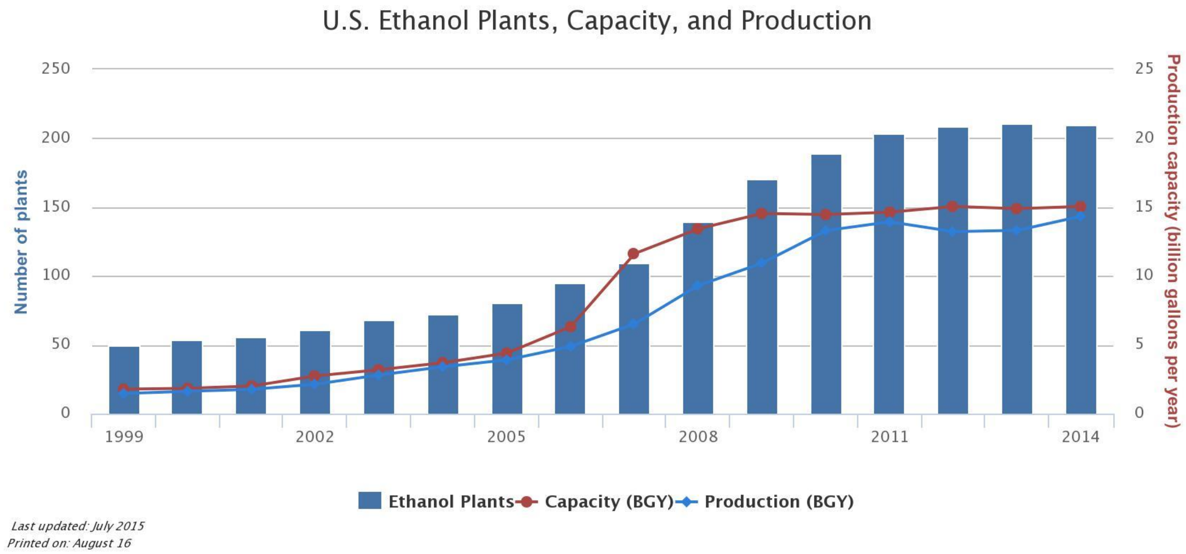

Figure 5: Ramp up in ethanol plants in the US between 1999 and 2014
Source: USDoE Alternative Fuels Data Center[35]

This sudden growth required significant investment and long-term policy signals, and large quantities of feedstock. Whilst the ramp up of corn ethanol in the US will not necessarily be a blueprint for the cellulosic ethanol ramp up in the US (or EU), it does provide a proxy indicative of the speed at which such an industry could potentially develop in the future.

Given the parallels between the growth curves for the nascent corn ethanol industry in the US and the scenarios described in this study, the ramp up rates in this study are considered to be feasible, provided that adequate long-term policy support is in place and finance is available.

6 Consideration of regional feedstock availability

Feedstock potential estimates for residues and wastes are highly variable due to differing assumptions about sustainable extraction rates, likely collection rates and competing uses. There are multiple recent studies on biomass potential within the EU, notably S2Biom[36], ICCT[37] and the

[35] Available online at www.afdc.energy.gov/data/widgets/10342
[36] http://www.s2biom.eu/en/publications-reports/s2biom.html
[37] ICCT (2013) "Availability of cellulosic residue and wastes in the EU". Available at www.theicct.org/sites/default/files/publications/ICCT_EUcellulosic-waste-residues_20131022.pdf

Globiom land use change study for the EC[38]. Due to this variability, these studies provide a range of estimates of technical potential, as well as what may be available taking into consideration competing uses. Even when using the most conservative feedstock availability estimates from the studies considered, the potential is sufficient to meet the ramp up estimates, albeit based on a range of feedstocks. However, it is crucial to consider not only whether there is sufficient feedstock in Europe, but whether it is available at suitable density and cost to supply the number of plants in the central scenario, and in locations where it is desirable to site a cellulosic ethanol plant (for example, where there are low labour costs). It is also necessary to consider whether the supply chains could be established in the timeframe available.

While the deployment of cellulosic ethanol plants in the EU will likely be based on a variety of feedstocks, we provide here some analysis of the number of plants that could potentially be based on straw alone, to put in context the ramp up rate provided. Previous analysis by E4tech for the ButaNexT project[39] found that around 58 Mt of straw could **currently** be sustainably sourced across the EU annually (Figure 6), taking into account already existing uses[40]. For comparison, ICCT (2013) estimated that in 2030 that there would be 54 Mt of wheat straw, 25 Mt of barley straw, and 23 Mt of maize straw available[41] for biofuel use.

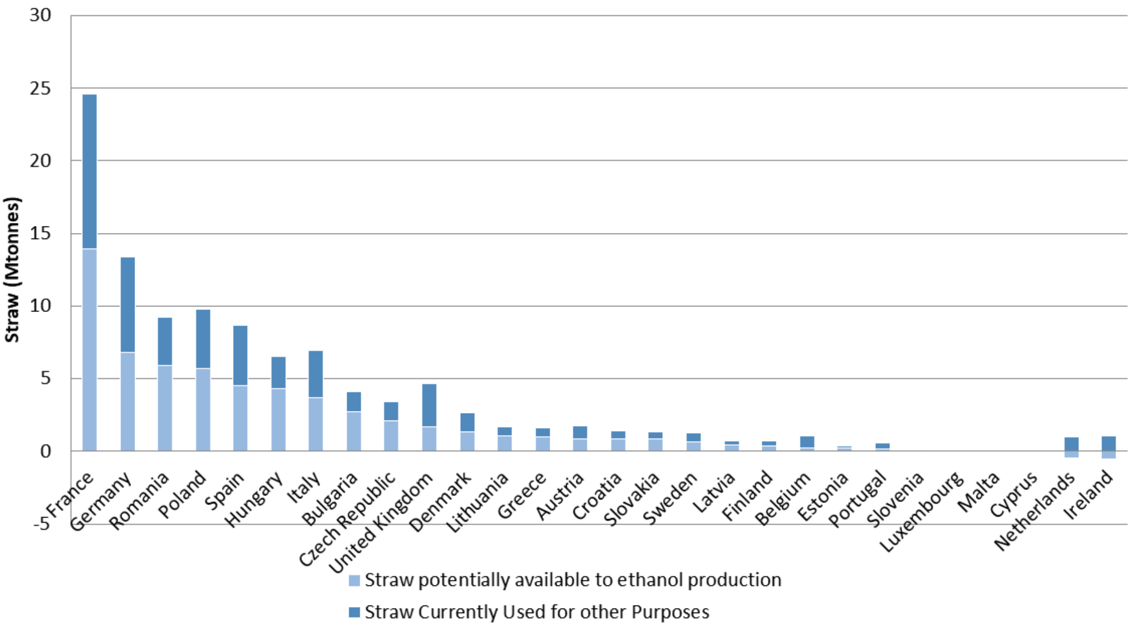

Figure 6: Amount of straw that can be sustainably removed from the field in each MS annually
Source: ButaNexT[39]

[38] https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf
[39] ButaNexT (2015) "D6.1 Feedstock Assessment". Available online http://butanext.eu/contents/publicdeliverables/butanext-deliverable-d6-1-feedstock-assessment-6785.pdf
[40] This figure is calculated from: 2013 data for crop production in Europe from Eurostat, crop-specific straw: crop ratios, and the same assumptions as used in the Globiom report with respect to the proportion of straw that can be sustainably extracted (40%), and the amount required for competing uses, such as animal bedding (based on livestock statistics per MS with an assumed straw use per livestock) as well as a 12.5% allocation for other minor uses
[41] ICCT considered that a third of residues would have competing uses (livestock and horticulture) and a third would remain in the fields

It is assumed here that the production of straw will not change significantly in the near- to mid-term in the EU[42]. However, it is expected that the competition for these straw resources will increase due to increased use in other areas, such as power generation, bio-materials or other advanced biofuel technologies. This increased competition is not considered here as this is highly uncertain and is anticipated to rely heavily on economics, market dynamics and policy prioritisation. However, this will have an impact on price of feedstock and is considered in terms of the range that is provided for feedstock costs in 2030 (see section 3.3.3).

The central scenario in this study sees 46 plants built across Europe by 2030, resulting in 2.75 billion litres of cellulosic ethanol being produced. This would require ~10 Mt (dry) feedstock overall, and 190-240 kt available locally per plant. The more ambitious scenario sees 64 plants being built, 3.8 bn litres of cellulosic ethanol being produced and requires ~14 Mt (dry) feedstock. Based on the prior estimate of 58Mt straw available, there would be a sustainable potential to nominally support around 245 straw based plants, taking into account competing uses, but not yet considering feedstock density. If the potential locations are narrowed down to focus only on those countries with particularly low cost straw (the expectation to 2030 is that developers will focus projects in locations where feedstocks cost <60 EUR/delivered dry tonne) and low labour costs, this figure reduces to around 63 plants (located mainly in Central and Eastern Europe). S2Biom also looked at the competing uses for straw and using their data, there would be enough straw alone for 84 plants in these same countries. Globiom models a smaller amount of available straw in the countries which S2Biom projected to be producing at a price <60 EUR/tonne, equivalent to around 16 plants[43] (although the potential would be much larger if including countries with higher feedstock prices[44] or labour costs).

The density of feedstock production is an important consideration for the establishment of a cellulosic ethanol plant, as a plant will ideally source feedstock from as short a distance as possible. For all the countries identified in Central and Eastern Europe as potential locations for cellulosic ethanol plants, it is possible to look at the maps provided in the S2Biom study as to the density of feedstock production (see Figure 7 for the example of Romania). Whilst these maps have their limitations, as they do not include competing uses on a regional level and all regions are not necessarily the same size in different countries, it does give some indication of the density of feedstock production in a country and how this varies by region. It could be concluded from these maps that the Central and Eastern European countries being considered (such as Bulgaria, Croatia, Poland, Romania) are likely to have several locations where the density of feedstock production is sufficient to support a cellulosic ethanol plant within the feedstock cost range considered in this study.

[42] A modest increase in cereal production was projected by the European Commission (2014) by 2024, driven primarily by livestock expansion. See "Prospects for EU Agricultural Markets and Income 2014-2024". Available at http://ec.europa.eu/agriculture/markets-and-prices/medium-term-outlook/2014/fullrep_en.pdf

[43] The Globiom study assumes that much of the straw that is currently extracted is done so unsustainably (i.e. too much is extracted) and moving to a more sustainable level of straw extraction would result in a large deficit of straw in some countries, e.g. Poland

[44] For the countries identified to have straw prices <90 EUR/tonne (the high feedstock cost scenario) in S2Biom, Globiom models the amount of straw that could be sustainably extracted (on top of that required for existing demands) would increase to supply 33 plants

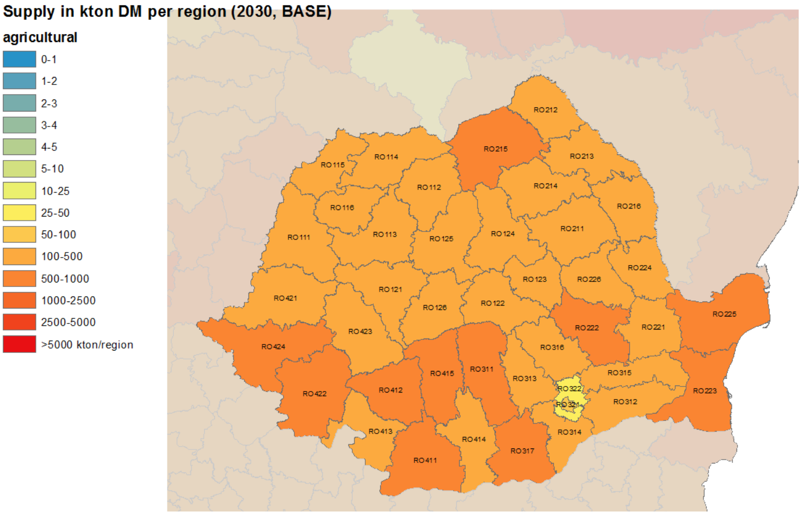

Figure 7: Potential sustainable supply of agricultural residues in Romania by NUTS2 region
Source: S2Biom[45]

In many countries, the process of developing supply chains on the scale required will be challenging. However, there is approximately a seven year period from initial project conception to the finalising of project construction for the first plants. Over this period, it will be crucial to build up an efficient feedstock supply chain and appropriate related business models. The time taken to develop these supply chains could also be expected to reduce over time, with experience.

7 The role of imports

This study does not look at the potential ramp up of cellulosic ethanol globally. However, in 2030, given the proposed policy support for advanced biofuels for transport, the EU is likely to be one of the major global centres of demand for cellulosic ethanol. Therefore, it is likely that a relatively high proportion of globally produced cellulosic ethanol may be exported to the EU. Assuming large targets for cellulosic ethanol continue in the US, it is also likely that the US will compete with the EU for cellulosic ethanol exports from South America, China and India (for the part that is not consumed domestically by these countries), as well as not exporting any of its own.

Without modelling the ramp up of the industry in other regions of the world and demand in those other regions, it is difficult to comment on how much cellulosic ethanol might be imported into the EU. However, using first generation ethanol as an indicator, it is possible to make an estimate of an amount of cellulosic ethanol that might be imported into the EU. In 2016, 67% (4.34 billion litres) of all ethanol (excluding ETBE and other chemicals/derivatives) consumed in the EU was used as fuel[46]. 0.44 billion litres of ethanol (excluding ETBE and chemicals) was imported into the EU. Assuming the same proportion of imports was used for fuel (67%), it is estimated that in 2016, 0.3bn litres of imported fuel ethanol was used in the EU, or 6.8% of all fuel ethanol consumed was imported. If the same proportion of imports (6.8%) is assumed for cellulosic ethanol in 2030, this would equate to the

[45] Map available online at: www.s2biom.eu/images/Publications/WP8_Country_Outlook/Final_Roadmaps_March/S2Biom-ROMANIA-biomass-potential-and-policies.pdf

[46] 2016 ethyl alcohol balance sheet, available online at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52017XC0713(01)&from=EN

import of 0.2 - 0.3 billion litres cellulosic ethanol. This is equivalent to the entire output between 2 and 4 large (76Ml) cellulosic ethanol plants sited outside the EU.

8 Conclusions

This study estimates that a central scenario for the ramp up in cellulosic ethanol production in the EU could supply of the order of 2.75 billion litres (or 1.4 mtoe) in 2030 from around 46 plants, providing 0.6% of the projected EU road and rail transport energy demand. The more ambitious scenario proposes 3.8 billion litres (or 1.9 mtoe) from 64 plants and providing 0.8% of EU road and rail transport energy demand in 2030. As such, cellulosic ethanol could offer a significant opportunity for transport decarbonisation, alongside other options, including first generation ethanol.

The ramp up rate in this study is slow in the immediate future, as although many projects are underway, it is expected that investors will wait until these first projects can demonstrate success over a significant period before they will be willing to invest in a subsequent plant.

Assuming there is willingness to pay for advanced fuels such as cellulosic ethanol at a price which reflects the production costs outlined in this study, there are two key factors that are most uncertain going forward and which are varied in the two scenarios:

- the development timelines (i.e. how long it takes to go from project inception to full scale production)
- the rate of project initiation by the industry (which encompasses a number of different factors, such as the number of technology developers, project developers, EPC contractors, availability of key equipment and importantly, the readiness of investors to keep investing in subsequent plants)

The third factor of plant size was not varied between the two scenarios. Should sufficient low cost feedstock be available at a sufficient density to support many larger plants, this could represent the basis for an even more ambitious scenario. However, sufficient evidence regarding the density of feedstock availability was not found to support such a scenario at this stage and so a more conservative approach was taken in relation to potential plant size. This was generally in agreement with industry views.

Although the link between production costs and the ramp up rate was not explicitly modelled, the availability of low cost feedstock is an important factor in achieving the proposed rate of development of projects. While sufficient feedstock could be available at a price of <60 EUR/tonne to achieve the central scenarios, a higher feedstock price in 2030 (<90 EUR/tonne) is also considered to assess the impact higher feedstock costs would have on the overall ethanol production cost. In order to mitigate against seasonal price spikes and increase feedstock availability, project developers indicate a desire to source some of their feedstock as energy crops. It will be critical to ensure that a framework is provided for the sustainable production of energy crops.

In practice, finding the right project location will be a critical element of project development. The development of expertise in establishing robust feedstock supply chains (particularly for energy crops, for which there is little experience to date) will also be a crucial part of realising the deployment outlined here. The timeline for feedstock supply chain development will need to be in line with plant development timelines.

It should be remembered that this study purposely only considers what level of cellulosic ethanol supply would be possible given a favourable demand environment. Whilst the scenario ranges presented in this study do not limit what could be achieved, it is also important to remember that a lack of regulatory support or investor confidence would jeopardise these estimates. Given the production costs outlined in this study for 2030 (reducing to 0.59-0.77 EUR/litre), a strong policy pull will be essential. Stable and favourable policy which extends beyond 2030 is going to be the key to investor confidence and realising the ramp up rates proposed here. In particular, the current blending obligation proposed by the EC for advanced fuels is going to be critical for providing the right signals to investors. Furthermore, policy will need to support higher ethanol blends, such as E20, to create a sustainable growing market for renewable ethanol.

Finally, the ramp-up rates modelled reflect those of a nascent industry in the early stage of growth. As such, it is expected that significantly higher ramp up rates could be realised post-2030 under a continuing favourable policy environment.