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Review

What is still Limiting the Deployment of Cellulosic Ethanol? Analysis of the Current Status of the Sector

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Received: 16 September 2019; Accepted: 15 October 2019; Published: 24 October 2019

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Abstract: Ethanol production from cellulosic material is considered one of the most promising options for future biofuel production contributing to both the energy diversification and decarbonization of the transport sector, especially where electricity is not a viable option (e.g., aviation). Compared to conventional (or first generation) ethanol production from food and feed crops (mainly sugar and starch based crops), cellulosic (or second generation) ethanol provides better performance in terms of greenhouse gas (GHG) emissions savings and low risk of direct and indirect land-use change. However, despite the policy support (in terms of targets) and significant R&D funding in the last decade (both in EU and outside the EU), cellulosic ethanol production appears to be still limited. The paper provides a comprehensive overview of the status of cellulosic ethanol production in EU and outside EU, reviewing available literature and highlighting technical and non-technical barriers that still limit its production at commercial scale. The review shows that the cellulosic ethanol sector appears to be still stagnating, characterized by technical difficulties as well as high production costs. Competitiveness issues, against standard starch based ethanol, are evident considering many commercial scale cellulosic ethanol plants appear to be currently in idle or on-hold states.

Keywords: cellulosic ethanol; GHG savings; R&D funding

1. Introduction

Ethanol production from cellulosic material such as agricultural residues (e.g., wheat straw and corn stover) and energy crops (e.g., switchgrass and miscanthus) is considered a highly promising option for future ethanol production, helping the energy diversification and decarbonization of the transport sector. Compared to conventional (or first generation) ethanol production from food and feed crops (mainly sugar and starch based crops), cellulosic (or second generation, 2G) ethanol is considered to provide better performance in terms of greenhouse gas (GHG) reduction and low risk of direct and indirect land-use change impacts. Those advantages have led to the promotion of cellulosic ethanol in the legislation around the globe.

In the EU, the current 2009 Renewable Energy Directive (RED) [1] and Fuel Quality Directive (FQD) [2] (in force until 2020), contain a 10% renewable energy target for the transport sector by 2020 and a 6% GHG reduction target for transport (set in FQD) that are both expected to be met largely with food-based biofuels. In response to the controversial issue of indirect land use change (ILUC), related to the global market-mediated agricultural area expansion, the 2015 ILUC Directive [3], amending RED and FQD, introduced a cap on crop-based biofuels, which can contribute up to 7% of the final consumption of transport energy in 2020. The directive [3] also introduced requirements for reporting ILUC emissions and measures to promote advanced biofuels. It [3] requires Member States to promote the use biofuels produced from feedstocks listed in Part A of Annex IX (which includes waste, residue, non-food cellulosic, and ligno-cellulosic feedstocks) by setting a non-legally binding target of 0.5% in energy content for their use in transport fuel. RED [1] also has a 'double-counting' mechanism, according to which the energy content of those biofuels is double counted towards the overall renewable energy in transport target. The recast of RED, Directive EU 2018/2001 [4], with effect from 1 July 2021, makes advanced biofuel mandate compulsory containing a sub-target of 3.5% for advanced biofuels for 2030 within the 14% target for renewable energy in transport. Advanced biofuels are defined by the directive as 'biofuels that are produced from the feedstock listed in Part A of Annex IX' that includes among others, agriculture and forestry residues as well as energy crops. Those biofuels will continue to count double towards the targets. In addition, biofuels must meet a 65% greenhouse gas reduction threshold (in installation starting operation from 1 January 2021), to try to ensure substantial GHG savings compared to fossil-based fuels.

Focusing on the US, a fuel is classified as advanced on the basis of its lifecycle GHG savings (which need to be at least 50% when compared to fossil fuels). Cellulosic biofuel is an advanced biofuel subcategory: it is required to have a greater than or equal to 60% GHG saving compared to a 2005 petroleum baseline [5]. The Renewable Fuel Standard (RFS) program required 36 billion gallons of biofuels to be used by 2022, of which at least 16 billion gallons were supposed to come from cellulosic biofuels [6]. However, every year, the Environmental Protection Agency (EPA) has exercised its 'cellulosic waiver authority' to reduce the cellulosic biofuel target. In 2014, EPA also redefined the term 'cellulosic biofuels' expanding the definition to include certain types of biogas and ethanol from corn kernel fiber [7]. Since then, most of the increase in cellulosic biofuel consumption is from biogas, in either compressed or liquefied form. The current cellulosic biofuel mandate (2019) has been set by EPA at 418 million gallons, corresponding to about 5% of the target envisioned by the Energy Independence and Security Act of 2007 [8]. Moving to Brazil, the recent RenovaBio program aims to decrease transport emissions by 10% in the next 10 years favoring fuels with lower carbon intensities [9]. Like the US Renewable Fuel Standard, it favors fuels with lower carbon intensities and biofuel producers will receive credits based on the lifecycle emission savings of their fuel compared to fossil fuel. Other programs for the promotion of second generation ethanol in Brazil include the Joint Support Plan for Industrial Technological Innovation in Sugarcane-based Ethanol and Chemistry Sectors (PAISS Program) that provides funding aiming to boost Brazil's presence in more advanced technologies [10].

In China, the "Implementation Plan for the Expansion of Ethanol Production and Promotion for Transportation Fuel", jointly announced by the National Development and Reform Commission (NDRC) and other ministries in September 2017, targets a national shift in production to cellulosic technology by 2025. Cellulosic ethanol production is supported via a subsidy of 600 RMB (Renminbi) per ton (about 78 €/t) since 2014. However, prospects for 2018 are uncertain since updates on the subsidy program have not been announced at this time [11].

In addition to the aforementioned policy measures, the evolution of the cellulosic ethanol sector is influenced by various aspects, such as past and current R&D investments, production costs as well as technical and environmental issues that must all be taken into account in order to provide a comprehensive picture of the sector and its future challenges.

Already in 2002, Badger [12] provided a general review on ethanol from cellulose in US concluding that "although several ethanol-from-cellulose processes are technically feasible, cost-effective processes have been difficult to achieve". Kumar et al. in 2016 [13] and more recently Liu et al. in 2019 [14] reached similar conclusions. They both reported that cellulosic ethanol is still not competitive compared to conventional ethanol and efforts are still needed to reduce costs.

The main purpose of this review is to provide a comprehensive overview of the status and different aspects of cellulosic ethanol production both inside and outside the EU, highlighting technical and non-technical barriers that still limit its production at commercial scale. A literature review of the status of cellulosic ethanol plants in the EU and worldwide is carried out in Section 2. Section 3 reports GHG emission savings and production costs associated to cellulosic ethanol production.

An analysis of R&D funding and programs mainly in EU is provided in Section 4, while barriers to large scale deployment of cellulosic ethanol are discussed in Section 5. Section 6 draws conclusions.

2. Current Cellulosic Ethanol Production Process in Commercial Plants

Cellulosic ethanol production can be summarized in four main steps: pretreatment, hydrolysis, fermentation, and product recovery (Figure 1).

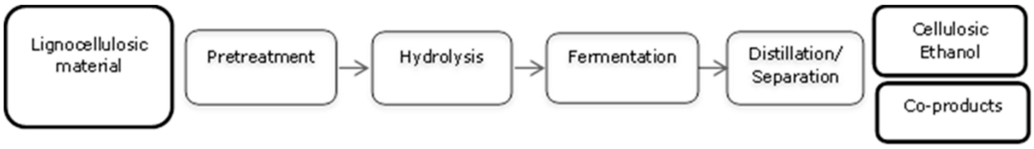

Figure 1. Cellulosic ethanol process.

Pretreatment makes the lignocellulosic biomass more amenable to biological conversion ensuring complete substrate utilization. Several pretreatment technologies have been developed and tested at various scales [13,14], and steam explosion has been recognized as the one most widely used by industrial companies [15]. In addition, hydrolysis (of the cellulosic and hemi-cellulosic structures) can also be enhanced by means of enzymes or dilute acid pretreatments. Following pretreatment, enzymatic hydrolysis is the most commonly applied hydrolysis method, although the cost of enzymes currently takes a major proportion of the production costs [15] (see Section 3 for more details on production costs). Bacteria or yeasts are then used to ferment sugars into ethanol.

In terms of production, around 109 billion liters (or 86 million tons) of ethanol were globally produced in 2018, most of which was made by US (56%), followed by Brazil (28%), EU (5%), and China (4%) [16]. For cellulosic ethanol, commercial size plants have been constructed in Europe, US, Brazil, and China, but regular and reliable production is yet to be proven. The actual cellulosic ethanol production to date has been markedly below the installed capacity.

For the EU, ePURE reports that almost 200 kt of European ethanol has been produced from ligno-cellulosic, other RED Annex IX-A feedstocks, or other feedstocks, representing 4% of the total ethanol production in 2017 [17]. However, according to the US Department of Agriculture (USDA) Global Agricultural Information Network (GAIN) report, EU28 annual production of cellulosic ethanol was estimated to be around 40 kt in 2017 down to 10 kt in 2018 [18]. In the US, the EPA's 2018 RFS data reports US cellulosic biofuel production levels, from which it's possible to estimate a total of about 30 kt of cellulosic ethanol produced domestically in 2017 [8]. In Brazil, total cellulosic ethanol production is estimated to be 25 million liters (or 20 kt) for 2018 representing an insignificant share of total ethanol production in Brazil [9]; while, for China, 2018 cellulosic ethanol production is forecast to stop at 20 million liters (or 16 kt) as its major cellulosic project appears idle [11].

There are several first-of-a-kind commercial scale cellulosic ethanol plants at a global level, according to the International Energy Agency (IEA) database [19] and other sources [9,11,18,20–24], although operations of some of the plants are currently idle or on-hold (Table 1).

Only a few commercial scale plants are reported as operational in Norway, US, and Brazil.

In addition to the plants listed in Table 1, Quad County Corn Processors and six other plants (using the Edeniq technology) adapted their conventional corn ethanol refineries to produce ethanol from corn kernel fiber, known as 1.5 generation technology. As reported in Section 1, it will qualify as cellulosic biofuel in US following the EPA definition. However, corn kernels consist of a significant content of fibers (10–12%) that impact on the conversion of fermentable sugar, but they are mainly comprised of starch [7]; therefore, they should not be strictly considered as second generation ethanol production plants. Other plants are also planning to produce 1.5 generation ethanol: D3Max and ICM are developing their own technologies [7].

Table 1. Overview on a global commercial scale cellulosic ethanol plants.

Company	Project	Country	Output Capacity (ktons)	Status	Start-Up Year
Abengoa Bioenergy Biomass of Kansas, LLC	Commercial (acquired by Synata Bio Inc. [21])	US	75	idle	2014
Aemetis	Aemetis Commercial	US	35	planned	2019
Beta Renewables (acquired by Versalis [22])	Alpha	US	60	on hold	2018
Beta Renewables (acquired by Versalis)	Energochemica	EU (Slovakia)	55	on hold	2017
Beta Renewables (acquired by Versalis)	Fujiang Bioproject	China	90	on hold	2018
Beta Renewables [1] (acquired by Versalis)	IBP-Italian Bio Fuel	EU (Italy)	40	idle	2013
Borregaard Industries AS	ChemCell Ethanol	Norway	16	operational	1938
Clariant	Clariant Romania	EU (Romania)	50	under construction	2020
COFCO Zhaodong Co.	COFCO Commercial	China	50	planned	2018
DuPont	Commercial facility Iowa (acquired by VERBIO [23])	US	83	idle	2016
Enviral	Clariant Slovakia	EU (Slovakia)	50	planned	2021
Fiberight LLC	Commercial Plant	US	18	under construction	2019
GranBio	Bioflex 1	Brazil	65	operational	2014
Henan Tianguan Group	Henan 2	China	30	Idle	2011
Ineos Bio	Indian River County Facility (acquired by Alliance Bio-Products in 2016 [24])	US	24	idle	NA
Longlive Bio-technology Co. Ltd.	Longlive	China	60	Idle	2012
Maabjerg Energy Concept Consortium	Flagship integrated biorefinery	EU (Denmark)	50	on hold	2018
POET-DSM Advanced Biofuels	Project Liberty	US	75	operational	2014
Raízen Energia	Brazil	Brazil	36	operational	2015
St1 Biofuels Oy in cooperation with North European Bio Tech Oy	Cellunolix®	EU (Finland)	40	planned	2020

[1] Joint venture of Mossi & Ghisolfi Chemtex division with TPG.

The POET-DSM Advanced Biofuels LLC is reported as operational, but it is not clear how much ethanol it is currently producing. The plant has been inaugurated in 2014 in Iowa with a production capacity of 75 kt per year of cellulosic ethanol from corn stover and cob. In summer 2017, the company installed a new pretreatment technology and announced the construction of an on-site enzyme manufacturing facility that will cut costs associated with the process [25]. According to Schill [20], the plant has reached the targeted 70 gallons per ton of biomass and further optimization is in progress.

One of the world's largest cellulosic ethanol production facilities, the Beta Renewables plant officially opened at Crescentino (Italy) in 2013 but it has been shut down since 2017 due to a restructuring effort of the parent chemical company Mossi & Ghisolfi [26]. The plant had an annual capacity of 40 kt of ethanol produced from wheat straw, rice straw, and giant reed (Arundo donax). On November 1, 2018, Eni's chemical subsidiary Versalis acquired the Mossi Ghisolfi Group's green portfolio and it is currently in the process of defining an action plan to restart the activities of the Crescentino plant [18].

Two commercial scale plants are in operation in Brazil. One is the Bioflex 1 plant from Granbio that began production in September 2014, with a current production capacity of about 65 kt per year; the other one is Raízen's Costa Pinto Unit with an annual production capacity of 36 kt of ethanol from bagasse using a technology developed by Iogen Energy, a joint venture of Raízen and Iogen Corp. According to USDA GAIN Brazil report [9], this is the only one producing at relatively large scale.

Other projects have been announced for the production of cellulosic ethanol, mainly in the EU. The construction of a new full scale commercial cellulosic ethanol plant has been announced in 2017 by Enviral, the largest producer of bioethanol in Slovakia, that recently signed a license agreement to use Clariant's Sunliquid®technology [27]. The plant is planned to be integrated into the existing facilities at the Enviral's Leopoldov site (in Slovakia) producing 50 kt per year of ethanol from agricultural residues. Clariant has also announced on-going construction of the first large-scale commercial Sunliquid®plant for the production of cellulosic ethanol in Romania [28].

The Cellunolix®project (managed by St1 Biofuels Oy in cooperation with North European Bio Tech Oy) is planned to be operational in 2020 in Finland with an annual capacity of 40 kt. The plant will use saw dust and recycled wood as feedstock and will be located at UPM's Alholma industrial area [18].

In China, COFCO announced plans to build several 63 million liters (or 50 kt) capacity cellulosic fuel ethanol plants in future [11].

3. GHG Emissions and Production Costs of Cellulosic Ethanol

Cellulosic ethanol from feedstocks such as agricultural residues and energy crops is generally considered to be environmentally sustainable providing higher reduction of GHG emissions and zero or low indirect emissions from land use change compared to conventional (or first generation) ethanol production from food and feed crops.

Focusing on the framework after 2020, the RED recast [4] specifies that biofuels must meet a 65% greenhouse gas reduction threshold, compared to fossil fuels, in installations starting operation from 1 January 2021.

The methodology to calculate 'life-cycle' GHG emissions is set by the Directive in Annex V part C [4]. GHG emissions should be calculated by taking into account all emissions associated to all steps of the production and use of biofuels, from cultivation of raw materials, to processing into biofuels, and transport and distribution of all products. Emissions from carbon stock changes caused by direct land-use change, if they occurred, should also be taken into account. The total GHG emissions are referred to as 'direct emissions'. The Directive includes a list of default GHG emission values for the main biofuels that economic operators can use only if biofuels are produced without direct land use change.

The default value associated to cellulosic ethanol from wheat straw is 16 gCO_2eq/MJ [4] that, compared to the fossil fuel comparator, results in 83% GHG emission reduction. A similar value can be assumed for perennial grass (such as miscanthus and switchgrass) ethanol [29].

However, those values do not include accounting of GHG emissions associated with changes in the carbon stock of land resulting from indirect land use change (ILUC) and other indirect effects.

The ILUC issue refers to global market-mediated agricultural area expansion in response to increased biofuel demand. If crops grown on existing arable land are used to make biofuels and are diverted from food and feed production, then the gap in the food supply will be partly filled by the expansion of cropland, because of the necessity to replace the food production. This is referred to as indirect land use change [30]. Economic models are typically used to estimate global land use change consequences due to an increased biofuel demand (more details on how the economic models work and on alternative approaches to estimate ILUC can be found in [30]). ILUC has been estimated by numerous studies in the literature and in regulatory analyses; results show that ILUC emissions can be significant for food-based biofuels [3,30–34]. Nevertheless, non-food feedstocks may also have a land use change impact as well as other indirect emissions as a result of the displacement with existing uses [29,31].

The emissions from land use change calculated by the GLOBIOM (Global Biosphere Management Model) [31] associated to the increase in the demand of cereal straw based ethanol in the EU corresponds to 16 g CO_2eq/MJ of ethanol (assuming 20 years of amortization) in the case of unsustainable straw removal and 0 g CO_2eq/MJ when straw removal is no more than 33–50% of the total straw biomass (considered as the sustainable straw removal in the study [31]). These emissions result from the conversion of land for new cropland for extra cereals production and from the soil organic carbon impact of removing crop residues in unsustainable management [31].

For energy crops/perennial grasses, land use change emissions depends on which type of land is used for their production (existing agricultural land, unused land such as abandoned agricultural land, or high-carbon stock land such as forests) which will in turn be determined by what is more profitable for farmers to do compared to growing other crops or leaving the land uncultivated [35]. Emissions from land-use change estimated by the GLOBIOM model [31] for miscanthus and switchgrass Fisher-Tropsch biodiesel (a value in the same order of magnitude can be assumed for ethanol) produced in the EU are negative (−12 gCO_2eq/MJ), indicating that land use change from these crops actually reduces GHG emissions compared to a baseline case without them, mainly due to the increase in soil carbon stock where they are grown [29,31]. Most other modeling studies, reviewed in [36], found that energy crops are not likely to displace food and fiber crops on agricultural land, but would mostly be grown on abandoned agricultural land, cropland-pasture, and other unused land with low-carbon stocks, resulting in low or negative ILUC emissions. However, there is some uncertainty in the magnitude of energy crop ILUC emissions and additional considerations on the environmental risks of energy cropping as well as options for risk mitigation can be found in [35].

A lifecycle analysis looking at indirect effects, i.e., including emissions which would arise when replacing a material that has been diverted from its original use into fuel production was performed by [29] for a number of pathways, and included wheat straw to ethanol. For this pathway, the current usage of straw in heat and power generation and livestock bedding and feed, mushroom cultivation, and horticulture was considered (more detail of the analysis can be found in [29]). The authors estimated a value of 8 g CO_2eq/MJ (central estimate) of indirect emission for wheat straw ethanol.

Direct and indirect emissions for the two considered pathways are summarized in the following table (Table 2).

Table 2. Estimated greenhouse gas (GHG) emissions (direct and indirect) associated with cellulosic ethanol production from cereal straw and perennial crops.

	Direct Emissions from RED Recast, Annex V—Default Values [4] (g CO_2eq/MJ)	**Indirect Emissions (ILUC Emissions from Valin et al., 2015 [31]) (g CO_2eq/MJ)**	**Indirect Emissions (Displacement Emissions from ICCT, 2017 [29]) (g CO_2eq/MJ)**
Ethanol from wheat straw	16	16 if unsustainable straw removal is assumed (more than 33–50%) 0 if sustainable straw removal is assumed (less than 33–50%)	8 displaced uses: Livestock bedding and feed; mushroom cultivation; horticulture; heat and power
Ethanol from perennial grass (miscanthus and swithgrass)	16	−12	0 no existing uses

Several sources mention costs as the main issue for the development of the cellulosic ethanol sector [12–14]. Results from recent studies investigating production costs of advanced biofuels, including cellulosic ethanol, are summarized below.

These studies are: the Joint Research Centre (JRC), Eucar and Concawe (JEC) cost analysis (in publication) [37], the 2017 European Commission report by the Sub Group on Advanced Biofuels (SGAB) [38], and the 2016 report from the International Renewable Energy Agency (IRENA) [15].

For cellulosic ethanol from agricultural residues or woody biomass, cost ranges reported by the three studies (for different years) are summarized in Figure 2.

The cost ranges depend on the assumptions on the various components of the cost calculations and, in particular, on the cost of feedstock, the scale of the plants, and capital cost.

Being at an earlier stage of commercialization, cellulosic ethanol is still facing significant technology challenges and is showing significant capital and operational costs due to the complexity of the conversion processes and low maturity of the technology, but there is potential for future cost reduction [37].

The cost of feedstock is the major contributing factor depending on its accessibility, transportation costs, and also the alternative use. Feedstocks that are used in cellulosic ethanol plants have usually regional prices and they are traded locally. Their price depends on the local amount of production as well as their competing uses [39].

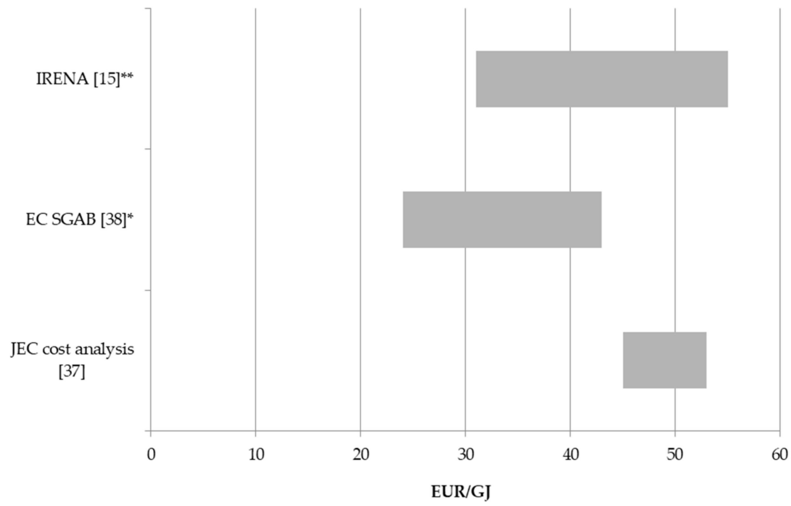

Figure 2. Production costs ranges of cellulosic ethanol from different studies. * Data extracted from Figure 18 of the report; ** Data from original source (reported for first commercial plants) has been converted from US dollar to Euro assuming 2015 exchange rate).

Cost of enzymes also represents a relevant cost component of the operational costs [15,37,40] and reducing this cost is key to making cellulosic ethanol economically viable [40]. Comparing the costs of three approaches for producing enzymes (off-site, on-site, and integrated), Johnson [40] found that the integrated method has the lowest cost.

Generally, the reported ranges of production costs for cellulosic ethanol appear to be substantially higher compared to conventional ethanol prices and far from being competitive with fossil fuel [37].

4. R&D Investment in Recent Years

This section collects information on relevant projects related to cellulosic ethanol funded under the European Union's Research and Innovation Funding programs in the last decade, namely the Seventh Framework Programme (FP7) (that covers the 2007–2013 period) and the current Horizon 2020 program (H2020) (that covers the 2014–2020 period). The projects were collected for the purpose of the Low Carbon Energy Observatory (LCEO) project, an administrative arrangement executed by DG-JRC for DG-RTD to provide data and analysis on developments in low carbon energy supply technologies. One of the technologies under analysis is the 'Sustainable advanced biofuels' sector, where cellulosic ethanol is considered. The LCEO project (started in April 2015) produces its main reports on a two-year cycle: the first set of reports was produced in 2016 (not publicly available) while the second set was prepared in 2018 and will be publicly available in 2019. In the reports, an analysis, in terms of objectives and main achievements of projects related to advanced biofuels technologies (including 'fermentation') was performed to define the project impacts on the development of the technology [41,42]. However, for the purpose of this paper, the number of considered projects has been limited exclusively to the projects which involve research on the cellulosic ethanol sector. Projects were collected from the European Commission's Community Research and Development Information Service (CORDIS) [43], that is the primary source of results from the projects funded by the EU's framework programs for research and innovation, by adopting 'cellulosic ethanol' or 'fermentation' as keywords.

Projects on cellulosic ethanol in both programs received the greatest amount of EU funding when considering all projects related to the advanced biofuel sector, with a share of around 27% in the recent H2020 program [42].

Figure 3 shows the number of FP7 (started between 2008 and 2015) and H2020 projects (started between 2015 and 2017) and the corresponding total amount of EU public funding. In general, projects in the cellulosic ethanol sector are large projects in terms of total investment needed for their implementation.

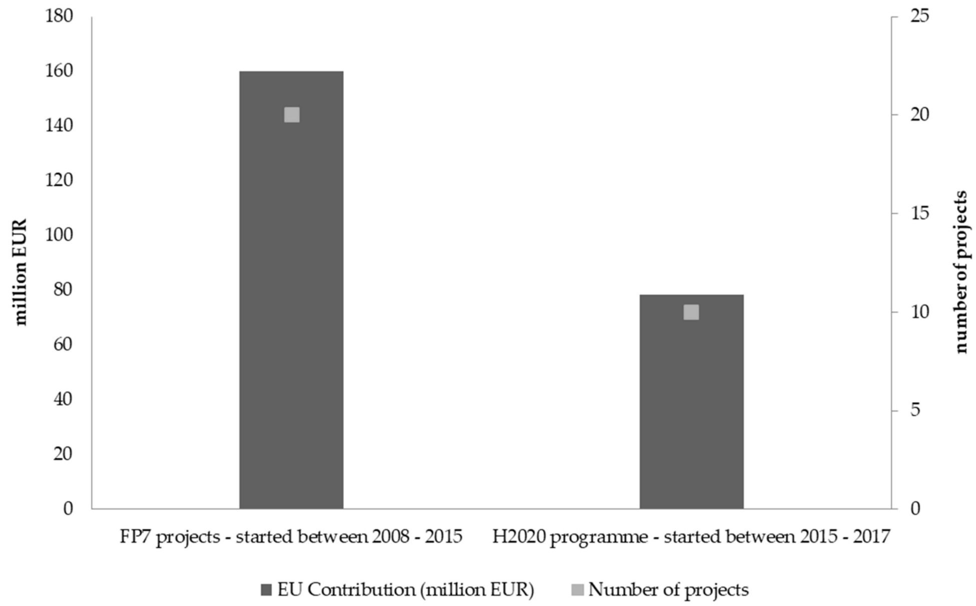

Figure 3. Numbers of Seventh Framework Programme (FP7) and Horizon 2020 program (H2020) projects and total amount of EU funding (million EUR) identified for cellulosic ethanol.

Figure 4 shows the total amount of EU funding by project coordinator countries identifying the leading countries involved in the development of this technology. The projects are mainly coordinated by Italy, Germany, and France.

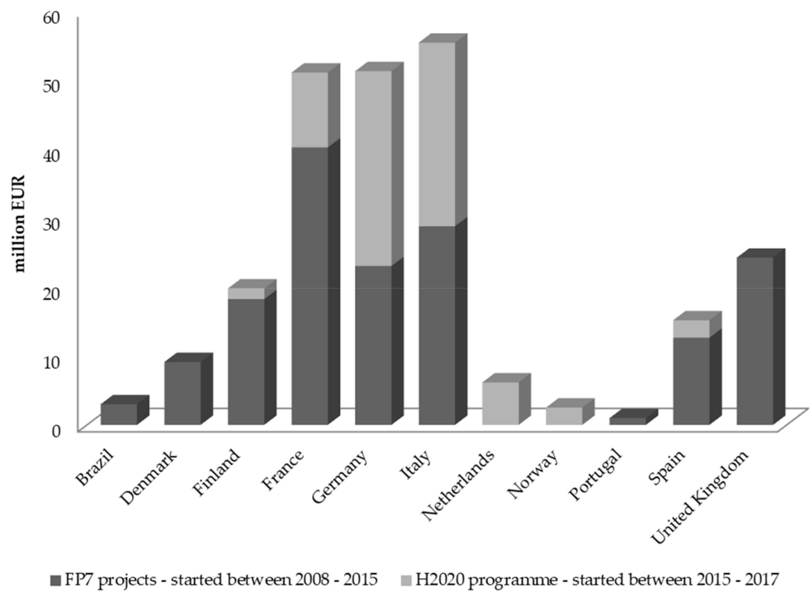

Figure 4. Total amount of EU funding by project coordinator country.

In the US, the Department of Energy (DoE) is supporting R&D projects through the Biomass Research and Development Initiative (BRDI). In 2018, DoE announced up to $3 million in funding for advanced biofuels, bioenergy, and biobased products and two selected projects received between $1 million to $2 million to develop biofuels from cellulosic ethanol and ligno-cellulosic biomass, respectively. Other funding was made available under the BioEnergy Engineering for Products Synthesis program, with a total funding of up to $28 million (in 2018), supporting projects that are aiming to create efficient conversion processes for biomass and waste derived fuels (16 projects were selected for this program). Process Development for Advanced Biofuels and Biopower is another program that supports 10 projects with $22 million. Some of the projects within this program are researching renewable fuels derived from domestic biomass feedstocks and wastes [44].

5. Technology Trends and Barriers to Large Scale Deployment

The trend in development of cellulosic ethanol production has been towards projects seeking to show (and indeed improve) upon the overall production chain; important to demonstrating the viability of this pathway. Overall, the development of both energy and cost effective pretreatment, hydrolysis and fermentation, remain the challenges hindering large-scale deployment of lignocellulosic biomass conversion to ethanol.

5.1. Pretreatment

One of the major challenges of lignocellulosic to ethanol is to ensure optimization of biomass conversion into components and by-products. Pretreatment schemes ensuring optimized use of the biomass continue to be developed. Raw material flexibility, minimum inhibitor formation, as well as maximum carbohydrate yields are central targets. Using feedstocks available in quantities large enough to supply a factory (as opposed to tiny amounts upon which a laboratory test could be carried out) brings its own technological challenges: the variability in quality and composition of the feedstock is clearly recognized as a key point, resulting in the need for a robust pretreatments section [45]. Among the various techniques applied in real plants, enzymatic hydrolysis has proven to be efficient, but enzymes cost can account for up to 30–50% of the total cost of ethanol production. In order to overcome this barrier, new types of cellulases are being studied, such as bacterial enzyme complexes. Additionally, the presence of lignin during hydrolysis behaves as an inhibitor when it deposits itself onto cellulose in biomass, making it inaccessible to enzymes, or it can even adsorb the enzymes itself [14].

5.2. Fermentation

Simultaneous utilization of pentose sugars by highly effective industrial yeast strains is still a challenge in developing continuous fermentation, which is expected to increase the yield and reduce the cost of the final product. The tolerance of ethanol producing bacteria for high substrate, inhibitor, and product concentration still needs to be improved; its progress on developments of co-fermenting microbes have been slower than projected. Review on "present technical issues" hindering cellulosic ethanol production indicated microbial species had been engineered to ferment both C5 and C6 sugars, but ethanol yields were low, and the microbes had low tolerance to high ethanol contents compared to C5 fermenting microbes [46]. Liu et al. [14] further reported that there has been considerable work trying to improve co-fermenting bacteria for at least four decades to date, but still today, it's possible to recognize familiar difficulties amongst various projects.

Other ethanol producing organisms such as yeasts, Escherichia coli, Klebsiella oxytoca, Lactobacillus sp., Clostridium sp., and others are developed for the simultaneous utilization of pentose and hexose sugars but their practical application has still to be proven. Alcohol producing strains with the ability to hydrolyze polymeric substrates have been in development for some time; although high end product concentration and selectivity (toward greater production of the desired alcohol), and insensitivity to inherent and generated inhibitors and process conditions remain major goals.

High dry matter concentration in a fermentation batch is also desirable as this will give high product concentration and help product recovery from fermentation broth. This could be achieved by developing novel process layouts involving systems aiming at immobilization of the fermenting organisms by the advanced use of non-fouling membrane systems, encapsulation of the organisms in polymer beads, etc. Efficient product separation is another advantage of advanced fermentation set-ups. This could be a critical step in the direction of a transfer from the current batch-wise into continuous fermentation processes, which would represent a more effective conversion.

5.3. Downstream

Downstream processing of products requires advances in membrane or adsorbent technology. One challenge is effective separation of alcohols from water. There is a need for membranes with high removal capacity of product, e.g., for pervaporation or suitable absorbents. Separation and rectification technology is the most demanding and needs further research on materials (membranes and adsorbents). The need to add water to the fermentation mixture to keep viscosity low and to limit bacteria inhibition creates another issue as the water will need to be driven-off during distillation. Thus, work to improve this need for water addition would likely improve the overall plant energy balance [14].

5.4. By-Products

The fate of lignin and hemicelluloses are one of the important challenges to be overcome. Processing has to avoid unfavorable conditions for sugar re-formation (back-reaction), chemical derivatization (pentoses to furfural, lignin to sulfo-lignin, and formation of lignin-carbohydrate complexes), and physical change. Separated raw material constituents (i.e., lignin and extractives) can be further converted into value-added products, for which a lot of research has been done. Fermentation broth as well as solid residues (including bacterial/yeast cell mass) are nutrient rich and can be recycled into the process, used as feed for animals, or added to biogas plants. However, it should be noted that an effective separation process for the biomass constituents after pretreatment remains a challenge.

6. Conclusions

Despite policy targets and significant R&D funding in the last decade (under EU and other programs), the cellulosic ethanol process appears to be still stagnating, mainly due to technical difficulties and high production costs that makes it uncompetitive with starch based ethanol production or fossil fuels [47]. External factors such as low oil prices may have also affected production [15]. Globally, there are several commercial scale cellulosic ethanol plants, but a substantial number of these plants are currently in idle or on-hold states.

Microbial strains which can ferment pentose and hexose sugars under large industrial-scale production are still under development, despite the past four decades of work and significant investment in R&D.

Finally, the authors note there are other possible issues potentially hindering future efficient cellulosic ethanol production, such as feedstock logistics, and storage; nevertheless, these aspects have not been analysed in this work, as they are likely to become relevant only once robust and efficient cellulosic ethanol production chains will be proven in regular operation, and at a reasonable scale.

Author Contributions: All three authors contributed significantly to the work with their expertise. M.P. led the work and performed the analysis, including the costs considerations, supported by A.C., A.C. and M.P. contributed with their expertise on technology trends and barriers.

Funding: This research received no external funding.

Acknowledgments: We wish to thank DG RTD colleagues, Maria Georgiadou and Thomas Schleker, for providing feedback on EU R&D aspects.

Conflicts of Interest: The authors declare no conflict of interest.

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