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Tracking cellulosic ethanol: commercialization and regional insights

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Received August 14 2025; Accepted October 1 2025;
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.70068; *Biofuels, Bioprod. Bioref.* (2025)

Abstract: Despite early momentum, large-scale production of cellulosic ethanol has yet to achieve its expected breakthrough. The sector has faced setbacks, including project cancellations, unmet capacity targets, and the closure of key plants. Drawing on 15 years of monitoring the industry, we examine the underlying causes and evaluate the status of demonstration plants recorded in the International Energy Agency (IEA) Bioenergy Task 39 database. Following an initial period of progress up to 2015, when 50 facilities were operational, many projects were either canceled or idled. The expected capacities were not reached, and the anticipated breakthroughs have not materialized. The slow advancement of cellulosic ethanol development has occurred due to technological complexity, limited feedstock availability, high production costs, and modest commercial outcomes. Investor confidence has been further undermined by inconsistent policy support, competition from lower-cost biofuels, and the collapse of several large-scale ventures. In recent years, however, cellulosic ethanol production has shown promising progress and capacity to expand, particularly in rapidly developing economies such as Brazil and China. Success in these regions depends on a combination of measures: a regulatory framework that provides market incentives and offsets higher production costs, sustained support for technological research and development, and public funding for large-scale, first-of-a-kind facilities. Brazil currently leads the field, largely because cellulosic ethanol production from sugarcane bagasse is integrated effectively into existing sugar and ethanol industries. © 2025 The Author(s). *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: cellulosic ethanol; deployment; advanced biofuels; capacities; Brazil

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Introduction

The transition to sustainable energy systems requires the development of renewable alternatives to fossil fuels, particularly in the transportation sector, which accounted for 11.9% of global greenhouse gas emissions in 2020.[1] Biofuels have emerged as a promising solution, with the potential to reduce carbon emissions and strengthen energy security.

First-generation biofuels are produced from crops that are also used for food and feed, like corn, sugarcane, soybean, and palm. They have been widely adopted because they are economically competitive with fossil fuels and can be produced on a large scale in many countries.[2] However, in some regions, their use raises concerns regarding food security and land use.[3]

In contrast, second-generation biofuels or advanced biofuels – such as cellulosic ethanol – are derived from nonfood biomass including agricultural residues, wood waste, and dedicated energy crops. This is a way of circumventing the food-versus-fuel conflict and enhances the overall sustainability of biofuel production.[4]

Cellulosic ethanol, also known as lignocellulosic or second-generation ethanol, is produced by converting lignocellulosic biomass into fermentable sugars, which are then fermented into ethanol.[5,6] Lignocellulosic feedstocks consist mainly of three biopolymers: cellulose (35% to 50%), hemicellulose (20% to 35%), and lignin (10% to 25%). Cellulose, a crystalline glucose polymer, forms the structural core of plant cell walls. Hemicellulose, a heteropolymer of five- and six-carbon sugars (pentoses and hexoses), surrounds the cellulose matrix, and lignin, a phenolic polymer, provides rigidity and resistance to microbial degradation. The proportions of these components vary by biomass type; woody biomass, for instance, generally contains more lignin and less hemicellulose than herbaceous crops.

The conversion process of lignocellulosic biomass to ethanol is technologically complex and includes four main steps: pretreatment, hydrolysis, fermentation, and product recovery. Pretreatment is essential to disrupt the plant cell-wall structure and to improve enzyme accessibility to cellulose and hemicellulose. Common methods include steam explosion (often acid catalyzed), and acid, alkaline, or organosolv treatments. These approaches typically hydrolyze hemicellulose into soluble sugars pentose and hexose sugars or solubilize lignin while increasing cellulose accessibility for enzymatic hydrolysis. Acid pretreatment efficiently removes hemicellulose through hydrolysis of glycosidic bonds but generates inhibitory chemicals like furfural that reduce fermentation efficiency.[7] Alkaline pretreatment cleaves ester and ether linkages in lignin, effectively removing lignin and partially solubilizing hemicellulose, but lignin recovery remains challenging.[8] Organosolv pretreatment promotes the cleavage of lignin-carbohydrate ether linkages and produces a relatively pure cellulose-rich solid fraction. The solubilized lignin can be recovered for high-value applications; however, it demands a solvent recovery process, which increases capital and operational costs and process complexity.[9]

Subsequently, enzymatic or acid hydrolysis converts polysaccharides into fermentable monosaccharides. The acid hydrolysis of cellulose faces challenges similar to acid pretreatment; because cellulose is more recalcitrant than hemicellulose, greater severity is required, which promotes inhibitor formation and requires expensive construction material for process equipment.[10] Enzymatic hydrolysis uses cellulase enzymes to cleave cellulose selectively into glucose under mild conditions, but enzyme costs can be high, and the overall reaction rate may require large, costly process equipment.[11]

Fermentation follows, with traditional yeast strains fermenting hexoses and genetically modified strains engineered to ferment pentoses. Ethanol is then recovered through distillation and dehydration, with synergies to conventional first-generation ethanol processes. Figure 1 illustrates these steps.

Despite the environmental and energy security benefits of cellulosic ethanol, its commercialization has progressed slowly. In 2010, former participants in the International Energy Agency (IEA) Bioenergy Task 39 posed the question: 'How close are second-generation biofuels?' and concluded

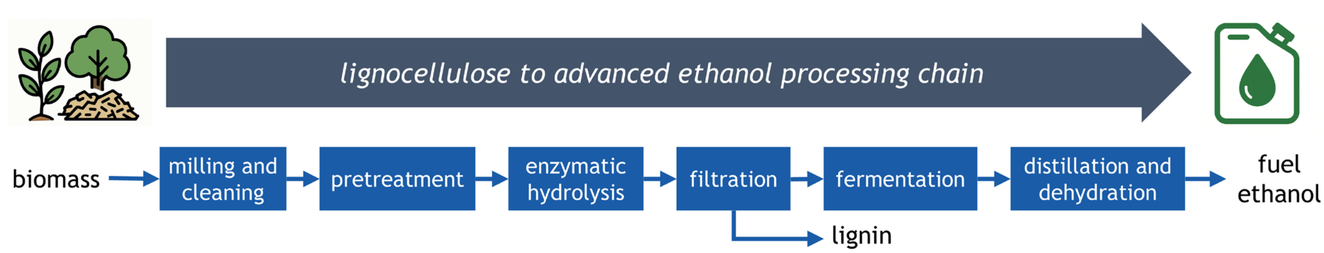

Figure 1. Processing steps in lignocellulose to bioethanol production.

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that commercialization appeared to be only a few years away.[12] It was anticipated that, following successful large-scale demonstrations, the sector would experience steady and accelerated growth, with substantial production volumes and commercial uptake expected within 1 to 2 years. However, these projections have not materialized; the commercialization of second-generation biofuels has advanced more slowly than anticipated, with the industry facing persistent technical, economic, and regulatory challenges that continue to hinder widespread deployment.

The recalcitrance of lignocellulosic material, high production costs, equipment wear from handling solids, and the need for tailored enzymes and microbial strains have posed substantial technical challenges. Economically, fluctuating oil prices, competition from mature first-generation biofuel technologies, and feedstock supply chain limitations have hindered the scalability of cellulosic ethanol, with economic viability very dependent on large-scale deployment. Biomass yield, seasonal availability, and low density of biomass further increase feedstock transportation, storage, and handling costs, while variability in biomass affects process reliability and efficiency. These factors constrain the capacity of cellulosic ethanol plants.[13] In addition, policy uncertainties and regulatory inconsistencies have limited investment and slowed industrial growth.[14–16]

Analyses from the IEA and other sources indicate that, although pilot and demonstration facilities have demonstrated the technical viability of the process, only a few have achieved sustained commercial operation. Many projects continue to encounter financial and operational setbacks, and global deployment remains limited despite ongoing research and governmental support.[17] As the field evolves, intensified research and innovation are essential to address current bottlenecks and improve the technoeconomic feasibility of cellulosic ethanol. This study traces the historical and current development of cellulosic ethanol production, contributing to a broader understanding of sustainable fuel technologies and informing future strategies for large-scale implementation.

Methodology

International Energy Agency Bioenergy Task 39 database on advanced biofuels demonstration plants

The international expert network IEA Bioenergy Task 39 (Biofuels to Decarbonize Transport) monitors the development of production and demonstration facilities of advanced biofuels globally. Since 2009, IEA Bioenergy Task 39 has maintained a database of facilities producing advanced biofuels, available at https://demoplants.best-research.eu/. The database was developed to provide a comprehensive overview of global pilot and demonstration-scale plants dedicated to the production of advanced liquid and gaseous biofuels. The creation of the database included systematic collection of information from multiple sources, including contributions from Task 39 member countries, and data from other international networks such as European Technology and Innovation Platform (ETIP) Bioenergy, and the IEA Advanced Motor Fuels TCP. In its initial stages, when public information on these facilities was limited, data collection relied heavily on direct communication with project owners and operators. Over time, as companies began to share more information through their websites and public reports, the database expanded to include data from publicly available sources, scientific literature, and technical documents.

The data are updated and verified regularly by the members of the Task 39 network and includes the following technologies for producing advanced liquid and gaseous biofuels for transport: alcohol-to-jet, e-fuels biomass hybrids, fast pyrolysis, fermentation, gasification, hydrothermal liquefaction, hydrotreatment, lignin depolymerization, and others. The collected information covers key parameters such as project name, location, technology type, feedstock, products, production capacity, operational status, and contact details, along with optional data like startup year, investment details, technology descriptions, and flow diagrams.

To ensure accuracy and reliability, the database employs a structured validation process involving regular input and review by Task 39 experts from various countries. These experts critically assess the information based on their technical knowledge and familiarity with national and regional biofuel developments. Updates are conducted systematically twice per triennium, incorporating new inputs from members, reviews of existing entries, independent research to revise outdated information, and cross-checks with external databases and industry sources. This iterative process maintains the integrity of the database and ensures that it reflects the latest developments in advanced biofuel technologies. As a result, the database has become a widely referenced resource for researchers, policymakers, and industry stakeholders monitoring the commercialization progress of advanced biofuels.

Worldwide capacity development of cellulosic ethanol production

This article examines the progress in the deployment of cellulosic ethanol, using the IEA Bioenergy Task 39 database as its primary information source. The analysis draws on annual data from 2009 to the present to assess developments in the field, incorporating insights from Task 39 experts and published literature. Although the database encompasses various advanced biofuel technologies, this article focuses specifically on cellulosic ethanol production.

The annual data excerpts were compiled into one file, checked for consistency, and updated as necessary. For three years (2010, 2014, and 2023) for which no annual data were available, data were calculated as the average of the preceding and the following year. The resulting global dataset was analyzed in terms of the number and cumulative capacity of facilities relative to their technology readiness levels and operational status. Data were then disaggregated by region and analyzed again with respect to cumulated capacity versus operational status.

The results were interpreted against the background of regional policies and supporting mechanisms, drivers and barriers, and climatic differences.

Results

Worldwide capacity development

Globally, since the establishment of the database in 2009, the number of facilities for processing lignocellulosic feedstock into ethanol that we were able to capture has risen quickly from 30 in 2009 (of which 13 were operational, three under construction, and 14 planned) to 119 in 2024 (41 operational, ten under construction, 16 planned, 21 idle, and 31 canceled plans).

As Fig. 2(a) shows, the number of operational facilities exceeded 30 in 2013, peaked at 50 in 2015, and then stabilized at approximately 40. During this period, there was a slight shift from pilot facilities (TRL 4–5) to demonstration (TRL 6–7) and commercial facilities (TRL 8–9). Figure 2(b) shows that, although facilities under construction were frequently reported in the early years, such announcements were rare after 2013, but picked up again, in particular for commercial facilities, from 2021 onward. Figure 2(c) presents the number of planned facilities per year, showing the development of cellulosic ethanol technologies from pilot to demonstration and first-of-a-kind stages. Most of the early pilot facilities remain operational, although they are likely not in continuous use throughout the year.

Figure 2(d) illustrates technological development. It shows the cumulative capacity of operational facilities over the years (as opposed to the number as in Fig. 2(a)). Technologies are initially tested in small pilot facilities, which do not operate all process steps. They are then demonstrated at larger scale across the full process sequence to assess interdependencies and optimize configuration. Finally, first-of-a-kind facilities at a small commercial scale are built. Capacities vary widely: pilot facilities typically reach up to 1000 t $year^{-1}$; demonstration facilities range from 1000 t yr^{-1} to 50 000 t yr^{-1}, and first-of-a-kind and commercial facilities usually range from 15 000 t yr^{-1} (particularly when integrated with cellulose production) to 150 000 t yr^{-1}. Cumulative operational capacities increased rapidly from 2013 to 2015, when several large-scale first-of-a-kind facilities became operational. Since then, global cumulative operational capacity has ranged between 380 000 t yr^{-1} and 580 000 t yr^{-1} due to the idling of some facilities while new ones came online. This pattern is explored further in the regional analysis.

Figure 2(e) depicts the development of facilities under construction, with a first small peak around 2013, and a later increase in activity in the early 2020s. As of 2024, capacities under construction were at an all-time high of 470 000 t yr^{-1}, which is almost as much as the current operational capacity of 555 000 t yr^{-1}.

However, announced plans for commercial facilities, as depicted in Fig. 2(f), must be viewed carefully. In 2015, worldwide, ten large-scale facilities (TRL 8–9) were operational and an eleventh facility was under construction, all of which together would provide production capacity of around 480 000 t yr^{-1}. At the same time, another 11 large-scale facilities were planned, promising additional production capacity of 880 000 t yr^{-1} – but none of these materialized. It remains to be seen how much of the currently planned capacity of 605 000 t yr^{-1} will actually come online.

The development of cellulosic ethanol technology has been challenging, with many companies canceling ambitious plans and changing strategic direction. Figure 3 provides an overview of the numbers and capacities of facilities that were idled and plans that were canceled over the years (the numbers are not cumulative). The data show that idling of facilities started in 2013 and was significant in terms of capacity from 2016 to 2018, and again in 2020. For comparison, oil prices were about $100 per barrel in May 2014 and dropped to $30 per barrel in Feb 2016, a variation that affected the economic feasibility of many biofuel projects.[18] A similar pattern can be observed for the cancellation of planned facilities, with an additional peak in 2013. The high values for 2024 reflect a more thorough review of older database entries and include facilities that were idled or canceled in 2024, such as the Clariant facility in Podaria, Romania.

The idling of pilot facilities is a normal part of technological development and moving to a larger scale, and demonstration

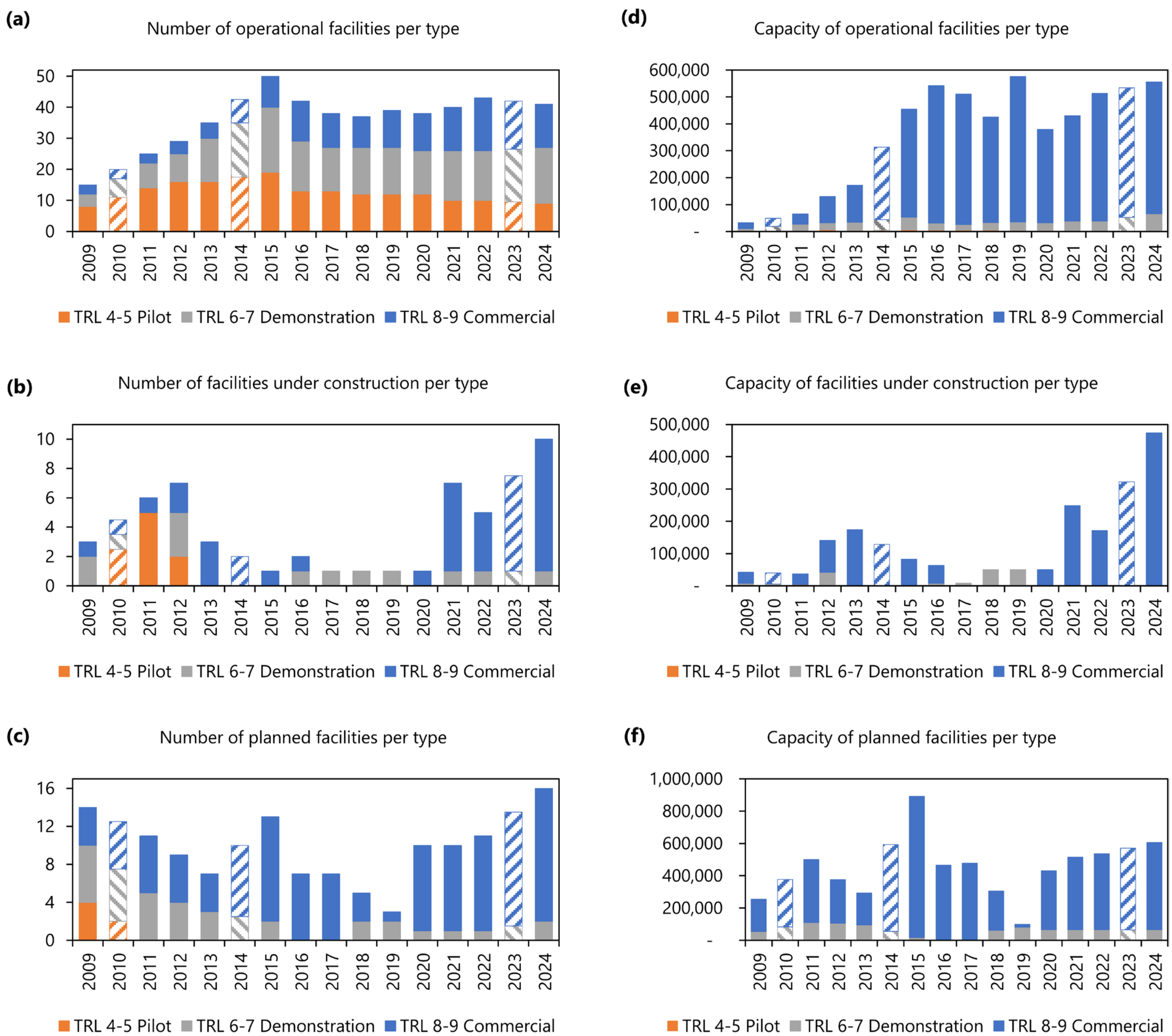

Figure 2. Compiled results from the Advanced Biofuels Demonstration Plants Database of IEA Bioenergy Task 39 showing the growth of cellulosic ethanol: (a) number of operational facilities by type, (b) number of facilities under construction by type, (c) number of planned facilities by type, (d) capacity of operation facilities by type (t yr^{-1}), (e) capacity of facilities under construction by type (t yr^{-1}), and (f) capacity of planned facilities by type (t yr^{-1}). Note: data for 2010, 2014, and 2023 were calculated as the average of the preceding and following years; these values are hatched.

facilities are often too large and inefficient to operate economically once development and demonstration tasks are complete. However, the idling of the first commercial-scale facilities that commenced operation in 2014 and 2016 was a major disappointment for the sector. The Abengoa facility in Hugoton, USA, POET-DSM in Emmetsburg, USA, and DuPont in Nevada, USA, were unable to operate economically and were either idled or returned to research at much smaller scale.

Table 1 lists large-scale facilities (>19 000 t yr^{-1}) with their startup year and status. Nineteen cellulosic ethanol facilities with more than 19 000 t yr^{-1} capacity have been started successfully, the first in 1940, producing ethanol as a co-product of specialty cellulose production. Of these, 11 remain in operation, while

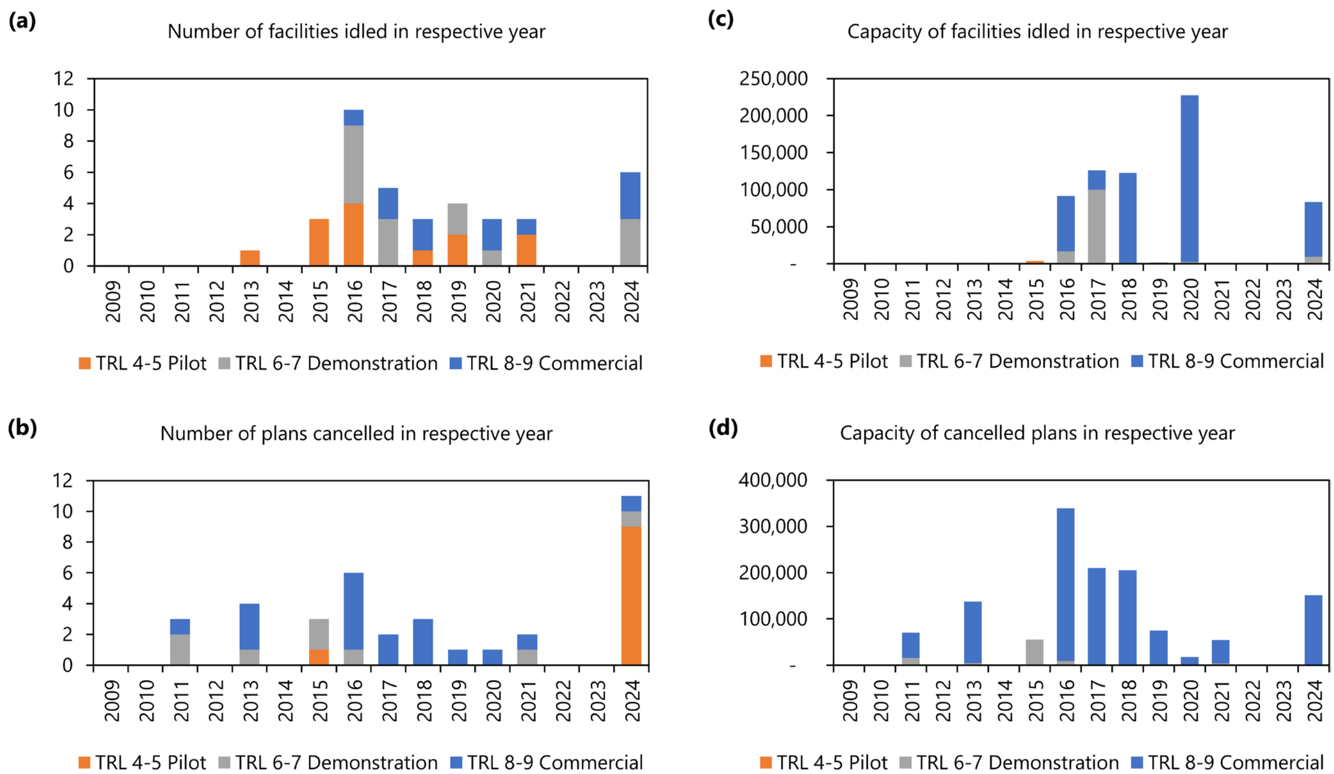

Figure 3. Compiled results from the database illustrating changes in project plans: (a) number of idled facilities per year, (b) number of canceled plans per year, (c) idled capacity per year (t yr^{-1}), (d) canceled capacity per year (t yr^{-1}).

the others have been idled. In the USA and Europe most large-scale facilities have been idled, except for those that operate on cellulosic sugars from cellulose production.

Regionally disaggregated results

Figure 4 disaggregates the global capacity development into different regions: the USA, Europe, Brazil, and China. It is striking how different the patterns of regional development are. In the USA, activity was high in the early 2010s, reaching a peak of almost 200 000 t yr^{-1} of operational capacity in 2015 and 2016 when the first large-scale facilities of Abengoa, POET-DSM, and DuPont came online. At that time, plans for further large-scale facilities were around twice the already installed capacity. However, as a result of idling the three largest facilities in 2016, 2018, and 2020, operational capacity in the USA dropped to around 12 000 t yr^{-1} in 2020 and plans for further facilities were canceled quickly.

Europe was home to the first movers, commissioning demonstration facilities with a capacity of about 5000 t yr^{-1} online as early as 2008 and 2009, in addition to the pre-existing ethanol production as a co-product of cellulose manufacture. Capacity expanded in 2013 with the addition of the Beta Renewables facility in Italy, reaching around 90 000 t yr^{-1} of total operational capacity in Europe. After the closure of Beta Renewables in 2018, capacity declined but rose again when the AustroCel Hallein and Clariant facilities became operational in 2020 and 2021, respectively. Total European capacity peaked at about 165 000 t yr^{-1} in 2022. Following the closure of Clariant's facility in 2024, capacity declined again, leaving mainly cellulosic sugar-based facilities in operation. Announced projects in Europe have totaled about 500 000 t yr^{-1} since 2021, but these have not yet materialized.

Early development in Brazil was probably not well captured by the database, but by 2014 three installations – operated by the Cane Technology Center, GranBio, and Raízen Energia – were already operational with a combined capacity of nearly 100 000 t yr^{-1}. No further projects were announced in the late 2010s until Raízen Energia began constructing its facility in Bonfim, which became operational in 2024 with a capacity of 62 000 t yr^{-1}. Raízen Energia has since completed two additional facilities of the same capacity, currently undergoing commissioning in Univalem and Barra. This replication builds on a decade of research and development at Raízen's facility in Piracicaba, which was recently decommissioned. In all cases, the feedstock is sugarcane bagasse sourced directly from a first-generation ethanol plant.

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Table 1. List of large-scale second-generation ethanol facilities already implemented.

Company	City	Country	Capacity $t\,yr^{-1}$	Startup	Current status
Domsjoe Fabriker	Ornskoldsvik	Sweden	19 000	1940	Operational
Henan Tianguan Group	Zhenping	China	20 000	2009	Operational
Beta Renewables (Joint Venture of Mossi and Ghisolfi Chemtex Division with TPG)	Crescentino (VC)	Italy	40 000	2012	Idle since 2018
Longlive Bio-Technology Co. Ltd	Yucheng, Shandong	China	50 000	2012	Operational
INEOS Bio	Vero Beach	USA	24 000	2013	Idle since 2017
Versalis/Eni	Crescentino	Italy	25 000	2013	Operational
GranBio	Sao Miguel	Brazil	65 000	2014	Operational
Abengoa Bioenergy Biomass of Kansas, LLC	Hugoton	USA	75 000	2014	Idle since 2016
POET-DSM Advanced Biofuels	Emmetsburg	USA	75 000	2014	Idle since 2020
Jilin Fuel Alcohol	Jilin	China	80 000	2014	Operational
Raizen Energia	Costa Pinto, Piracicava	Brazil	31 767	2015	Idle since 2025
DuPont	Nevada, IA	USA	82 672	2016	Idle since 2018
SDIC Biotech Group and SDIC Bioenergy Hailun Co.	Hailun	China	30 000	2018	Operational
Inner Mongolia Lisheng Bio-refining Co. and Inner Mongolia Zhongneng Biotechnology Co.	Bayannaoer	China	150 000	2019	Likely idle since 2020
AustroCel Hallein	Hallein	Austria	30 000	2020	Operational
Yigao Bioenergy Co.	Cangzhou	China	25 000	2021	Operational
Clariant	Podari	Romania	50 000	2021	Idle since 2024
Indian Oil Corporation	Panipat	India	27 000	2022	Operational
Raizen Energia	Guariba	Brazil	62 000	2024	Operational

Unlike in the other regions, developments in China are difficult to track. The IEA Bioenergy Task 39 network has, however, proven valuable in filling this gap by providing data on facilities from 2013 onwards. Based on available information, China's operational capacity was about 65 000 t yr^{-1} in 2015, increased to 160 000 t yr^{-1} in 2016, and peaked at 340 000 t yr^{-1} in 2019. It remains unclear which feedstocks are being processed in these facilities.

We are aware of six large-scale facilities in China, most of which presumably are still operational (see Table 1). It is, however, uncertain whether the largest of these is currently operating and, if so, which feedstock it processes. We have therefore considered it idle in our analysis after a first year of operation in 2019. We are also aware of five ethanol production facilities, each with a capacity of 300 000 t yr^{-1}, but it is unlikely that plants of this scale process exclusively cellulosic feedstock; they have thus not been included in our calculations. Based on these assumptions, China's total operational capacity is about 230 000 t yr^{-1}, the highest among all regions.

Discussion

Although the number of operational cellulosic ethanol facilities worldwide (Fig. 2(a)) appears relatively stable, the total operational capacity has fluctuated significantly over the years (Fig. 2(d)), due to the idling of facilities in later years (Table 1 and Fig. 3). Disaggregating the data by region reveals markedly different regional trends (Fig. 4).

These regional differences are driven largely by the availability of suitable biomass (in terms of quality, yield, and overall production volume), the strength of regional regulatory frameworks, mechanisms to stimulate market demand, and financial support for the construction of pilot and demonstration plants.

In the USA, strong growth in the early 2010s was supported by the Integrated Biorefineries Program of the US Department of Energy's Bioenergy Technologies Office (BETO). Established in 2007, this program provides federal funding to a range of projects aimed at advancing American leadership in the global clean energy transition. Between

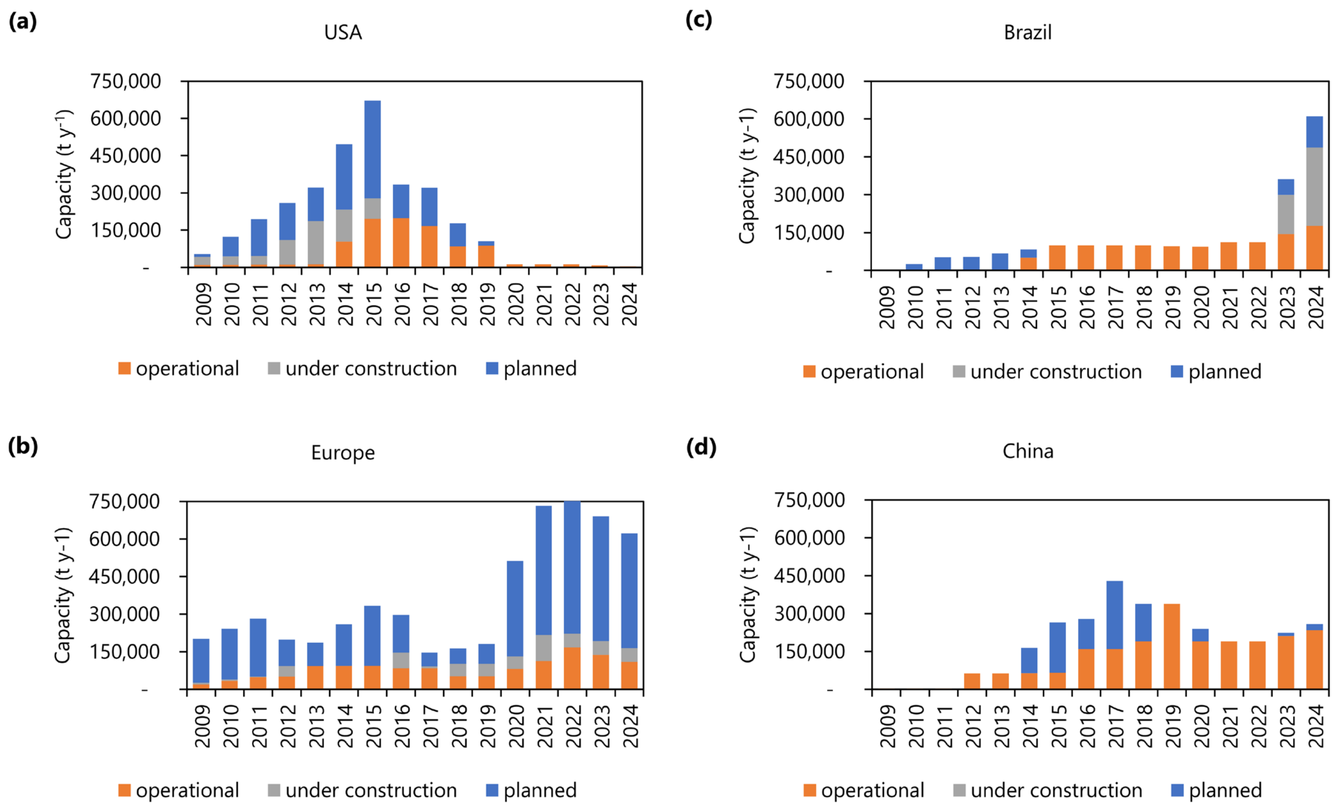

Figure 4. Results derived from the database showing project capacities in selected regions: (a) the USA, (b) Europe, (c) Brazil, and (d) China. Data for 2010, 2014, and 2023 were calculated as averages between the previous and the following years; these values are hatched in the figure.

2007 and 2009, 12 projects for ethanol production from lignocellulosic feedstocks via biochemical conversion received a total of USD 356 million in funding. Each funding year targeted a distinct technology readiness level (TRL): in 2007, three projects at TRL 8; in 2008, five projects at TRL 7; and in 2009, four projects at TRL 6. The two largest projects funded under this program were Abengoa's facility in Hugoton and POET's facility in Emmetsburg.[19]

Although the Integrated Biorefineries Program played a key role in advancing research, development, and demonstration of cellulosic ethanol production, the commercial viability of projects was supported through the Renewable Fuels Standard (RFS), which mandated a defined share of cellulosic biofuel production to increase over time. In 2015, 18 cellulosic ethanol facilities were operational in the USA (four at TRL8, eight at TRL 6–7, and six pilot facilities). However, as large-scale production failed to develop as anticipated, RFS mandates were repeatedly waived, reducing the obligation for fuel providers to purchase cellulosic biofuel and creating uncertainty for prospective producers.

In Europe, development was initially driven by the EU Biofuels Directive, published in 2003, which set a target of 5.75% of transport fuels from biofuels by 2010, and later reinforced by the Renewable Energy Directive, which mandated 10% of transport fuels from renewable sources by 2020. Following concerns over the sustainability of biofuels produced on agricultural land from food or feed crops, in 2015 the Indirect Land-Use Change (ILUC) Directive was published, capping production of biofuels from these crops while creating a subtarget for advanced biofuels, produced from a list of biomass residues and wastes.

The need for public funding for biofuel production facilities was recognized and addressed through the NER 300 program, which supported the demonstration of a wide range of technologies, including bioenergy. It was funded from the sale of 300 million emission allowances under the EU Emission Trading System. The first call for proposals was issued in 2011, and the second call in 2013. A total of 42 projects were selected for funding, 14 of which were in the bioenergy sector. However, due to the complex award process, payments contingent on production, and the rapidly declining oil price, most projects never reached the Final Investment Decision (FID). Of the 14 bioenergy projects, only two have actually become operational, one of them being Beta Renewables' facility in Crescentino, Italy.[20]

In Brazil, the development of ethanol from lignocellulosic biomass, particularly sugarcane bagasse and sugarcane straw, has been a strategic priority for companies and research institutes. This development aimed to increase land-use efficiency and leverage the existing infrastructure of the established first-generation (1G) ethanol industry as well as the availability of surplus biomass (bagasse) in these facilities. Funding programs such as the Business Plan for Agricultural Technological Innovation in the Sugar-Energy Sector (PAISS-Agrícola), created in 2014 by the Brazilian Development Bank (BDNES) and the Funding Authority for Studies and Projects (FINEP), provided financial support for research, development, and pilot to large-scale demonstration of 2G technologies. These efforts were complemented by fiscal incentives, credit lines, and partnerships involving universities, research centers, and industrial stakeholders.

In parallel with RenovaBio, launched in 2019 to establish decarbonization targets and provide a market-based mechanism for reducing carbon intensity via decarbonization credits (CBIOs), other international policy and regulatory frameworks have also supported interest in cellulosic ethanol in Brazil. For example, the Low Carbon Fuel Standard (LCFS) incentivized cellulosic ethanol through its reduction targets and the considerable potential of cellulosic ethanol to reduce greenhouse gas (GHG) emissions relative to US corn ethanol. Regulations by the Brazilian Agency for Oil, Gas, and Biofuels (ANP) also facilitated the registration and commercialization of cellulosic ethanol, while sectoral R&D initiatives coordinated by the Interuniversity Network for the Development of the Sugar-Energy Sector (RIDESA), the Brazilian Agricultural Research Corporation (EMBRAPA), and the Brazilian National Laboratory of Biorenewables (LBNR) continued to generate scientific knowledge and process innovations.

This combination of financial mechanisms, regulatory adaptation to stricter requirements, access to low-cost biomass feedstock, and alignment with international climate policy incentives has collectively sustained the development of cellulosic ethanol technology in Brazil. A decade of continued research and development at Raízen has enabled the fast replication of large-scale cellulosic ethanol production. Such production is integrated into existing, optimized sugarcane mills, where the efficient use of energy in first-generation ethanol and sugar production processes frees sugarcane bagasse for use as feedstock in cellulosic ethanol production.

In China, the principle of focusing ethanol production on nongrain feedstocks was introduced in 2006. In 2010, the COFCO group was given the task of establishing the National Energy Bio-Liquid Fuel R&D Center, and the 13th Five-Year Plan for Biomass Energy (published in 2016) emphasized the need to develop cellulosic ethanol. An implementation plan promoted the use of ethanol as a gasoline blending component, and attempted to bring about large-scale production of cellulosic ethanol by 2025. In 2021, several regulations were introduced with the aim of accelerating cellulosic ethanol production and related research.

More recently, the 14th Five-Year Plan on Renewable Energy Development and Modern Energy Systems emphasized the development of cellulosic ethanol, and the National Energy Administration's guidance on energy work advocated support for fundamental research on core technologies and pilot demonstrations for producing cellulosic or other nonfood ethanol. It is unclear whether all facilities depicted in our database produce ethanol from lignocellulosic feedstock but it is clear that China's ethanol production has expanded rapidly over the past decade, with a strong focus on nonfood feedstocks.

In addition to differences in regulations and public funding, climate conditions influence the choice of raw materials and technologies. In temperate regions, such as in large parts of the USA and Europe, feedstocks have focused on residues from agricultural crops, including wheat straw, other cereal straws, and corn cobs. This biomass must be collected from the fields with special agricultural machinery and delivered to the facility separately. The process often carries soil particles together with the biomass, which can increase equipment wear at large scale, a challenge already compounded by the handling of solid biomass.

In the case of Brazil, the primary feedstock for operating second-generation ethanol plants is sugarcane bagasse, which is available at the gate of first-generation ethanol facilities. However, since the phasing out of sugarcane straw burning in Brazil in the last decade (a practice still used in some countries, including sugarcane plantations in Florida, USA), researchers, industry, and cane producers have explored methods to recover sugarcane straw from the field. For instance, in 2020, the Brazilian National Laboratory of Biorenewables published a report that included guidelines for straw recovery from the field based on large-scale tests spanning agricultural systems to industrial processing, with a primary focus on using the biomass for cogeneration of heat and power in biomass boilers.[21]

Despite significant progress in enzyme engineering, production, and recycling, enzymes remain one of the largest operating costs in cellulosic ethanol plants. Their economic efficiency is constrained by inhibition, limited access to biomass fibers, and the need for energy-intensive pretreatment steps to enhance digestibility, all of which contribute significantly to process costs. The sugars released during biomass hydrolysis are not limited to ethanol production. These sugars can serve as feedstocks for higher value-added biobased chemicals such as organic acids, monomers for the polymer industry, and specialty chemicals. Diversifying the product portfolio in this way has the potential to improve the profitability of lignocellulosic biorefineries, as many of these biochemicals have higher market prices than ethanol. Such a strategy may also be necessary to offset development costs and support the advancement of new technologies.

Another technological option in temperate climates is to produce ethanol as a byproduct of specialty cellulose production. In this case, pretreatment is already integrated into the main process and ethanol can be recovered from the resulting brown liquor. This reduces ethanol production costs, although the process conditions are determined by the requirements of the primary products (pulp and paper), not ethanol. The cellulose production process also demands energy, and the black/brown liquor byproducts are a renewable energy source for the process. Internal competition for this stream could therefore limit the potential output of second-generation ethanol.

Outlook and conclusions

Until 2015, cellulosic ethanol production showed positive momentum, and second-generation biofuels such as cellulosic ethanol were considered to be approaching commercialization. However, the sector subsequently faced setbacks, including project cancellations, unmet capacity targets, and the closure of key plants.

Progress in cellulosic ethanol development remains slow because of technological and logistical barriers, high costs, and weak market performance. Political uncertainty, cheaper competing biofuels, and the setbacks of major projects have also diminished confidence among investors.

In recent years, however, promising developments and growing production capacity have emerged, particularly in rapidly developing economies such as Brazil and China. As can be seen from the development in the four regions considered here, a mix of measures is required to drive success: a regulatory environment that creates the market and offsets higher fuel production costs; strong and continued support for technological research and development; and public support to fund first-of-a-kind, large scale facilities. Currently, Brazil seems to lead in large-scale cellulosic ethanol production, likely due to the advantageous integration of cellulosic ethanol production from sugarcane bagasse with existing sugar and first-generation ethanol production.

Acknowledgements

The database is operated and financed within the framework of the International Energy Agency (IEA) Bioenergy Task 39 – Biofuels to Decarbonize Transport. The work of GMS and JFLS was supported by The São Paulo Research Foundation (FAPESP) through its Bioenergy Research Program (BIOEN FAPESP; grants #2018/16098-3, #2022/07946-6, and #2022/14692-0) and the IEA Bioenergy Technology Collaboration Program (Task 39). The work of DB and AS was supported by the IEA Bioenergy Technology Collaboration Program (Task 39).

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