biofuelwatch

Dead End Road

The false promises of cellulosic biofuels



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Dead End Road: The false promises of cellulosic biofuels
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Executive Summary

Although the world's first commercial wood to ethanol plant opened in South Carolina one hundred and eight years ago, more than 99% of biofuels worldwide are still made from plant oils, animal fats and sugars in starch (mainly from cereals, including corn), and not from wood. Despite massive subsidies and other state support measures, the most abundant sources of sugar and energy in plants, found in the cell walls of plants, remain beyond the reach of fuel refiners.

This report looks at the history, the technologies and the experience of refineries where cellulosic ethanol production has been attempted. The technical challenges remain, suggesting that there is little likelihood that large new markets for wood and energy crops for biofuels will emerge any time soon. The illusion that cellulosic biofuel production has dramatically increased recently reflects a redefinition of "cellulosic" to include transport fuels made from landfill gas, biogas and corn kernel fibre. Even though large-scale production of cellulosic biofuels appears destined to fail, the development of risky genetically engineered (GE) trees, crops and microbes associated with this quest introduces imminent and serious risks.

Political context

First generation biofuels (those made from corn and other cereals, sugar and plant oils) have proven highly problematic. To date, they replace less than 3% of transportation fossil fuel use, but have already caused the displacement of peoples and communities, resulted in competition with food production which has exacerbated hunger, and biodiverse ecosystems have been lost. Furthermore, when full lifecycle accounting is undertaken, first generation biofuels are often worse for the climate than the oil-based fossil fuels they replace.

Cellulosic biofuels (liquid transportation fuels produced from wood, grasses or agricultural residues), have been touted as a solution to the problems of first generation biofuels, since they would be produced using "nonfood" feedstocks. Yet crops or trees grown for cellulosic biofuels would also require a very large land area, and hence compete with food production, and the energy and climate impacts remain questionable.

Subsidies and supports in the US and Europe

Policy supports and subsidies for the production of cellulosic biofuels abound. In the USA, the Renewable Fuel Standard and California Low Carbon Fuel Standard, and grants and loan guarantees from the US Department of Energy, Agriculture and Defense, all support cellulosic fuels. In Europe, incentives within the Renewable Energy Directive support cellulosic and other biofuels, along with supports under Research and Development programmes. Support has also come from individual states, yet none of this has led to any significant commercial breakthrough.

Cellulosic biofuel failures: is history repeating itself?

The first commercial-scale cellulosic ethanol refineries were built by Standard Alcohol and Classen Chemical Co. in the early 20th century, with one account claiming that production of up to 2.5 million gallons per year was achieved and another citing a far lower production rate. Differing claims made at the time about the production figures, or circumstances and timing of the closure of the facilities, makes it impossible to assess how much was produced and what yields were achieved. All that is certain is that the refineries shut down within a few years. The early history of cellulosic ethanol seems to have been marked by hyperbolic claims, obfuscations, unmet expectations and investment losses. Which, as this report shows, was a foretaste of what was to come many decades later.

Cellulosic ethanol made by fermenting sugars

Ethanol is conventionally made by fermenting sugars found inside plant cells (sugar cane and sugar beet for example) or converting starches such as maize or wheat into sugars, and then fermenting them. But most of the sugars found in plant biomass are locked up in cell walls as complex carbohydrates: cellulose and hemicelluloses. It has long been possible to access some of the sugars in cellulose and ferment them into cellulosic ethanol. But doing so consistently and efficiently has been problematic. Accessing enough of the “cellulosic” sugars in order to ferment them is difficult because of the complex chemical structure of plant cell walls. Furthermore, cell walls contain different types of sugars and no species of microorganism has been found in nature that can ferment all of them into ethanol.

Cellulosic ethanol production usually involves three stages: first, biomass is pretreated in some manner to break it down (often using heat). The carbohydrates are then broken down into the constituent sugars (called hydrolysis). Today, this usually involves adding enzymes produced by GE microorganisms to access sugars. The final stage is fermentation, now commonly by GE yeast and bacteria.

As is the case with all cellulosic biofuel technologies, few details are published as to why refineries have shut down or failed to achieve full production. Such information is commonly withheld as commercial secrets. However, based on a limited number of statements by companies, together with information from scientific studies, key challenges can be discerned.

It appears that problems with the first stage, i.e. pre-treatment, have been responsible for most of the recent failures and difficulties associated with cellulosic ethanol refineries. But this does not mean that the challenges associated with the other stages have been overcome.

Is anybody producing any cellulosic ethanol at present?

Raízen in Brazil, which produces cellulosic ethanol from sugarcane bagasse, announced the production of 1.58 million gallons in 2016. Operating far below capacity, it appears to be the most successful refinery of its type to date. GranBio, also in Brazil, claims to have achieved some recent production, but it has not announced any details other than that the plant is not running at full capacity. Both plants use sugar cane bagasse as the feedstock, which is far easier to refine than wood.

A closer look at the six recently opened commercial-scale cellulosic ethanol plants which ferment sugars from biomass

Six facilities claim to have been “operational” since 2010. In spite of much hype at the time of commissioning, not a single one has been operating continuously at capacity with economically viable yields. These six plants are:

1) **Beta Renewables in Italy:** Closed 15 months after opening, with the company admitting technical difficulties and filing for bankruptcy in 2017;

2) **GranBio in Brazil:** Was to use the same technology as Beta Renewables, but 21 months after opening remained plagued with difficulties, had to replace the pretreatment facility altogether and hadn't released any production figures;

3) **Project Liberty in Iowa, USA (a joint venture between DSM and POET):** Opened in September 2014, admitted ongoing technical problems in November 2017, and has not pulished production figures since;

4) **Abengoa refinery in Kansas, USA:** Successful production was never achieved, and the plant was sold to a company with no cellulosic ethanol ambitions, due to Abengoa’s wider financial difficulties;

5) **DuPont refinery in Iowa, USA:** Opened in October 2015, but shut down in November 2017 without having produced any cellulosic ethanol;

6) **Raizen Energia refinery in Brazil:** As stated above, the only cellulosic ethanol refinery which has achieved regular production. However, early 20th century cellulosic ethanol plants may have achieved higher volumes from wood, a more challenging feedstock.

Cellulosic biofuels made by gasification

A second approach to making cellulosic biofuels involves gasification: exposing biomass to high temperatures and controlled oxygen delivery. This results in a gas (syngas) which must then be cleaned and further processed using either chemical catalysts (Fischer-Tropsch synthesis) or syngas fermentation. Most biomass gasification facilities worldwide have failed. Furthermore, cleaning of the syngas is especially challenging as it must be free of impurities for successful processing to fuel. Two refineries using gasification and syngas processing have been opened this decade: Indian River Bioenergy Center in Florida, USA, which has since closed, and Enerkem, in Alberta, Canada, which has produced limited quantities of methanol from waste, and no ethanol, despite being open for 6 years.

Cellulosic fuels made via pyrolysis and cracking

The third approach involves pyrolysis and "cracking". Pyrolysis refers to exposing biomass for a short time to high temperatures in the absence of oxygen, resulting in formation of "bio-oil". Bio-oil can – in theory – be processed into transport fuels through "cracking", as is achieved in oil refineries using heat and chemical catalysts. However, the energy balances associated with this approach are particularly bad and there are no credible proposals for improving them. One company, KiOR, opened a refinery based on this technology in 2006, and subsequently filed for bankruptcy and remains embroiled in legal action for fraud. In Canada, Ensyn has been producing bio-oil through pyrolysis since 2006 but, despite publicly speaking about upgrading it to transport fuels, has never done so (apart from minor experiments involving collaboration with oil refiners), nor has it invested in the technology that would be needed.

Legislating "cellulosic ethanol" into existence: corn kernel fibre ethanol and fuels from landfill gas

The Renewable Fuel Standard was enacted in the USA in 2007 and requires the addition of 16 million gallons of cellulosic fuels by 2022. Given that such fuels remain essentially nonexistent, the Environmental Protection Agency (EPA), responsible for implementation, responded by redefining the term "cellulosic biofuels" to include fuels made from biogas, landfill gas and corn kernel fiber. This allowed the EPA to claim that "cellulosic biofuel" production had risen from near zero to over 250 million gallons in 2017.

Ironically, while cellulosic fuels were touted as an alternative to using corn, thus avoiding competition with food production, the redefinition of corn kernel fibre ethanol as a cellulosic fuel means that most of the fuel defined as "cellulosic" is in fact now made from corn. Compared to other cellulosic ethanol production approaches, corn kernel fibre processing is relatively straightforward, but undermines the intent of the cellulosic mandate. Furthermore, an unknown proportion of the so-called "cellulosic" fuel from corn kernel fibre is likely to be nothing other than ordinary corn starch ethanol.

Cellulosic biofuels as a false pretext for developing GE trees

The desire to develop cellulosic biofuels is widely promoted as one of the key drivers behind the development of GE trees, including eucalyptus and poplar, among others. In particular, reducing lignin content would in theory enable better access to the sugars in cellulose. Producing healthy low-lignin GE trees remains elusive. In order to access public funding, biotech companies trying to develop such trees routinely cite cellulosic biofuels as their purpose, but there is strong evidence that cheaper pulp and paper production has been the primary motivation. GE trees involve serious but only partially known risks, because forest trees are long-lived, disperse through different methods and across large distances, and because their functions and interactions within ecosystems are not fully understood.

Manipulating microbes for cellulosic biofuels

Most cellulosic biofuel research and development involves genetically engineering microbes, mainly for enzyme production and fermentation. Yeasts, fungi and bacteria are subjected to very drastic manipulations to force them to adopt entirely different metabolic pathways and to synthesize and/or degrade molecules they would not normally be capable of. Risks from any deliberate or accidental release of GE microbes are especially worrisome given that bacteria and yeast reproduce, proliferate and evolve very rapidly, and can exchange genes with other species. Once released, they would be impossible to track, much less recall. Microbes are the basis for all life on earth and play a fundamental role in virtually all life processes. As this report shows, accidental releases of GE microbes from biofuel refineries are all but guaranteed.

Conclusions

Despite huge public subsidies, there is little evidence that commercial cellulosic biofuel production today is any more successful than the first, short-lived wood-to-ethanol refineries built more than a century ago. There is little public awareness of this, and little to no regulatory oversight or review. The taxpayer funds that continue to flow into research and development could be put to far better use, for example to improve public transportation systems. Furthermore, while it appears highly unlikely that cellulosic biofuels will ever become commercially viable, they are spurring the development of GE microbes, trees and crops, which introduces serious biosafety risks. Finally, the ongoing hype that cellulosic biofuels will "soon be available" and will alleviate competition with food production has only served to perpetuate the policies and supports that underpin problematic first generation biofuels.

1. Foreword

For more than a century, researchers and companies have been trying to turn wood and – more recently – grasses and agricultural residues into fuel for cars and trucks. Such fuels are called cellulosic biofuels. Over the past decade, there have been concerted efforts to develop cellulosic biofuels for aircraft, too.[a]

Nonetheless, 108 years after the world's first 'commercial' wood-to-ethanol plant opened in South Carolina, at least 99% of biofuels worldwide are still made from plant oils, animal fats and sugars contained in starch (mainly from cereals), sugar cane or sugar beet [1] - i.e. essentially from food. The most abundant sources of sugar and energy in plants remain beyond the reach of fuel refiners.

This report examines the reasons why hardly any cellulosic biofuels have ever been produced and why one cellulosic biofuel project after another has failed. It summarises all of the publicly available information on the ten commercial-scale cellulosic biofuel refineries worldwide that have been officially 'operational' any time since 2010.

It also shows that the reason for an apparent surge in US cellulosic biofuel production is a re-definition of the term in 2014, when a fraction of biofuels made from corn starch, as well as fuels made from landfill and biogas, were included in the definition in order to boost production figures.

Given the persistent failure of attempts to produce cellulosic biofuels at scale, there appears to be little prospect of a new market for wood and energy crops being created for transport biofuels – although the demand for wood for biomass heat and electricity is increasing steeply. However, the quest for cellulosic biofuels is being used to legitimise the development of genetically engineered (GE) trees as well as being a driver behind the development of GE microorganisms, both of which pose very serious risks to the environment and – in the case of GE microbes – possibly also to public health.

Scope of the report

The report focuses on cellulosic biofuels, i.e. made from plant materials other than sugar in sugar crops[b], oils and starch. Waste-to-liquid conversions involving municipal and industrial waste have been included even though fuels made from such waste (which is high in fossil-fuel derived plastics) are not biofuels. However, the technologies developed to turn non-biomass waste into transport fuels are identical to ones being developed for biofuels.

Excluded from the scope of the report is the conversion of biomass to biochemicals and fuel additives, including methanol. Only those biofuels which can be used in conventional cars and trucks are considered (even if they can only be used in limited quantities as is the case for all types of ethanol for example). Fuels made from landfill gas and biogas (anaerobic digestion of biomass) are not discussed in any detail. Such fuels can replace natural (i.e. fossil fuel) gas in engines made to run on compressed or liquefied natural gas.

The US Environmental Protection Agency's decision to classify them as cellulosic biofuels has been responsible for an apparent major expansion in cellulosic biofuel production worldwide – due not to any technological breakthrough but to a mere change in definitions.

[a] See Biofuelwatch's report on Aviation Biofuels for a detailed discussion about these: biofuelwatch.org.uk/2017/aviation-biofuels/
[b] The two main sugar crops are sugar cane and sugar beet. They contain high concentrations of sucrose and are widely used for ethanol production. However, their residues – especially the straw, or bagasse, from sugar cane, is classified as a cellulosic feedstock and conversion of sugarcane bagasse is therefore included in the scope of this report.

Why cellulosic rather than ‘advanced biofuels’?

Both terms are often used interchangeably. However, the term ‘advanced biofuels’ is much broader than ‘cellulosic biofuels’, and different governments and companies include different technologies within it.

In the US, under the Renewable Fuel Standard all biofuels other than corn ethanol, biodiesel and fuels classified as cellulosic are subsidised as ‘advanced biofuels’. Sugar cane ethanol, for example is treated as an advanced biofuel, even though it has been produced on a large scale, especially in Brazil, since the 1970s.

The EU includes not just biofuels from cellulosic feedstocks (except for saw logs and veneer logs) and algae, but also those made from wastes and residues using conventional technologies in its definition of ‘advanced biofuels’. [2] Biodiesel made from used cooking oil thus qualifies as an ‘advanced biofuel’.

Companies such as Neste Oil make biofuels from vegetable oils, especially palm oil and, to a smaller extent, from animal fats using a technology called hydrotreating and they refer to those as ‘advanced biofuels’. Such Hydrotreated Vegetable Oil (HVO) account for around 4% of global biofuel production in 2016 but is expanding at ten times the rate of biofuels overall. [3]

Finally, new types of biofuels are being researched and developed – such as biobutanol made from corn sugar or sugarcane – which are technically highly challenging, but which rely on the same feedstocks as conventional biodiesel. Those are clearly ‘advanced’ biofuels, but they are not cellulosic ones and thus not the subject of this report.

2. Political context

Evidence of serious harm caused by existing 'first generation' biofuels, i.e. those made from plant oils, cereals and sugar crops, has been increasing for many years. Such biofuels – together with biomass electricity – have the highest land footprint of any type of energy. The replacement of less than 3% of fossil fuels in transport with biofuels worldwide has therefore caused large-scale land conversions to plantations at the expense of forests and other biodiverse ecosystems, small farmers, Indigenous Peoples, pastoralists and other communities, driving land-grabbing, biodiversity destruction and worsening food price volatility worldwide. Studies show that the impacts on the climate are often even worse than those of the fossil fuel oil that is replaced. [4]

The biofuel industry and its political supporters have been able to justify ongoing renewable energy subsidies for biofuels, partly with the promise of cellulosic biofuels which would not compete with food (although energy crops and tree plantations would still compete for food with land), and which could even be made from agricultural residues.

In the US, both President Obama and his first Secretary of Energy, Steven Chu, explicitly described corn ethanol as 'transitional', i.e. a bridge to cellulosic biofuels. [5] In recent years, the corn ethanol industry and its advocates in government have argued in favour of ongoing subsidies for conventional corn starch ethanol, on the grounds that the companies producing it also support and often invest in cellulosic biofuel developments (though, as shown below, with no commercial success). [6]

In the EU, biofuel industry associations lobbied against any cap on support for crop-based, first generation biofuels, threatening to withdraw support for advanced (including cellulosic) biofuels otherwise: "*With a grounded RED II, we would continue to invest, including in exactly the advanced biofuels that everyone is hoping will flourish and become viable in coming years. With a bad policy — we will not invest*". [7] Industry lobbying has paid off: The EU has now decided not to exclude crop based biofuels from renewable energy subsidies until 2030. [8]

Subsidies for cellulosic biofuels in the US

In the US, the biggest subsidy scheme[c] for biofuel use is the Renewable Fuel Standard, which was enacted under the Bush Administration in 2005 and amended in 2007. It requires 36 billion gallons of biofuels to be used in the US by 2022. Of those, a maximum of 15 billion gallons can come from corn starch ethanol, and at least 16 billion gallons must come from cellulosic biofuels that are deemed to reduce greenhouse gas emissions by 60% compared to fossil fuel alternatives. However, even with corn kernel fibre ethanol and landfill and biogas-derived fuels included in the definition, it will not be possible to meet the cellulosic biofuel target. Year after year, the EPA has been using its "waiver authority" to downsize the volume requirement for cellulosic fuel, and to offer "cellulosic waiver credits". Another subsidy scheme that seeks to promote cellulosic biofuels through higher subsidy rates is the California Low Carbon Fuel Standard. Yet another scheme is the producer tax credit which provides $1.01 per gallon tax credit for cellulosic biofuels.

Although not enough cellulosic biofuels have been produced for anyone to profit from those biofuel support schemes, companies have cashed in on billions of dollars in grants, tax credits and loan guarantees (including for loans subsequently defaulted on), awarded by various federal agencies (especially the Department of Energy and US Department of Agriculture) for research and development and for building commercial-scale plants (many of them now closed). The main recent mechanisms have been:

[c] Note that the term subsidy is used in line with the Global Subsidies Initiative definition to encompass blending mandates which drive up market clearing prices and guarantee the competitiveness of biofuels: iisd.org/gsi/sites/default/files/bf_stateplay_2012.pdf.

- the 2009 American Recovery and Reinvestment Act, which earmarked $480 million for "Demonstrations of Integrated Biorefinery Operations", and $800 million for bioenergy overall; [9]
- the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program, which makes available $250 million of loan guarantees for "the development, construction, and retrofitting of new and emerging technologies for advanced biofuels, renewable chemicals and bio-based products" from 2014-18; [10]
- the Biomass Research and Development Initiative was awarded $9 million in 2017 alone, for "(A) feedstocks development, (B) biofuels and biobased products development, and (C) biofuels development analysis"; [11]
- the DOE's Bioenergy Technology Office, which was given $397.5 million from 2013-15 alone for Research and Development of advanced biofuels; [12]
- support by the DOE's Office of Science for research related to advanced biofuels at three bioenergy research centres. ($424.1 million for 2013-15);
- the Defense Production Act which awarded $210 million to three refineries in 2014. [13] One was to convert Municipal Solid Waste to fuels, the other was to make biofuels from wood. Neither are under construction so far, although construction of the wood-to-biofuel refinery, by Red Rock Biofuels, may be imminent.

The bonanza for cellulosic biofuel developers did not end with Trump's election. In September 2017, Secretary of Energy Rick Perry selected 8 integrated biofuel refinery projects for an award of $15 million. [14] In May 2018, Perry announced $78 million for "early-stage bioenergy research and development" including cellulosic biofuels. $40 million of those are earmarked for genetic engineering of microorganisms for biofuels and biochemicals. [15]

Subsidies for cellulosic biofuels in the EU

EU-wide, cellulosic biofuel research and development have been supported under the 7th Framework Programme, including through Horizon 2020, which is the EU's Research and Innovation Programme. Project support for biofuels and liquid fuels from waste includes €5 million EU funds for the Brazil-EU Cooperation for Development of Advanced Lignocellulosic Biofuels, [16] almost €6 million for "*the transformation of bio-liquids from fast pyrolysis and hydrothermal liquefaction into advanced biofuels*", €10 million for "development of next-generation biofuel technologies", €4.6 million for biobutanol from wood and wastes, €5 million for "Compact Gasification and Synthesis process for Transport Fuels", and many more. Cellulosic biofuel research and development has also been supported under the European Commission's NER300 programme. Individual member states have been making grants available as well.

Beta Renewable's unsuccessful cellulosic biofuel refinery in Italy, for example, received €28.5 million in NER300 funding, €8.59 million under the 7^{th} Framework Programme, and undisclosed sums from the Italian Ministry for Economic Development. [17]

The proposed post-2020 Renewable Energy Directive that is expected to be finalised later in 2018 sets a binding mandate for 3.5% of transport fuels to come from advanced biofuels although those would include, for example, biodiesel from used cooking oil and tallow, as well as biofuel from feedstock which is controversially classified as a residue even though it is of high value to other industries (e.g. corn oil).

3. Cellulosic biofuel failures – Is history repeating itself?

For many years, chemists have produced sugar derived from wood cellulose with the aid, generally, of acids but, up until lately, no means had been discovered by which it could be produced on a commercial basis. It would, however, seem that a correct and cheap process has at last been discovered. (J.W. Ellis, 1910)

In 2012, shortly before INEOS's cellulosic ethanol refinery in Vero Beach opened, industry analyst Robert Rapier pointed out that "the first cellulosic ethanol plant is not about to open". [18] He stated: "*Actual production 100 years ago was up to about 2.5 million gallons of cellulosic ethanol per year. Planned production at the INEOS facility is 8 million gallons per year.*" As it turned out, INEOS's "commercial refinery" failed to produce much, if any, ethanol. The only concrete figure for cellulosic ethanol production by any plant is Raízen's from 2017, when the company produced 2.6 million gallons.[d] Could it really be true that refineries in the 1910s produced so much more? Or might these historic figures have been as inflated as many claims made about cellulosic ethanol in recent years? A look at records about the earliest cellulosic ethanol plants shows some interesting parallels with contemporary developments, albeit with two important differences: Firstly, genetic engineering had of course not been developed at the time, so the process relied on acid, heat, pressure and ordinary brewer's yeast (see below for the discussion of how cellulosic ethanol can be made). And secondly, we can find no evidence that the early plants attracted public subsidies.

Robert Rapier relied on an article published in 1945, [19] at a time of renewed interest in making ethanol from wood. It outlines the key early developments and describes in detail four (unsuccessful) pilot plants and three commercial-scale plants, two of them supposedly successful. The first of those larger plants was built by Standard Alcohol Corporation in Georgetown, South Carolina, in 1910. Another one, built by the same company, opened in Fullerton, Louisiana in 2016. Those two supposedly operated successfully for a number of years, whereas a third, built by the Classen Chemical Company in Port Hadlock, Washington State, failed to operate properly. All three relied on the same basic technology: a much simpler technology than what is used today, with much lower theoretical yields but, on the other hand, less different and complex systems and components that can fail. According to the authors of the 1945 article, each one produced 5-7 million gallons a day, i.e. a maximum of 2.5 million gallons a year. But the

Old Alcohol Plant, Port Hadlock, Washington State, from Images of America, JCHS.
Source: Port Townsend Jefferson Country Leader

[d] Figures for gallons refer to US liquid gallons.

article is strangely vague about the production figures and the circumstances and timing of the plants' closure. About the Fullerton plant, it says: "*The plant operated successfully under the management of F.W. Kressman until some time after WW1*". F.W. Kressman was a co-author of the article – surely, he must have known more.

A 1919 article, [20] written by, G.H. Tomlinson the first manager of the Georgetown plant and one of the technology developers, [21] paints quite a different picture. Tomlinson reported that the plant had been designed with a capacity of 2,000 gallons a day (not the 5-7,000 claimed later!) but, during 1910, it produced an average of just 675 gallons per day (around one third of its nameplate capacity), a far lower yield than what had been expected and achieved in small-scale experiments. After the plant was sold and became the DuPont Wood Alcohol and Dynamite Mill in 1911, [22] the new owners did not publish any further information except for a telegram in 1916, saying: "*Trust that those interested in ethyl alcohol from wood waste realise that the process is a great commercial success.*" Did they increase their yields and production spectacularly without telling anybody what they achieved? Or are there parallels with DuPont's optimistic promises in 2015, which were followed by a refusal to share any insights into the problems with their recent plant in Iowa, even though they did not deny the fact that it had failed.

The second plant, in Fullerton, produced an average of 715 gallons a day, according to G.H. Tomlinson – again a small fraction of the 5-7,000 gallons later claimed, and the yields varied from just 2 to 17 gallons per dry tonne of wood – far below what had been hoped for. Improvements were carried out, but the plant was closed and later re-opened under new management which also claimed success – but, it appears, failed to publish any data except that the above-mentioned 1945 article, co-authored by the second manager of the Fullerton plant, claimed that yields of 22 gallons per tonne were achieved. A photo from 1928 shows the remains of the plant, which had long been abandoned and gutted. [23]

Finally, there was the Alcohol Mill of Port Hadlock, in which local businessmen had invested large sums of money. One of them, Charles Adam, later wrote: "*We made fine alcohol out of sawdust and a fine cattle food, but something was wrong somewhere and this is the end for a time. You will get something out of your stock someday I hope*". Investors lost everything. Around a century later, public and private investors would once more lose everything they put into numerous cellulosic biofuel ventures.

In short, the early history of cellulosic ethanol seems to have been marked by hyperbolic claims, obfuscations, unmet expectations and investment losses. Which, as this report shows, was a foretaste of what was to come many decades later.

4. Cellulosic ethanol made by fermenting sugars

What is it?

Ethanol is an alcohol that is produced through the fermentation of sugars by microorganisms[e] – usually yeast. In 2016, ethanol accounted for 72% of all biofuels used in transport worldwide. [24] There are two main pathways for making ethanol:

One is to directly ferment sugar which plants (e.g. sugar cane and sugar beet) store inside their cells to provide them with energy. The other is to convert starch (e.g. in maize or wheat) to sugar which is then fermented.

By far the most sugars found in plants, however, are locked up in the cell walls, in carbohydrates called cellulose and hemicelluloses. Fermenting those sugars produces cellulosic ethanol, sometimes called ligno-cellulosic ethanol, because plant cell walls also contain lignin (which is not made up of sugars).

Plant cell walls consist of around 30-50% of cellulose. [25] Cellulose, like starch, is a carbohydrate that is made up of units of glucose (a sugar which can be easily fermented by yeast). But unlike starch, cellulose is far more difficult to break down so as to make the glucose molecules accessible. As a result, there are very few organisms which can digest it. Furthermore, the cellulose is closely intertwined with other types of molecules, especially hemicelluloses and lignin, and that makes the glucose in the cellulose even less accessible – a vital defence mechanism which plants have developed over hundreds of millions of years.

Hemicelluloses, which make up 15-35% of plant cell walls, are different carbohydrates which contain chains of a variety of sugars. Many of those sugars cannot be fermented by the same microorganisms that ferment sugars derived from cellulose, or for that matter from starch. Finally, lignin makes up 15-25% of the weight of cell walls and contains no sugars at all. Even worse for cellulosic ethanol developers, it is thought that lignin makes it more difficult for enzymes to render the sugar in the cellulose accessible. Furthermore, the products for degrading, i.e. breaking down lignin, are toxic to enzymes and yeast used in cellulosic ethanol production and thus make them less productive. [26]

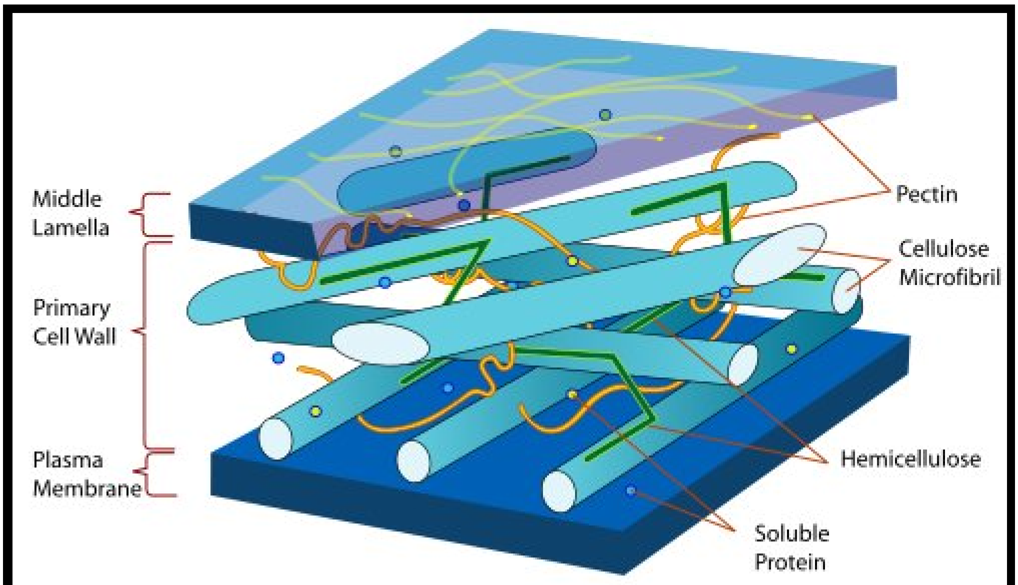


Diagram of a plant cell wall, By LadyofHats (Own work), via Wikimedia Commons

[e] Ethanol can also be made from crude oil products, but this is not relevant in the context of biofuels.

What are the challenges?

As discussed in the chapter about the history of the technology above, it has been possible to access and ferment some of the sugars found in the cell walls of plants for over a century, with cellulosic ethanol from wood having first been produced in commercial-scale refineries in the early years of the 20^{th} century. The challenge has been to produce cellulosic ethanol efficiently and smoothly (i.e. without needing to shut down and repair refineries too often). Efficient production means accessing and fermenting a large enough proportion of the sugars in the biomass and getting more energy out of the ethanol than is needed to produce it.

In the early 20th century, making cellulosic ethanol involved boiling biomass in an acid solution and under pressure, washing out the sugars and fermenting them using the same brewer's yeast still used in conventional ethanol refineries. The inherent problems were low yields (partly because unwanted byproducts of the process inhibited the yeast's ability to ferment sugars to ethanol) as well as acid corrosion (pushing up equipment costs). [27]

All of the recently opened commercial-scale refineries use a different approach: They rely on mixtures of enzymes, produced by genetically engineered microorganisms, to access the sugars, which are then fermented by genetically engineered yeast or bacteria.

Commercial secrecy around the cellulosic biofuel plants means that very little is known about the reasons why they have produced little, if any, ethanol. The few problems which have been reported in the media relate to:

- The need for the biomass to have just the right amount of consistency before the sugars in it can be accessed: Grit and sand mixed with, for example, straw, can stop the process from working. Feedstock such as straw needs to have just the right moisture content before its sugars can be accessed, and wetting appropriately and quickly is a major challenge.
- Corrosion of equipment, as experienced in the Raízen facility. This is surprising because one of the supposed advantages of enzyme-based technologies compared to the acid-based ones used in the early 20^{th} century, is that they should not cause corrosion. [28]

Difficulties with achieving high enough ethanol yields to justify the energy inputs and costs, have not been acknowledged by the refinery operators, yet they are widely reported in literature. These are partly due to the fact that a variety of harmful byproducts, as well as some of the sugars themselves inhibit the actions of the enzymes and the yeast needed to produce ethanol. [29] It is worth noting that Mascoma's technology (see text box), subsidised with up to $155 million, [30] was supposed to have overcome inherent problems with the existing cellulosic ethanol technologies leading to low yields and high costs.

According to one article published in 2011 (co-authored by the then CEO of Mascoma): "*the mechanism of enzymatic hydrolysis and the relationship between the substrate structure and function of various glycosyl hydrolase components is not well understood. Consequently, limited success has been realized in maximizing sugar yields at very low cost*".

Claims that those technologies are commercially proven are as premature now as they were back in 1910. Experience with the recently opened "commercial" cellulosic ethanol plants confirms this.

Is anybody producing any cellulosic ethanol at present?

In 2017, Raízen Energia, produced 10 million litres (2.6 million gallons)[f] of cellulosic ethanol in Brazil according to its co-owner Shell. [31] However, as discussed below, Raízen's cellulosic ethanol refinery has been operating at a small fraction of its capacity and yields have been much lower than they had hoped. The company has not so far disclosed its production figures for 2017.

GranBio claims to have recently started producing cellulosic ethanol, although well below the plant's capacity. We could find no publicly available production figures. POET-DSM may be producing small quantities of cellulosic ethanol in Iowa, although their annual losses from their refinery keep increasing.

Nonetheless, the US Environmental Protection Agency accredited[g] over 10 million gallons of cellulosic ethanol in 2017. [32] That is because the majority, if not all, of the accredited cellulosic ethanol is so-called corn kernel fibre ethanol. We discuss below why the definition of this as cellulosic ethanol is contentious and, we believe unjustified. By comparison, the US produced just under one billion gallons of ethanol from corn starch that year – a much more straightforward process.

A closer look at the six recently opened "commercial" cellulosic ethanol plants which ferment sugars from biomass

Since the start of this decade, seven commercial-scale ethanol refineries have been opened, six of which are based on fermentation of sugars (the seventh relies on gasification and is discussed in a separate chapter below):

- A refinery in Crescentino, Italy built by Beta Renewables, (a Joint Venture between Mossi & Ghisolfi Group, TPG Capital and Novozymes) which officially opened in October 2013 with a nameplate capacity of 20 million gallons a year;
- A refinery in São Miguel dos Campos, Alagoas, Brazil, owned by GranBio (subsidiary of Gran Investimentos SA) which officially opened in September 2014 with a nameplate capacity of 21 million gallons a year;
- "Project Liberty" in the state of Iowa, USA, owned by a Joint Venture between the Dutch company DSM and US ethanol producer POET: This was officially opened in September 2014 with a nameplate capacity of 20 million gallons and with the declared aim of scaling up to 25 million gallons a year;
- A refinery built by Abengoa in Hugoton in the state of Kansas, USA, with a nameplate capacity of 25 million gallons a year, which officially opened in October 2014;
- Raízen Energia's refinery in Piracicaba, Brazil, which was officially opened in October 2014 with an 11-million-gallons a year nameplate capacity;
- A refinery built by DuPont in Nevada in the state of Iowa, USA, which was officially opened in October 2015 with a nameplate capacity of 30 million gallons a year.

As shown below, four have now closed and none has so far been operated successfully (i.e. continuously and with economically viable yields).

[f] All figures for gallons in this report are for US rather than imperial gallons.
[g] By 'accredited' we refer to the award of Renewable Identification Numbers (RINs) under the US Renewable Fuel Standard.

Beta Renewables - Crescentino refinery, Vercelli region, Italy

The opening of the cellulosic ethanol refinery in Crescentino was hailed by the Danish company Novozymes, minority shareholders in Beta Renwables as "*the beginning of a new era*": "*Today we have a facility, it's there, it's producing, it's not a fantasy fuel*". [33] A promotional video featured a local farmer next to giant reeds (*Arundo donax*), a supposed feedstock for the plant, proclaiming: "*It's a great opportunity for agriculture to produce bioenergy*". The Editor in Chief of "Biofuels, Bioproducts and Biorefining" later reported that he had asked several farmers around Crescentino whom he knew as friends: "*The response of my friends was essentially this: 'are you completely out of your minds?' Farmers regard Arundo as a noxious weed. If the farmers planted Arundo they would not be able to plant anything else for a long time.*"

Arundo donax – the Crescentino refinery's feedstock that farmers weren't willing to grow, Photo: commons.wikimedia.org/wiki/File:Arundo_donax_CBMen_1.jpg

Nor was Beta Renewables anywhere close to being fully operational at the time Novozymes produced the video. In March 2016, a company spokesman declared: "*Crescentino is now operating at industrial scale and on a daily basis*" while admitting that it had taken 15 months to overcome hurdles and get the plant to operate steadily. [34] Yet that same month, a newspaper in Denmark reported that Novozymes had written down the value of the project to zero because the plant had consistently been producing far below its capacity due to its technical problems. Beta Renewables had to give up on using wheat straw (the original alternative to the giant reed farmers would not grow), because it contained too much sand and dirt for the equipment to handle. They had resorted to using virgin wood chips instead. Clearly, Novozymes was no longer expecting a breakthrough. [35]

In October 2017, the parent company of Beta Renewables and its sister company, Biochemtex, Gruppo Mossi Ghisolfi, together with its subsidiaries, was forced to file for bankruptcy in Italy and the US, having accumulated debts which it could no longer service. The cellulosic ethanol plant had been funded partly through subsidies – 37 million Euros from the European Commission and an unknown sum from the Italian government. [36] The ethanol plant had only been a small part of Gruppo Mossi Ghisolfi's failing portfolio. According to business analysts, the main causes of the bankruptcy application were delays and cost overruns related to the construction of a new plastics factory in Texas. [37] The ethanol plant was shut down, although a combined heat and power plant built to use residues from ethanol production continued to operate for several more months – burning woodchips made from virgin wood instead. [38] Although the Italian oil company Eni expressed interest in buying up the refinery, such a buy-out is considered unlikely at the time of writing this article. [39]

Following the closure of the Crescentino plant, a regional newspaper reported that, the refinery had been "*beset with technical problems and problems with biomass supplies*" throughout the entire period and produced only a small fraction of the ethanol it was designed to produce. On several occasions, farmers had complained about water pollution causing fish deaths, and at other times, the environmental protection agency had to intervene due to complaints about odour. [40] Recently, GranBio disclosed major failings of Beta Renewables' pretreatment system (see below).

Around the time the Crescentino plant was officially opened, projects using the company's pre-treatment technology involving GE microorganisms, called PROSEA were announced around the globe: In Alaska, North Carolina, Gujarat, Punjab, Malaysia, Fuyang (China), Slovakia and Brazil. [41] In Brazil, the technology was adopted by GranBio, but subsequently abandoned. In 2014, Biochemtex, a sister company of Beta Renewables, reportedly signed an agreement to build three more cellulosic plants with the Italian government. [42] None of the other projects have materialised, although the European Commission has approved a €21.6m grant for a refinery in Slovakia planned by a consortium called BIOSKOH, led by Biochemtex. Bizarrely, the consortium has continued to promote the venture without mentioning that the lead company is part of bankruptcy proceedings, nor that its pretreatment technology has failed elsewhere. [43] The plant proposed in North Carolina by Biochemtex had been awarded a loan guarantee from the US Department of Agriculture as well as a federal and state grant in 2012, yet construction never started.

GranBio – BioFlex1 plant in São Miguel dos Campos, Alagoas, Brazil

GranBio is a subsidiary of the Brazilian finance company GranInvestimentos, supported by the Brazilian development bank BNDES, which holds a 15% stake in the company. In September 2014, it officially opened the second refinery in the world equipped with BetaRenewables' PROSEA technology. Initially, GranBio claimed success, stating that 3 million litres of cellulosic ethanol had been produced by August 2015. [44] Yet in June 2017, 21 months after the plant was opened, the company admitted that it had still not succeeded in operating the plant successfully, due to "challenges with the pre-treatment technology", i.e. Beta Renewables' technology. [45] It has since transpired that the PROSEA technology involved a two-stage process, including steam explosion (high temperature and pressure followed by sudden decompression), during which severe corrosion occurred. Furthermore, the pre-treated bagasse formed a thick slush which became difficult to transport or drain and which clogged up the equipment, as well as corroding it. [46] A court case between GranBio and Mossi & Ghisolfi group is pending although the latter is embroiled in bankruptcy proceedings.

GranBio has now installed a new pretreatment system and has reportedly started producing and exporting ethanol from bagasse, albeit still well below the plant's capacity. Breaking down the sugars now takes up to 90 hours, instead of the 19 hours initially promised by Mossi & Ghisolfi Group. Reportedly, significant further investments are still needed. [47]

GranBio's business model has been predicated on growing "energy cane", a variety of (non-GMO) sugar cane which it has developed and which is high in fibre but

GranBio's cellulosic ethanol refinery, Photo: commons.wikimedia.org/wiki/File:Bioflex1.JPG, Marcusbcarmo contains less sugar juice, making it particularly suitable for cellulosic ethanol. [48] In October 2016, a sugar company called Grupo João Lyra announced that it would lease a sugar mill around 30km from the cellulosic ethanol plant, together with large areas of land which were previously used for sugar cane plantations. [49] Only - João Lyra was in no position to sign a lease, having been bankrupt for six years at that time. Social movements had previously negotiated an agreement with the Government of Alagoas, the Court of Justice and representatives of the bankrupt company under which, land around three sugar mills – including the one GranBio planned to lease – would be distributed under the state's land reform programme. In 2017, social movements, including the Landless Workers' Movement MST, launched an ongoing mobilisation for the lands to be distributed as agreed. [50] By December 2017, GranBio had finally given up its quest for the land, which had still not been freed for land reform. [51]

GranBio appears to not have been the best of neighbours, even if one leaves aside the fact it had tried to undermine a land reform agreement and grow its sugarcane on land that was supposed to be given to landless labourers. In December 2016, the company was fined by the Environment Institute of Alagoas for failing to prevent repeated fires of sugarcane bagasse bales stored in the open next to the refinery. A month later, a third major fire in just three months broke out. [52] Spontaneous ignition of bagasse bales is a known hazard, particularly when stored over lengthy periods. [53] Perhaps GranBio's problems with operating the refinery has made excessive storage periods inevitable and thus polluting fires more likely?

POET-DSM – Project Liberty in Emmetsburg, Iowa, US

POET-DSM's refinery was built with a $100 million grant from the US Department of Energy and $20m from the state of Iowa. [54]

Its Grand Opening took place on 3rd September 2014 in a packed hall, attended by the King of the Netherlands, the US Secretary of Agriculture and various politicians and company CEOs. [55] It was hosted by Fox News reporter Krista Voda who opened it with a homage to "*the soil that's about to change the energy landscape for the entire world*". POET's founder and CEO Jeff Broin declared: "*Some have called cellulosic ethanol a 'fantasy fuel,' but today it becomes a reality*".

By November 2017, POET issued a slightly more sobering statement, although this too, might turn out to be too optimistic about the schemes prospects:

"*Project LIBERTY is now running pretreatment at 80 percent uptime…With a newly installed pretreatment system, designed by POET engineers, POET-DSM is now able to direct its attention to fine-tuning downstream processes and prepare for future licensing efforts that will spread this technology around the world.*"

As of June 2018, POET has not declared its plant to be fully operational, but merely issued an obscure update, saying: "*We are bringing all levels up together now*". [56]

Problems at the plant first transpired in April 2017, when POET launched a law suit against Andritz Inc., the company which had delivered the pretreatment system. [57] POET had notified Andritz of the problem as early as 2014, but no solution had been found, and subsequently a different system was fitted.

This must have come as a surprise to observers, given that POET had announced a year earlier that commercial production had commenced and that "*the plant is ramping up to its full 20 million gallon-per-year capacity*" [58] – something which we now know would not have been possible at the time.

Pre-treatment, however, is only the first stage in cellulosic ethanol refining. Other stages, now being tested by POET-DSM, have been the cause of problems for other developers in the past.

One of the "attractions" of POET-DSM's technology was the onsite production of enzymes by DSM's genetically engineered microorganisms. This was to make the whole process more efficient and significantly lower production costs, whilst removing the need for antibiotics[h] to be used in the plant. [59]

[h] Antibiotics are widely used in ethanol refineries to kill acid-producing bacteria which interfere with the ability of yeast to ferment sugars to ethanol. Poet-DSM hope that producing their own enzymes onsite will allow them to prevent contamination with such bacteria.

POET-DSM's Project Liberty. Source: flickr.com/photos/usgao/31451302816

Yet, as of June 2018, the companies have not yet opened an onsite enzyme production plant. POET's and DSM's losses in respect of the plants were $26 million each in 2015, $48 million each in 2016, and $100 million each in 2017, according to DSM's Annual Reports.

Clearly, the plant's cellulosic ethanol is still not the "reality" that POET's CEO proclaimed back in 2014.

Even if all the problems could be overcome in future, the cost of ethanol production at the plant would still far exceed that of conventional corn ethanol. According to a peer-reviewed study published in 2016, the plant's capital costs per litre would be 5.3 times greater than that of a conventional corn ethanol refinery, even if the plant was operating at full capacity. Since then, capital costs – and with them production costs of the ethanol - have risen further because the pre-treatment technology has had to be replaced, and they will rise again as the enzyme production facility is built. [60]

Abengoa's cellulosic ethanol plant in Hugoton, Kansas, US

Abengoa, a Spanish energy company, celebrated the Grand Opening of its cellulosic ethanol plant in Hugoton in October 2014.

The US Energy Secretary, at the time, Ernest Monitz, lauded the supposed milestone: "*Every gallon of cellulosic ethanol produced and used to fuel our vehicles reduces the impact of harmful greenhouse gas emissions by greater than 60 percent as compared to conventional gasoline*". Abengoa's thanked the government: "*This would have been simply impossible without the establishment of the Renewable Fuel Standard*" [61] - though the plant would probably not have been built without a $97.5 million grant and a $132.4 million loan guarantee from the Department of Energy[i] either.

Far from reducing greenhouse gas emissions, the refinery never got close to producing enough ethanol to pay back the energy that went into building it.

In November 2015, Abengoa was forced to file for insolvency protection, having accumulated around €9 billion in debts which it could no longer service. What would have been Spain's largest ever bankruptcy was finally avoided with a restructuring programme, which included Abengoa selling off many of its assets. [62] Cuts to renewable energy subsidies in Spain (affecting Abengoa's solar power investments) as well as the company's business and financing model have been blamed for this near bankruptcy. In the US, Abengoa had to sell all of its ethanol refineries. Six of them were conventional ones, five of which appear to now be operated by other companies, with the sixth having been bought by a firm intent on producing biodiesel instead. [63]

In December 2016, the Hugoton plant, too, was sold – to a company called Synata Bio, which holds the assets of Coskata, a cellulosic biofuel company featured in Wired in 2008 with the headline: "*Startup Says It Can Make Ethanol for $1 a Gallon, and Without Corn*". [64] Coskata trialled its process, gasifying woodchips and using genetically engineered microbes to convert the resultant syngas to ethanol in a demonstration plant in Pennsylvania. It obtained a $250 million loan guarantee from the US Department of Energy to build a commercial plant in Alabama but gave up those plans in favour of trying to turn natural gas into ethanol. [65] Industry magazine BiofuelsDigest suggested that Synata Bio might want to convert the Hugoton plant from a biomass-to-ethanol to a natural gas-to-ethanol one. [66] So far, however, the plant remains idle.

[i] According to the US Department of Energy, guaranteed loan was repaid in full by Abengoa.

Can the closure of the Hugoton plant be blamed on Abengoa's financial problems alone? After all, almost all the corn ethanol refineries it had owned are still operating. When news about staff being laid off at Hugoton first emerged, Abengoa stated: "*the Hugoton, Kansas, plant has also been temporarily idled in order to implement various modifications and improvements.*" [67] In May 2015, i.e. four months before Abengoa's financial troubles emerged, its CEO conceded that the Hugoton plant was still not operating properly, stating:

"*We continue working in the startup of the plant...The bad news is that we still have our work to do to fix all identified challenges and the good news is that none of this is related to the biochemical process, which is the innovative part of the project.*" [68]

No further progress was announced between then and the plant's closure.

Abengoa's failure to operate the plant successfully does not explain its wider financial problems, but it likely explains why the refinery remains idle today, unlike most of Abengoa's former corn ethanol refineries.

Former Abengoa Hugoton refinery, Google Images, accessed March 2018

Raízen /Iogen – Costa Pinto project in Piracicaba, São Paulo State, Brazil

Raízen Energia was founded in 2010 as a joint venture between Shell and the Brazilian conglomerate COSAN. On its website, the company describes itself as "*the country's leading producer of sugarcane ethanol and the largest individual exporter of cane sugar in the international market, as well as being one of the main players in the distribution and sale of fuels in Brazil*". [69] In 2014, Raízen officially opened a cellulosic ethanol plant which is located next to a conventional sugar cane ethanol refinery and designed to use the sugar cane bagasse (i.e. residues).

There are several reasons as to why Raízen's should be the most likely to succeed of the cellulosic ethanol plants built so far:

According to cellulosic ethanol analyst and critic Robert Rapier, bagasse should be the most suitable feedstock for cellulosic ethanol, because "*it contains residual sugars, and it is washed, pulverised and already delivered to a factory*". Sugar mills generate far more bagasse than they can use to meet their own needs for heat and power. Since Raízen owns the adjacent sugar mill, too, one might assume that there would be no additional feedstock or transport costs – although the consultancy LuxResearch states that Raízen has to pay $38 per tonne of bagasse. Still, this is cheaper than the feedstock that other commercial-scale cellulosic ethanol refineries have used, or planned to use. [70]

What is more, the technology was supplied by a company with more years of experience in cellulosic ethanol production than any other in the world: Iogen Corporation. Iogen Corp started researching cellulosic ethanol technology in the late 1970s, and opened its first pilot plant in 1982. In 2002, Shell and Iogen Corp formed the Joint Venture Iogen Energy (now owned by Iogen Corp and Raízen), which opened a demonstration plant in Ottawa in 2004. According to Iogen, the plant regularly produced ethanol between 2007 and 2012. [71] Since then, it has been used for testing. [72] In 2012, Iogen announced that its ethanol production in Ottawa "*tops 2.1 million litres (561,000 gallons)*", though it is not clear whether this was produced over one or eight years. In 2013, the company's CEO admitted that Iogen has had to work "*through all sorts of bugs*", achieving continuous operations for months, rather than years. [73] But unlike several other companies investing in cellulosic biofuels, Iogen has taken years to try and make its process work rather than entering into one ultimately unsuccessful venture after another. Nonetheless, so far, Iogen has not achieved a single year of continuous operations, at any scale.

Back to Raízen's plant: 20 months after the plant was officially opened, Iogen Corporation's CEO admitted that it was still not properly operating. One problem was that the bagasse that arrived at the plant was not clean but full of sand and stones, another problem was corrosion: "*It really is a battle of 1,000 individual things*", he stated. [74]

In 2017, Raízen finally announced a success: the production of 7 million litres of cellulosic ethanol in 2016, [75] a figure it expected to double by the end of 2017. Thus, after more than a year, the company managed to operate the plant at 17% of its capacity. Have the figures improved since then? Contradictory answers have been published:

Satellite view of Raízen Energia's Costa Pinto plant, Image: Google Maps


Sugarcane bagasse. Photo: Thamizhpparithi

In March 2018, a Brazilian industry magazine reported that, during the past year, 7 million litres were produced, i.e. the same figure as in 2016. [76] In June 2018, another magazine cited a figure of 12 million litres. [77] Perhaps most credible is the figure published by Joint Venture partner Shell, which is 10 million litres. [78]

Even if the plant had operated at full capacity from the start, without requiring significant repairs and reconfiguration, the capital costs per litre would have been more than twice those of conventional sugar cane ethanol. Lux Research predicted in 2016 that the plant would be able to sell cellulosic ethanol more cheaply than any other – at $2.17 per gallon. By comparison, corn ethanol in the US is selling at or below $1.43 per gallon as of July 2018. [79] With the additional work and intermittent production, the production cost of Raízen's ethanol will be significantly higher than predicted.

While 10 million litres (2.6 million gallons) of cellulosic ethanol would be more than any other plant seems to have produced in any one year, the amount is negligible compared to the 30.4 billion litres of ethanol produced in Brazil in 2016. [80] Crucially, this means that the plant operated at just 25% of its capacity in the most recent year for which figures have been disclosed – far less than the 34% reported to have been achieved by the world's first ever cellulosic ethanol plant back in 1910.

Interestingly, Iogen's website suggests that the company is shifting at least part of its focus to upgrading biogas – especially landfill gas – to biofuels, a well-established technology which, as we discuss below, should not be classified as producing cellulosic biofuels. [81]

DuPont's refinery in Nevada, Iowa, US

Like Abengoa's Hugoton plant, DuPont's cellulosic ethanol refinery has unequivocally been a failure.

The plant was officially opened in October 2015, and was designed to convert corn stover to ethanol. Again, a Grand Opening ceremony was attended by dignitaries, celebrating the "*world's biggest cellulosic ethanol refinery*". [82] DuPont had received $14 million in grants and $3.54 million in tax credits from the State of Iowa. [83] The City of Nevada gave a further $600,000 to annex the land for DuPont, as well as providing tax increment financing. [84] And since 2000, the company had been paid $51 million by the US Department of Energy to develop the technology deployed in Nevada. [85] Six months later, it became obvious that the plant was not yet working: DuPont ran out of space to store corn stover being supplied by farmers who had signed supply contracts. A spokesperson admitted: *"We are off our original estimates for start-up. So we're off our schedule a little bit but we've been moving forward steadily all the time*", [86] expressing hope that the plant would produce cellulosic ethanol soon.

DuPont's cellulosic ethanol refinery in Nevada, Iowa, Photo: Scott McLeod, flickr.com/photos/mcleod/26824985630

The next major announcement, in November 2017, was that the plant would be closed and put up for sale. The immediate reason was a fundamental restructuring of the company which had merged with Dow Chemicals to become DowDuPont at the end of August 2017: the merged company will continue to invest in making and selling enzymes and genetically engineered yeast for cellulosic ethanol production, but no longer intends to produce any biofuels itself (although it retained its interests in Butamax, a company trying to develop bio-butanol). A company representative disclosed that, after two years, the Nevada refinery had not advanced to distillation – meaning that it had never produced a single drop of ethanol [87] - although the reasons behind this failure are not public knowledge. Unsurprisingly, nobody has come forward so far to purchase this failed plant.

Mascoma: Millions in public subsidies for failed ventures

As shown in a previous Biofuelwatch report (biofuelwatch.org.uk/2016/mascoma-report/), the former cellulosic ethanol company Mascoma obtained tens of millions of dollars in US and Canadian public subsidies for different refineries that were never built (apart from a small demonstration plant which never sold any ethanol). Instead of facing fraud or even bankruptcy proceedings, the company quietly changed its name to Enchi Corporation, after selling off its former name and most of its assets to a Canadian biotech firm called Lallemand.

Mascoma's technology was aimed at combining the two main stages in ethanol production from cellulosic sugars: hydrolysis (rendering the sugars accessible), and fermentation (converting the sugars to alcohol). The rationale was to overcome fundamental problems with all of the other cellulosic ethanol projects that have relied on sugar fermentation.

As detailed in our report on Mascoma, the company provides a potent case study about how both research into and funding for cellulosic biofuels have been coopted by business interests: the co-founder Mascoma, Lee Lynd, was able to exploit both his academic position at Dartmouth College and his position in the company to leverage large federal US grants. He obtained a position on the BioEnergy Science Center (BESC), set up and funded by the Department of Energy (DoE), which then awarded grants to Mascoma and which seems to have persuaded the DoE to do the same.

Unlike the commercial-scale refineries discussed in this report, Mascoma's were not ever built, and Lee Lynd had acknowledged in 2011 that the technology was nowhere close to being commercialised.

5. Cellulosic biofuels made via biomass gasification

What is it?

This is a completely different approach to producing cellulosic ethanol as well as other types of cellulosic biofuels to that described above. It involves three basic stages:

a) exposing biomass to high temperatures with a controlled oxygen stream or with steam (gasification);

b) cleaning the gas that results from the process, which primarily consists of carbon monoxide, hydrogen and carbon dioxide, called syngas;

c) converting the syngas to ethanol or another fuel, including to biofuels which have the same chemical properties as the petroleum fuels they are meant to replace ('drop-in biofuels').

Güssing biomass facility, where a biofuel trial involving wood gasification and Fischer-Tropsch conversions was carried out and subsequently abandoned, Photo: Gerfriedc

There are two fundamentally different pathways for (c), i.e. for converting clean syngas from biomass gasification to liquid fuels:

One is to convert the hydrogen and carbon monoxide in the syngas to hydrocarbons[j] using chemical catalysts. The oldest process for this was invented in the 1920s and is called Fischer-Tropsch synthesis which produces a fuel with the same properties as fossil fuel diesel.

The other pathway involves what is commonly called "syngas fermentation", i.e. using microorganisms, usually bacteria, to convert the carbon and hydrogen in the syngas to ethanol as well as acetic acid, or to other alcohols and organic acids. Strictly speaking, this biochemical pathway is different from fermentation.[k]

What are the challenges?

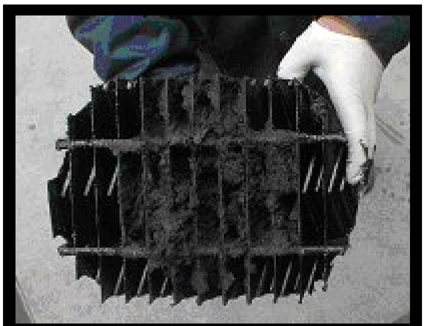
Both pathways depend on reliably operating a biomass gasifier and on cleaning the syngas to a high degree of purity. According to the final report about a European Commission-funded research and development project that focused on Fischer-Tropsch conversion (i.e. chemical catalysts), "purity of the syngas needs to meet ppb [parts per billion] concentrations". [88]

In theory, syngas does not have to be quite as pure for "syngas fermentation", but the Indian River BioEnergy Center plant in Florida nonetheless had to close down after impurities in the gas killed the bacteria needed to ferment it.

Biomass gasifiers are highly challenging to operate. Most of those built worldwide have failed, although some

[j] Hydrocarbons are compounds that contain only carbon and hydrogen atoms. Natural gas and fossil fuel oil are hydrocarbons.
[k] The pathway used by microorganisms for what is falsely described as 'syngas fermentation' relies on the Wood–Ljungdahl pathway, also called the reductive acetyl-coenzyme A (Acetyl-CoA) pathway. Fermentation, on the other hand, is defined as the reduction of sugar to carbon dioxide and alcohol.

have achieved successful operation, often after lengthy periods of adjustments and repairs, as we discussed in a previous Biofuelwatch report. [89] Challenges are far greater still where the feedstock is not homogenous, e.g. if mixed waste is used, as shown in reports by the UK Without Incineration Network [90] and by GAIA (Global Alliance for Incinerator Alternatives). [91] All of those reports focused on gasifiers that produce syngas for electricity generation, which should be much more straightforward because the syngas does not have to be as pure as is required for making biofuels. Even then, the presence of tars in syngas caused many projects to fail. Tars can clog up equipment ('fouling') as well as corrode it. When it comes to biofuel production, tars can also stop chemical catalysts used to convert the syngas from working.


Fouling of gasifier equipment caused by tars, Photo: Energy Research Centre of the Netherlands, https://www.ecn.nl/.

The need for extremely pure syngas appears to be the main obstacle to using chemical catalysts to convert biomass syngas to biofuels.

As far as "syngas fermentation" is concerned, one review lists problems that include the length of time needed for microorganisms to convert the syngas, and the fact that those organisms grow more slowly and are less productive compared to ones fermenting sugars to ethanol. [92] Another scientific article points out that nobody has ever demonstrated a method for achieving stable microbial cultures which maintain high levels of ethanol production, and that bacteria are highly sensitive to temperature, pH, gas composition, pressure, and the different media used to grow them, amongst other factors. [93]

Industry analyst Robert Rapier suggests that the bacteria's intolerance to ethanol may be the biggest problem faced by companies trying to convert carbon monoxide (whether in syngas or flue gases, e.g. from steel mills) to fuels. [94] If the bacteria can only withstand, say, 4% ethanol concentrations, then the amount of energy required for distilling – i.e. boiling off the water to obtain pure ethanol – will be far greater than for conventional ethanol refineries. Low ethanol concentrations thus stand in the way of profits.

As is the case with cellulosic ethanol from sugar fermentation, most of the companies invested in the technologies have been highly non-transparent and have failed to disclose their ethanol concentrations, as well the reasons why their plants have not operated successfully.

Is anybody producing cellulosic biofuel through processes involving biomass gasification?

Since the start of this decade, two commercial-scale biofuel refineries have been officially opened which rely – or were to rely - on biomass/waste gasification, followed by syngas conversion to biofuels:

- The Indian River BioEnergy Center refinery in Vero Beach, Florida built by **INEOS New Planet BioEnergy LLC**, a Joint Venture between INEOS subsidiary INEOS Bio and New Planet LLC. Commissioning started in 2012 and it had a nameplate capacity of 8 million gallons a year.
- A refinery opened by **Enerkem in Edmonton**, Alberta, Canada in 2014, with a nameplate capacity of 10 million gallons of ethanol a year. This plant uses Municipal Solid Waste (MSW) rather than biomass as its feedstock, however it is discussed in this report because the technology would be no different for biomass and, furthermore, Enerkem's demonstration plant, in Westbury, Quebec, was originally built with the intention of using waste wood. [95]

INEOS New Planet Bioenergy - Indian River BioEnergy Center, Vero Beach, Florida

The Indian River BioEnergy Center was the first commercial-scale cellulosic ethanol refinery to open this decade. It was also the only cellulosic biofuel refinery opened this decade which was to rely on non-GE microorganisms.

The technology had been developed in a pilot plant developed by Bioengineering Resources Inc. in Fayetteville, Arkansas, opened in 2003 and acquired by INEOS in 2008. [96] The US Department of Energy awarded grants of $4.8 million for developing the technology and $50 million for building the plant. The US Department of Agriculture awarded an unconditional $75 million loan guarantee (of which $49 million were reportedly called up, i.e. paid by the government); [97] the state government gave a $2.5 million grant and the county awarded a further $1.2 million in tax breaks and job grants – all of which covered nearly the full $130 million construction costs. [98]

In July 2013, the plant's owners announced that they were "*now producing cellulosic ethanol at commercial scale*", with the first ethanol due to be supplied to customers the following month. [99] It soon became clear that all was not well.

According to investigations by the Florida newspaper TCPalm, [100] INEOS Bio released an update in December 2013, according to which modifications and upgrades would be required. In 2014, a biofuel company in nearby Indian town approached INEOS to try and buy 1,500 gallons of ethanol from them – but INEOS did not sell any, presumably because none was being produced. That same year, INEOS officially suspended operations to install scrubbers: moisture in the wood being gasified apparently led to syngas being contaminated with hydrogen cyanide or prussic acid. This was killing the bacteria needed to ferment the syngas with the ethanol. The scrubbers were installed by September, but in 2016, the company announced that it had given up on the plant and was seeking to sell it. A company called Alliance BioEnergy made an offer but withdrew it, complaining that INEOS Bio had failed to disclose a number of problems. It stated:

"*Engineers found that the equipment at the plant, which ceased most activity in 2014, was not in perfect shape and that those parts that are working are not ready to be permitted because of a lack of documentation of regulatory compliance. Some equipment that was supposed to be useful is not and there is missing paperwork on all the major components.*" [101]

According to Alliance BioEnergy, biomass delivered to the plant had been left behind and was rotting away.

The site has now been acquired by a company with quite different plans while the technology has reportedly been sold to a Chinese biofuel company, Jupen Bio. [102]

The then Agriculture Secretary, Tom Vilsack, visits the building site the Indian River BioEnergy Centre, 2011, USDS. Photo: Lance Cheung

Enerkem's Edmonton plant in Alberta

Enerkem started building its Edmonton refinery in August 2010, having promised Edmonton City Council to have it up and running by 2012 so that the city could meet its target of diverting 90% of residential waste from landfill. [103] In January 2018, the City Council published a damning audit report of its waste services: The biofuel plant was still not running, and not expected to do so before 2019. Meantime, the City's landfill diversion rate had dropped from 49.5% in 2013 to just 35.7% in 2016. [104] If Enerkem cannot get its process to work, it will have been an expensive failure for the City of Edmonton, which paid C$40 million for the waste treatment and sorting plant meant to supply the biofuel feedstock, and for Alberta Province, which gave a C$23.35 million grant. Already, the city (together with Enerkem) has ended up mired in court cases raised by unhappy suppliers and subcontractors. [105]

Officially, Enerkem's plant was opened in 2014. In March 2018, the company informed Biofuelwatch by email that 5 million litres (i.e. 1.3 million gallons) of methanol had been produced during 2016-17 and that the plant was "*in ramp up stage for ethanol production and will soon reach commercial-stage production*". [106] Perhaps, after a delay of nearly six years, commercial production by 2019 would pass as 'soon'.

As is the case for other cellulosic biofuel plants, nothing has been disclosed about the problems encountered by Enerkem.

Its technology consists of gasifying waste and then using chemical catalysts to first convert it to methanol and then from methanol to ethanol.

Converting syngas to methanol (not a fuel in itself)[l] is much cheaper and simpler than converting it to ethanol (presuming that chemical catalysts are used, as is the case with Enerkem). According to a 2011 presentation by the National Renewable Energy Laboratories (NREL) in the US, the capital cost for converting syngas to ethanol is almost double that of turning it into methanol. [107] But Enerkem has not just failed to produce any ethanol so far – it has only produced small amounts of methanol, equivalent to a mere 13% of the plant's supposed capacity. We can only assume that the company must have encountered serious problems which it has failed to disclose.

Those problems have not stopped Enerkem from confidently announcing similar new projects, in Quebec, China and the Netherlands. Remarkably in the City of Rotterdam, the province in which it is located, the regional development agency and the Dutch Government have all pledged support for such a venture: A Rotterdam refinery more than seven times the size of that in Alberta, albeit entirely for methanol production. [108] Just why they would risk repeating the so far disastrous experience by the City of Edmonton seems baffling.

[l] Methanol is used by the chemical industry and in the production of biodiesel. Some methanol may be used as a fuel additive, but it is highly corrosive and thus not suitable as a fuel (with the rare exception of specially designed engines). Almost all methanol worldwide is made from fossil fuel gas.

6. Cellulosic biofuels made via pyrolysis and cracking

What is it?

This is the final of the three pathways towards making cellulosic biofuels which companies have attempted at a commercial scale. It is a two-stage process:

The first stage is called pyrolysis. It involves exposing biomass to high temperatures for short periods in the absence of oxygen.[m] Under the right conditions, this converts most of the biomass into oil – called pyrolysis oil or bio-oil. Bio-oil is not suitable for cars, but it can be used for heating and possibly in heat and power plants. It is highly corrosive and therefore requires boilers and other equipment to be made of stainless steel. [109]

During the second stage, bio-oil is converted to biofuels, through cracking processes which are routinely used in oil refineries. Cracking involves vaporising fuels and then splitting the long molecules into more desirable ones, using heat and chemical catalysts. Hydrogen may also be used, in which case the process is called hydrocracking.

What are the challenges?

The first challenge is to operate a biomass pyrolysis facility continuously and efficiently. Pyrolysis converts at best around 70% of the biomass into bio-oil, with the rest ending up as syngas and char. [110] High efficiency requires all of those products to be used for energy. Pyrolysis for bio-oil production is a highly challenging and still experimental technology even in comparison to biomass gasification. We could only find two examples of companies operating such plants at present: One is Ensyn (see below), the other is Fortum in Finland, which runs a heat and power plant on bio-oil. [111]

The second challenge is to convert the bio-oil to transport fuels. The processes are broadly similar to ones widely used to refine crude oil petroleum into gasoline/petrol and other hydrocarbon products – but bio-oil is very different from petroleum.

Compared to petroleum oil, bio-oil contains a lot of oxygen and 15-30% water, both of which must be removed. Furthermore, it has just about half the calorific value, i.e. burning one gallon of bio-oil releases about half as much energy as burning a gallon of petroleum. Removing the water is difficult, because when bio-oil is heated, it quickly forms different, larger molecules. Also, a lot of the bio-oil is turned into unwanted char/coke and tar rather than biofuels. This makes the process highly inefficient and, furthermore, those particles stop the catalysts from working, meaning they must be replaced with a new catalyst, which is expensive. [112] Altogether, Ensyn reported that just 30% of the carbon in the bio-oil ended up in the biofuels. [113]

[m] Depending on the length of time biomass is exposed to high temperatures – and to the temperatures themselves – the process is called slow, fast or flash pyrolysis. Slow pyrolysis produces the lowest yields of bio-oil, so is not suitable for making cellulosic biofuels.

Is anybody producing cellulosic biofuel through processes involving biomass gasification?

In short, no. Two plants have opened since the start of this decade but neither of them has sold any biofuels, although Ensyn's plant is supplying unrefined bio-oil for heating. The two plants opened are/were:

- A 25-million-gallon a year refinery officially **opened by KiOR (a joint venture formed by Khosla Ventures and BIOeCON) in Columbus**, Mississippi in September 2012;
- A 3-million-gallon a year plant operated by **Ensyn in Renfrew, Ontario**, which was commissioned in 2006 for the production of speciality chemicals in 2006 and converted to bio-oil production for heating in 2014, despite having procured a grant for manufacturing transport biofuels.

KiOR's Columbus refinery in Mississippi

KiOR's refinery was completed in September 2012 and reportedly sold a first batch of ethanol in early 2013. The plant was shut down within a year, KiOR filed for bankruptcy in November, and Mississippi's Attorney General later described KiOR's venture as "*one of the largest frauds ever perpetrated on the State of Mississippi*". [114]

When KiOR filed for bankruptcy and became the subject of fraud suits, there were echoes of a previous fraud case perpetrated by Cello Energy in Bay Minette, Alabama. Cello Energy claimed to have produced biofuels from hay and other biomass, also using pyrolysis followed by refining. [115] It was exposed as a fraud after lab tests revealed that Cello had passed conventional fossil fuel diesel off as 'cellulosic biofuels'. Both companies had attracted investment from Khosla Ventures. [116]


KiOR's refinery in Columbus, Mississippi, which has now been demolished.

KiOR's case, however, was quite different: there is no doubt that this company tried very hard to make the technology work. The fraud charges relate to KiOR having misinformed investors and the State of Mississippi about its yields and production costs. Yet, as this report shows, failure to honestly report on yields, production costs and technical challenges – at least to the public - is widespread amongst cellulosic biofuel companies. Thanks to Freedom of Information requests associated with the fraud cases, more is known about KiOR's problems than about most other cellulosic ethanol ventures.

KiOR first built a pilot and then a demonstration plant, before progressing to the commercial-scale one in Columbus, Mississippi. The company obtained over $76 million from the state by the time it went bankrupt. [117] Court proceedings over those funds– which the state argues were granted as a result of fraudulent claims – were still ongoing as of July 2018. [118]

KiOR had told investors in 2011 that it had achieved a yield of 67 gallons per dry tonne of biomass, at a cost of $1.80 per gallon. The actual yield obtained in Columbus was just 22 gallons per dry tonne of wood, produced at such a high cost that it could never be viable. [119] KiOR had been granted the public loan on the basis that an oil company would refine the bio-oil to biofuels, yet none were prepared to do so. Instead, KiOR invested in adding the expensive refinery process itself, which further pushed up the costs.

According to a senior scientist working for KiOR at the time, the key reason for the low yields and high production cost was that the chemical catalysts needed for refining had to be constantly replaced because they were deactivated by metals which were already contained in the biomass, and which had been added during KiOR's pre-treatment. Catalysts were lost at ten times the expected rate.

At the ground-breaking ceremony in 2011, the Governor of Mississippi at the time, described KiORs process as "*almost like making gold out of straw*", [120] words which must have come back to haunt him.

Ironically, the yield achieved by KiOR was precisely the same as the yield reported for the cellulosic ethanol plant in Fullerton, Louisiana before 1920.

Ensyn's plant in Renfrew, Ontario

Ensyn's biomass pyrolysis plant should have no place in a discussion about transport biofuels: first opened in 2006, it sold just over 1.7 million gallons of bio-oil for heating in 2017, [121] for which it was receiving Renewable Fuel Standard subsidies for the latter. Ensyn's plant does not include any technology for upgrading bio-oil to biofuels that can be used in cars, and no agreement with any oil refinery to convert them either.[n]

Yet in 2014, Ensyn obtained a C$1.5 million grant from Ontario Province's Centre for Research and Innovation in the Bio-Economy for "increasing production capacity and making it a first-of-its-kind dedicated biofuels plant". [122] And in 2016, Ensyn announced that construction of a larger, 10.5 million-gallon a year refinery had commenced in Port-Quartier, Quebec, in which it holds a 50% stake. This venture has attracted C$59.18 million in public grants. [123] It was to start production in 2017, but this does not seem to have happened.

It remains to be seen whether Ensyn will continue to cash in on subsidies while producing low-grade bio-oil for heating, or go down a similar route as KiOR (as far as the technology is concerned) and waste 70% of the carbon in the bio-oil as char, coke and tar, [124] just to be able to call itself a 'cellulosic biofuel producer'.

[n] Trials have been carried out to test the upgrading of Ensyn's bio-oil in oil refineries, but these have not so far led to any commercial production or long-term refining agreement.

7. Legislating 'cellulosic ethanol' into existence: Corn kernel fibre ethanol and fuels from landfill gas

The Renewable Fuel Standard (RFS) enacted in 2007, requires a minimum of 16 billion gallons of cellulosic ethanol to be blended with gasoline by 2022. Starting in 2009, The US Environmental Protection Agency (EPA), responsible for administering the RFS, set ever increasing cellulosic biofuel targets, even though none was being produced. In 2013, the American Petroleum Institute took the EPA to court, complaining that its members should not be penalised for failing to buy a product which simply did not exist. [125] Clearly the EPA had to do something, and repealing the RFS cellulosic biofuel target for 2022 was not in its power. Nor could it prevent one cellulosic biofuel venture after another from failing.

This left the EPA with one easy – if temporary - solution: to change the definition of cellulosic ethanol so that it would include biofuels which companies could actually produce.

Thus, in 2014, they approved two new pathways for making 'cellulosic' biofuels, ones which bear little resemblance to attempts to turn wood, switchgrass or corn stover into fuels for cars. The newly defined 'cellulosic biofuels' are unlikely to provide the billions of gallons mandated under the Renewable Fuel Standard by 2022, but they have boosted production figures from virtually zero to over 250 million gallons in 2017. [126]

The first pathway consists of adapting corn ethanol refineries so as to produce additional ethanol from the thin hull and fibre which surrounds the starchy bulk of corn (maize) kernels. Corn kernels consist mainly of starch but contain 10-12% fibre, too. For corn ethanol refiners, this can have the added advantages of raising starch-based ethanol yields, as well as corn oil production (which can be processed to biodiesel), on top of the additional income from cellulosic ethanol RFS credits.

The second consists of upgrading landfill gas or biogas from manure or other residues to biomethane, which can replace Compressed Natural Gas (CNG) and Liquified Natural Gas (LNG) as transport fuels for cars and trucks that are designed to run on natural gas.[o] Anaerobic fermentation to make biogas, followed by upgrading to biomethane is a mature technology. However, driving cars adapted for natural gas with a mix of that and gas from landfill sites is hardly what cellulosic biofuel production was supposed to be about. And while, in the short term, capturing landfill gas and using it for energy might make sense, much of what goes into landfill waste is not renewable. Making renewable fuel targets dependent on perpetuating landfill (or, for that matter factory farms for large-scale manure) is hardly compatible with moving towards a lower-carbon, sustainable economy.

Corn kernel fibre ethanol

In the US, cellulosic ethanol has long been promoted as an alternative to corn ethanol. George Bush described it in his 2006 State of the Union speech (which paved the way for the large-scale subsidies for it) as fuel made from "*wood chips or stalks or switchgrass*", which would allow the US to scale up biofuel production while leaving enough corn for food. [127] President Obama and his first Secretary of Energy, Steven Chu, described corn ethanol as a "transitional technology" which would eventually be replaced by much more efficient cellulosic fuels from grasses, wood and waste which would end biofuel competition with food. [128]

[o] Biomethane can also be made from crops and grasses, but the US EPA only classifies biofuels made from biomethane derived from waste as 'cellulosic'.

It is highly ironic that nearly all the ethanol classified as 'cellulosic' is now made from the very corn kernels it was meant to replace.[p]

QCCP's plant in Galva, Photo: Tim Gallagher, Sioux City Journal file

So far, six corn ethanol refineries are receiving cellulosic ethanol subsidies under the Renewable Fuel Standard, on top of those they are getting for conventional corn ethanol.

The first refinery to add technology to make ethanol from corn kernel fibre was the **Quad County Corn Processors (QQCP)** corn ethanol refinery in Galva in the US state of Iowa. It has been receiving "cellulosic ethanol" RFS credits since October 2014. It was originally designed to produce 2 million additional gallons this way, however this capacity is expected to double during 2018. [129] In April 2018, the company stated that it had generated almost 40% of RFS cellulosic biofuel credits to-date. [130]

QQCP's process was developed in collaboration with Syngenta. After the conventional corn ethanol fermentation process, the leftovers ('whole stillage') are pre-treated and then fermented again. The two companies have disclosed very little information about their process, but a patent description suggests that it relies on grinding, soaking and heating the slurry under pressure. [131]

The Environment Protection Agency acknowledges that a proportion of the so-called cellulosic ethanol will in fact be from starch, not cellulose, but claims that this will be no more than 5%. [132] Yet according to an Associate Professor at the Department of Agricultural & Biological Engineering, University of Illinois, corn kernel fibre contains around 25% starch. [133] This means that a lot more of the 'cellulosic ethanol' could potentially be nothing other than conventional corn starch ethanol. The QQCP-Syngenta process relies on the use of a highly

Enogen corn

Enogen corn is engineered to incorporate an enzyme needed to break down the starch into sugars so that it can be fermented more cheaply. It was approved for commercial use by the US Department of Agriculture in 2011, against objections including from the North American Millers Association (NAMA) which represents 43 companies in North America. NAMA warned: "*If it should enter the food processing stream, the same function that benefits ethanol production will damage the quality of food products like breakfast cereals, snack foods, and battered products*" (namamillers.org/nama-disappointed-with-usda-decision-to-deregulate-3272-amylase-corn).

In 2017, Syngenta was ordered to pay $218 million to Kansas farmers over contamination of their corn with Enogen, and they reached a settlement for an undisclosed amount with around 22,000 Minnesota farmers who had raised a a similar lawsuit. Further trials are pending, with some 350,000 farmers claiming as much as $13 billion in losses (bloomberg.com/news/articles/2017-09-26/syngenta-settles-minnesota-corn-contamination-suit-in-trial).

[p] While corn kernel fibre ethanol is classed as 'cellulosic ethanol, upgraded landfill gas and biogas from waste are classified as different types of cellulosic biofuels'.

controversial GMO corn patented by Syngenta, called Enogen, which has been widely promoted to farmers growing corn for ethanol and which is not suitable for food.

Another process for making corn kernel fibre ethanol has been developed by EdenIQ and this is currently used in six corn ethanol plants, producing an estimated 550,000 gallons of ethanol classified as “cellulosic” per month between them. [134] There are plans to introduce the system in several more corn ethanol plants. Unlike QQCP-Syngenta, EdenIQ does not attempt to separate the fibre from the starch at all. Its technology consists of pre-treating all off the corn slurry and then adding cellulase enzymes.

Two other companies, D3Max and ICM, have been developing their own technologies, which are not yet used commercially, and DuPont has developed an enzyme mix specifically for this type of ethanol. [135]

Corn kernel fibre ethanol can boost the output of corn ethanol refineries by a few points, but significantly increase their profits: According to Aemetis, a company that had tried but failed to buy up EdenIQ, cellulosic ethanol attracts $3 per gallon more in subsidies than conventional corn ethanol. [136] Moreover, the technologies also boost corn starch ethanol and corn oil production and its main residue is a more valuable livestock feed than that from traditional ethanol refineries.

Compared to ethanol from genuinely cellulosic feedstocks (e.g. straw, switchgrass, wood), producing corn kernel fibre ethanol is very simple: there are no problems with dirt or sand in feedstock, the fibre contains far less lignin, and it takes far less enzymes to access the sugars in the cellulose. [137] Far from being a ‘stepping-stone’ [138] to genuinely cellulosic biofuels, it is first and foremost a lucrative earner for corn ethanol.

8. Cellulosic biofuels as a false pretext for developing genetically engineered trees

The desire to develop cellulosic biofuels is widely seen as one of the key drivers behind the development of genetically engineered (GE) trees in particular.

As the Center for Food Safety, a US-based non-profit organisation, wrote in 2013: "*Trees genetically engineered to reduce lignin content for easier breakdown of plant sugars and production into cellulosic ethanol are a major part of the biofuel strategy*". [139]

One of the world's leading tree biotech companies is ArborGen, which is based in South Carolina, USA. The company was founded by International Paper, MeadWestvaco (now WestRock) and Rubicon (based in NZ), initially with Monsanto, and it is now fully owned by Rubicon. ArborGen hopes to become the first company in the USA to be permitted to commercially sell GE eucalyptus trees. It has already been told by the US Department of Agriculture that it can grow GE loblolly pine trees without any permit at all, although the company claims to have no current plans of doing so [140] - a claim which must be viewed with some suspicion since ArborGen was ordered to pay workers $81 million after a US court upheld a claim that the company had used "*deception, misplaced trust and pressure tactics*". [141]

During the years that ArborGen was looking for permission for its GE eucalyptus field trials, the company presented itself as being strongly motivated by the quest to help commercialise cellulosic ethanol. In 2007, ArborGen became a partner in a $125 million bioenergy research centre funded by the US Department of Energy with the aim of developing advanced biofuels. [142] In 2008, it teamed up with the cellulosic biofuel company Range Fuels, growing trees next to its ill-fated refinery in Georgia. Range Fuels received a $43.6 million federal plus a $6.25 million state grant and a $40 million federal loan guarantee before closing the plant and filing for bankruptcy in 2011. [143] Its Vice-President told an international conference in 2008 that the company's "*targets are similar to those that have been defined by the U.S. Department of Energy and others for the long-term feasibility of renewable energy production from cellulosic biomass*" [144] and an ArborGen consultant told the Scientific American in 2010: "*If we're going to rely on biofuels as a significant part of a diverse portfolio of renewable technology, then harvesting trees is the best way to go*". [145]

Women members of MST, Brazil's Landless Workers Movement, occupy a tree nursery to destroy genetically engineered eucalyptus in Itapetinina, owned by Suzano Papel y Celulose, Photo: mst.org.br/2015/03/05/apos-ocupacao-na-suzano-outros-300-camponeses-ocupam-predio-da-ctnbio-em-bsb.html

Yet a closer look at the GE trees being developed by ArborGen and the information given by them and their parent company, Rubicon, in patent applications, suggest that cellulosic biofuels have never been a major motivation, contrary to media statements. The GE eucalyptus trial – and commercial release application – focus on freeze tolerance, i.e. on extending the climatic range in which eucalyptus can grow. They cannot help to overcome any of the barriers to cellulosic biofuel production. The one barrier that could conceivably be addressed through genetic engineering of trees and other plants would be the amount and structure of lignin in plant cells. As discussed above, lignin is believed to make it more difficult for enzymes to access and break down the sugars contained in plant cell walls, and some of the products into which lignin is degraded during the refining process are toxic to the enzymes and the microorganisms needed to make ethanol.

ArborGen and Rubicon have obtained a series of patents, several of which involve lignin modifications. [146] Yet the background information submitted with the patent applications consistently states that the potential benefits would be to reduce the costs, energy and amount of chemicals needed in pulp mills and to develop forage grasses that can be more easily digested by livestock. Fuel applications are mentioned just twice:

In a patent description for the development of a hybrid loblolly tree "*characterized by high rust resistance, uniform, rapid growth, stem straightness and moderate branch angle". [147] it is claimed that this provides "high biomass production for fiber or fuel use*". Unlike the other patents, this one does not relate to genetic engineering. Nor does it involve lignin reduction or modification, i.e. any of the challenges faced by cellulosic biofuel developers. The word 'fuel' might of course refer to burning the wood for heat or electricity, rather than conversion to biofuels.

Quite bizarrely, ArborGen claims in another patent description that a method intended to increase lignin concentrations would have an application in developing "*trees such as willow and fast growing aspen hybrids used for biofuels*". [148] This is clearly the opposite of what cellulosic ethanol companies would need.

The EU funded an "ENERGYPOPLAR" project with almost €3 million between 2008 and 2012. The stated aim was "*to unravel genetic mechanisms controlling growth yield and cell wall structure and composition, in order to design new SRC poplar tree cultivars with enhanced agronomical traits for industrial production of bioethanol*". [149] Ten public and private partners from six EU states were involved, and field trials with GE poplar were carried out in several countries. Developing low-lignin poplars for ethanol production was one of the key aims.

Yet it appears that no wood from any of the ENERGYPOPLAR trials was ever tested in a pilot or demonstration cellulosic ethanol plant, hence there is no way of knowing whether any of the GE poplars would in fact be easier to refine to biofuels than non-GE trees. In May 2018, the lead researcher in the GE poplar trials in Belgium, which formed part of this project replied to questions from Corporate Europe Observatory: *"Such basic research provides, among other things, knowledge to make paper production processes more environmentally friendly, and also to use trees for the production of other products such as polymers and cleaning agents."* [150] He failed to even mention biofuels as an objective.

Low-lignin trees might – in theory - benefit cellulosic biofuels and biochemicals as well as pulp mills, yet the reality is that trees cannot grow without sufficient lignin (i.e. with lignin rates much below those that can be obtained without genetic engineering): lignin is needed not just to stop them from breaking and toppling, but also for the efficient transport of water within trees and for resistance to pests and pathogens. Biotech companies and researchers are thus increasingly focussing on modifying rather than reducing lignin. Yet there is not even a consensus as to what type of modifications may or may not be useful for cellulosic ethanol refiners. Thus, a 2014 review states that modifying lignin in one direction[q] has been shown to boost the efficiency of cellulosic ethanol refining, and that the same modifications benefit paper production and forage production for cattle. [151] Yet a 2016 study based on a GE poplar trial concludes that a modification having the very opposite effect on lignin[r] boosts cellulosic ethanol yields. [152]

In the absence of a full understanding of the multiple biochemical barriers to cellulosic ethanol production, claims that they can be overcome by GE trees remain little more than hype.

[q] Increasing the amount of syringil compared to guaiacyl in lignin.
[r] Increasing the amount of guaiacyl compared to syringil in lignin.

Risks of GE trees

GE trees may not come to the aid of cellulosic biofuel producers, but the hype about cellulosic biofuels has helped to funnel millions of euros and dollars of public funds into GE tree developments.

The environmental risks from a release of GE trees go beyond risks associated with GMO crops – and credible risks assessment for specific GE tree releases are impossible to conduct. The reasons for this can be summarised as follows based on a 2008 report published by the Federation of German Scientists: [153]

- Forest trees are genetically highly diverse. Unlike agricultural crops which have been domesticated – i.e. purposefully bred – for centuries or even millennia, domestication of trees (except fruit trees) only started some 70 years ago, which means that trees developed for plantations are more able to spread and survive in nature than agricultural crops are. Furthermore, forest ecosystems and the interactions between different plant species – as well as those between trees and soil microorganisms and animals - are highly complex and poorly understood;

- Trees live much longer than agricultural crops. The full effects of genetic manipulations may not become apparent for years or decades, until trees have matured or have been exposed to stresses, such as extreme drought, flooding or pest attack. This is due to the fact that one gene can influence several different characteristics of an organism and that some of those may only become apparent over time or under stress. Furthermore, genetic engineering techniques are associated with unpredictable mutations and their effects, again, may not become apparent when young trees are first planted;

- Tree pollen has been shown to successfully disperse over distances of hundreds and even thousands of kilometres. Birds and other animals can help trees reproduce over large distances, not just by transporting pollen but also by transporting plant materials resulting in asexual reproduction (through cuttings or shoots). Furthermore, tree hybridisation, i.e. cross pollination between different tree species are common and would be a way for modified/new genetic material to be passed on with unpredictable results given that the same gene can behave differently in different organisms;

- Forests play a vital role in regulating the carbon cycle as well as hydrological cycles and genetically engineered trees could impact on both;

- Genetic engineering of sterility (to prevent GE plants from spreading) is unproven in all cases, but particularly impossible in trees, not least because they can spread asexually (through shoots/cuttings) across large areas. And if pollen and seed production could be stopped, it would disrupt food chains and thus harm biodiversity.

- There are particular concerns about GE trees with reduced or modified lignin: [154]

- Although several GE tree trials showed that reducing lignin content made trees less able to grow well and to survive stress, one experiment reportedly resulted in low-lignin FE aspen with enhanced growth, which could make it more invasive;

- Low lignin trees can speed up wood rotting in soils, thus increasing CO_2 emissions, affecting soil structure and soil fertility, and impact on [presumably reduce] soil carbon storage;

- Lignin modification can also impact on the degradation of wood by fungi, [155] i.e. on soil nutrients and carbon.

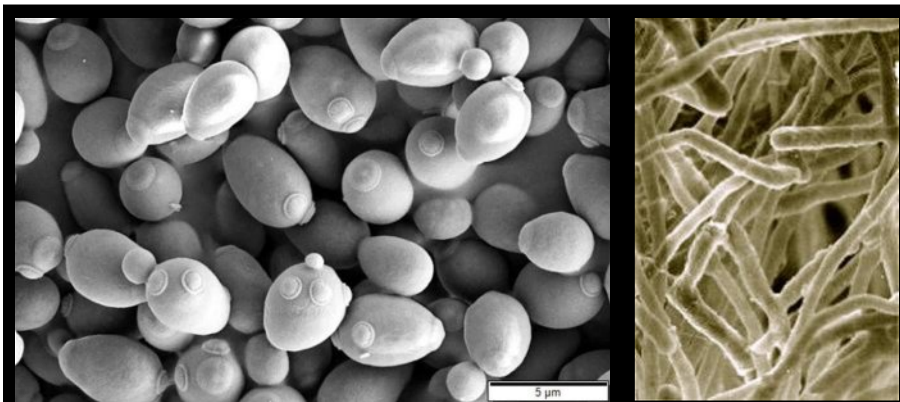
9. Manipulating microbes for cellulosic biofuels

Most cellulosic biofuel research and development involves genetically engineered microorganisms (GE microbes). All of the cellulosic ethanol refineries discussed above which did/do not involve gasification have relied both on a mix of enzymes made by GE fungi and also on GE yeast or bacteria for fermentation.

In cellulosic ethanol production, GE microbes are used both for enzyme production (to break down the constituents of biomass to make sugars accessible) and for fermentation of these sugars: They are engineered to survive in toxic environments, to break down and ferment sugars they could not naturally ferment, to produce more or different sorts of enzymes, etc. In cellulosic biofuel production involving gasification of biomass (or waste), GE microbes may be used to ferment the syngas.

Several other cellulosic biofuel pathways are being researched and developed but have not so far resulted in any credible attempts at building commercial-scale refineries, and some of those also involve GE microbes. Here are some examples:

- **Biobutanol** from ligno-cellulosic biomass is made using a similar process as cellulosic ethanol, but relies on a different microbial metabolic pathway to that used in cellulosic ethanol production. At least three companies – Gevo, Butalco (now owned by Lesaffre) and Butamax – have used metabolic engineering to design a strain of brewer's yeast[s] which is capable of efficiently fermenting sugar to biobutanol – rather than fermenting it to ethanol, which this yeast naturally does. The yeast has also been engineered to tolerate butanol concentrations higher than the 1-2% which kill non-GE brewer's yeast. [156] Gevo has never refined lignocellulosic biomass to isobutanol and the company is presently unable to regularly produce isobutanol even from corn starch. [157] Butamax and Lesaffre do not operate any biobutanol (pilot) facilities at present;[t]
- Research into producing **biopropane** (a potential replacement for LPG) involves metabolic engineering of E.Coli bacteria to synthesise propane, something no organism found in nature is capable of. [158] No lignocellulosic bio-propane plant of any size has ever been built,[u] however, in British Columbia, the City of Revelstoke, Revelstoke Community Forest Corporation and Downie Timber are investigating the feasibility of building such a plant; [159]



Brewer's yeast (Saccharomyces Cerevisiae) and the fungus Trichoderma reesei – two of the microorganisms most commonly used in genetic engineering for cellulosic biofuel production.

[s] Saccharomyces cerevisiae, the yeast commonly used in ethanol refineries. It has long been used to make bread, wine and beer.
[t] Lesaffre has no public biobutanol plans. Butamax Advaned Biofuel acquired a corn ethanol company and facility in 2017 and is in the process of adding capacity to produce isobutanol to this, however it is understood that the sole feedstock will be corn starch.
[u] Neste Oil has opened a bio-propane facility in Rotterdam, however this uses byproducts from Hydrotreated Vegetable Oil production, i.e. from vegetable oils including palm oil and animal fats, not lignocellulosic feedstock. It is not clear from Neste Oil's publications whether any GE microorganisms are involved.

- Research into metabolically engineering *E.Coli* bacteria to convert glucose, which could be derived from lignocellulosic ethanol, to **biodiesel (fatty acid ethyl esters)**. [160] This has not so far progressed beyond the laboratory.

GE microbes have been used in first generation ethanol production, especially corn ethanol production, for many years, with the aim of increasing process efficiency and yields. However, genetic engineering undertaken for cellulosic biofuel production often involves more complex and fundamental genetic manipulations – such as engineering microorganisms to adopt entirely different metabolic pathways and to synthesise or degrade molecules, some of which, in nature, are not synthesised or degraded to such products by microbes at all or only under very specific conditions (e.g. in the guts of termites). Such methods go far beyond the genetic manipulations used to develop GMO food crops for herbicide or insect resistance and they are widely referred to as synthetic biology and/or metabolic engineering.

No meaningful regulation

JBEI researcher genetically engineeering microbes to ferment complex sugars into advanced biofuels. Photo: Roy Kaltschmidt / Lawrence Berkeley National Laboratory via Flickr (CC BY-NC-ND)

All use of GE microorganisms inside industrial plants such as biofuel refineries is classified as 'contained use'. "Contained use" of genetically modified organisms (GMOs) is not subject to the same risk assessments and regulation as environmental releases. Thus, under the international Cartagena Protocol, international trade in GMOs intended for contained use is largely exempt from trade restrictions.[v] In the US, notification for the commercial production of microorganisms must be submitted to the Environmental Protection Agency (EPA), however, if GE microorganisms are intended to be used inside enzyme production plants or refineries, the EPA invariably exempts them from regulation. [161] GE microbes developed for research activities rather than commercial use are even exempt from any notification requirement (unless they are to be used in a field trial). In the EU, a directive on the Contained Use of Genetically Modified Micro-organisms requires member states to classify GE microorganisms according to the level of risk and thus required containment. GE microorganisms inside refineries and other industrial plants will not normally be subject to a full risk assessment. In the UK, for example, companies or research institutes do not even have to notify the authorities about GE microorganisms whose contained use they argue carries 'no or negligible risk', and organisms classified as being used with 'low risk' do not require any consent. The UK authority responsible for enforcing the regulations is the Health and Safety Executive which had its budget cut by 40% from 2011-17. [162]

[v] Article 6 of the Cartagena Protocol states that the Advance Informed Agreement procedure for international trade in GMOs does not apply to those intended for contained use, although individual states can regulate their trade through domestic laws.

The impossibility of containing GE microbes in biofuel refineries

Containment strategies – whether physical or biological - can reduce the risk of GE microorganisms escaping, but they cannot eliminate it. According to a 2015 report on Synthetic Biology published by the Secretariat of the Convention on Biological Diversity, "*there is no consensus regarding the degree of physical containment that is needed for organisms developed through synthetic biology*" [163] (as many GE microbes developed for cellulosic biofuels have been). Nonetheless, there is a great difference between trained microbiologists handling GE microbes inside a laboratory designed to high biosafety standards on the one hand, and refinery employees operating fermentation tanks filled with GE yeast or bacteria inside an industrial facility on the other. Unlike microbiologists working in laboratories, plant technicians and engineers will have the most rudimentary awareness of biosafety at best.

One example of a company that has developed GE microorganisms is Amyris. Amyris has been using GE yeast to make a product called farnesene from sugar cane. The company obtained a $24 million grant from the US Department of Energy (DOE) in 2009 for developing biofuels from farnesene, but it now exclusively makes high-value chemical products rather than fuels. In 2016, Amyris was given a further 3-year DOE grant to develop farnesene from cellulosic biomass. [164] By 2006, Amyris had reportedly inserted 13 different genes into brewer's yeast to make a yeast capable of fermenting sugar to farnesene, and by 2012, it was making and testing 400,000 different strains of GE yeasts per week, shipping the most promising ones from California to Brazil. [165] In 2012, the industry magazine Biofuel digest reported:

"*A friend of the Digest writes: "I was in Brazil last month and got an earful about that from a very high up there on [Amyris]. If their shiny high grade fermenter was not up to snuff they are really in trouble…having worked in nice university labs and clean room pharmaceuticals they did not know what was awaiting them in the down market dirty world of biofuel. You can't make biofuels with anything you got to keep that clean.*" [166]

Problems with microbial containment are well recognised by cellulosic (and other 'advanced') biofuel companies and investors, who acknowledge concerns about 'contamination'. A 2012 article in the investors' magazine Alt Energy Stock puts it thus:

"*What can these pesky contaminating microvarmints do? They can eat your highly-engineered magic bug. Or, sugar hogs, they can eat all the food. They can slow down your process. Or, they can have so many children that they crowd out everyone else. Or, they can poison the well with a waste by-product that dilutes your critical titers and yields. In the end, they can eat your company alive too, by causing companies to fall short of their scale-up production targets*". [167]

Surely, if microbes can get inside the supposedly sealed and secure fermentation vessels, then GE microbes can also get out of them. Biobutanol company Gevo acknowledges problems with and risks of microbial contamination in its annual reports. [168]

According to peer-reviewed articles, microbial contamination of ethanol fermentation vessels is commonplace and may not be possible to avoid entirely. [169] It is the reason why antibiotics are widely used in ethanol production for killing bacteria that compete with yeast in fermentation tanks, contributing to the growing global threat of antibiotic resistance. In a cellulosic or other 'advanced' biofuel refinery there is the added risk of GE yeast or bacteria escaping from the tanks.

Risks of GE microbes

There are several reasons why the risks of engineering microbes are particularly high:

- Bacteria and yeast are capable of exchanging genes with different species, and passing their own genes on to multicellular species, even to plants and animals. This is called horizontal gene transfer. Horizontal gene transfer between bacteria species is the key reason for the spread in antibiotic resistance, for example. There is evidence of horizontal gene transfer by fungi, too. [170] This makes it possible for both inserted genes and unintended gene mutations (which routinely occur in genetic engineering) to be passed on far more widely than in the case of GE plants;
- Due to their small size, escaped GE microorganisms are impossible to track and capture;
- Microorganisms evolve and proliferate far more rapidly than multicellular organisms;
- Microbial communities are the basis for all life on earth: they recycle nutrients and carbon and produce much of the oxygen in the atmosphere. Yet the great majority of microorganisms have not even been isolated/identified and their interactions and their role in ecosystems are, on the whole, very poorly understood.

10. Conclusion

Despite many decades of research and development, supported with billions of dollars in public finance, large-scale cellulosic biofuel production remains a distant prospect. In the US, 'cellulosic biofuels' have now been defined into existence by classifying more efficient ethanol production from corn kernels as being partly 'cellulosic' and by including biomethane production, mostly from landfill gas.

Only one genuine cellulosic biofuel refinery in the world appears to be regularly producing biofuels, albeit well below its capacity. That plant, located in Brazil, uses sugar cane bagasse as the feedstock which is far easier to refine than, say, wood. Very small-scale production may have started in a second Brazilian plant using the same feedstock and in a plant in Iowa which uses corn stover. However, no production figures have been published for those two plants, they are not fully operational yet and the annual reports published by one of the owners of the Iowa plant show how losses incurred from the plant are mounting year on year.

Regardless of this near-universal failure, governments, especially in the US, Canada and the EU, continue to support such developments through large grants and policy incentives. One of the main arguments put forward by researchers is that "*the future success of cellulosic biofuel may depend on the learning by doing effects*". [171] However, operators of cellulosic biofuel plants remain highly secretive about the problems they have encountered, and vital information, for example, about process yields are being withheld as business secrets. As long as the lessons from each attempt to commercialise cellulosic biofuels are being withheld, nothing can be learned from them.

The adverse impacts of cellulosic biofuel developments are fourfold:

1) An ongoing waste of relatively scarce public funds for 'clean energy' that are being diverted from genuine solutions to the climate crisis;

2) The false promise of cellulosic biofuels being used to legitimise continuing support for biofuels from cereals, sugar crops and plant oils, including palm oil, which are associated with increased forest and other ecosystem conversion to plantations, with increased land-grabbing and human rights abuses, with biodiversity loss, greater food price volatility and commonly even greater greenhouse gas emissions than the fossil fuels they replace;

3) They are being used to legitimise the development of GE trees which pose very serious but poorly researched and understood risks to forest ecosystems;

4) Cellulosic biofuel research and development is one of the main drivers of synthetic biology, including metabolic engineering of microorganisms. Industrial plants such as biofuel refineries are not equipped to safely contain GE microorganisms, yet the potential environmental and public health risks of their unintended release have been consistently ignored by regulators and researchers alike.

Cellulosic biofuels cannot help to achieve the aim of the Paris Climate Agreement to keep global warming to 1.5ºC and, instead, divert funding as well as attention from genuine solutions. The promise of what is a non-existent techno-fix continues to hide the urgent need to drastically transform transport systems worldwide. Such a transformation needs to include greatly reducing reliance on private car use through expanding public transport, supporting active travel and reducing the need to travel through planning policies. It would also need to include electrification based on genuinely low-carbon, renewable energy such as wind and solar power, in the context of a shift from private to public transport.

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