COMMENTARY

The grand challenge of cellulosic biofuels

Lee R Lynd

Why cellulosic biofuels have fallen short of expectations and what we can do about it.

A robust second-generation biofuels industry based on inedible cellulosic biomass available as wood, grass, and various wastes was widely expected to be in place by now. Anticipated benefits include climate change mitigation and rural economic development while avoiding the limitations of first-generation biofuels. Progress has been made but at a much slower pace than expected. It is important to understand why. The experience of the past decade and the need for low-cost technology in a world of low oil prices necessitates a strategic reset for biofuels as part of a 'grand challenge' renewables strategy[1].

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Miscanthus gianteus (elephant grass; above shown near Insitioge, County Wexford, Ireland), switchgrass and hardwood are potential dedicated feedstocks for cellulosic biofuels. Feedstocks arising from activities undertaken for purposes other than fuel production include corn stover, wheat or rice straw, sugarcane bagasse, residues from the forest products and paper industries, and municipal solid waste.

The promise

Two years ago, at the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21), over 190 nations (including the United States) committed themselves to keeping the increase in global average temperature 2 °C below pre-industrial levels, with an aim of limiting the increase to 1.5 °C. Plant biomass provides 10% of global primary energy today[2] and is widely expected to provide on the order of a quarter of primary energy in prominent low-carbon scenarios for 2050 (ref. 3). Biomass provides as much energy as oil, natural gas, and coal combined in Shell's (The Hague, The Netherlands) net zero energy scenario[4], as well as opportunities for carbon removal that must be deployed at a large scale to have more than a 50% chance of achieving the 2 °C goal[5].

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Among various types of plant biomass, cellulosic feedstocks are thought to have the greatest potential for mitigating climate change[6] and are widely available at a lower cost per unit energy (e.g., per megajoule) than petroleum[7]. Transport is both one of the largest and fastest-growing energy sectors and one of the most difficult to decarbonize. Even if the rest of the global economy were completely decarbonized, a failure to displace the fossil fuels used in aviation, ocean freight, and long-haul trucking with low-carbon alternatives would result in emissions exceeding the 2 °C COP21 target[8]. Biofuels are the leading low-carbon option for these transport modes, which represent about half of global transport energy.

A spate of recent studies recognize the substantial number of jobs created by renewable energy technologies, including biofuels. Bioenergy is responsible directly and indirectly for almost 3 million global jobs globally—about the same as photovoltaics and three times that of wind—with liquid biofuels responsible for a little over half this total, and solid biomass and biogas making up the balance[9]. Estimates for direct liquid biofuel jobs in the United States range from 100,000 to 300,000 (ref. 10), which may be compared to about 370,000 direct jobs in the US solar industry and about 70,000 for coal mining[11,12]. Sugarcane production in Brazil, about half of which is used for ethanol, is the largest agricultural employer in that country. Compared with other agricultural workers, laborers in the cane industry have the greatest representation in the formal economy and achieve higher levels of education[13]. Towns with ethanol plants in Brazil have higher tax revenues than comparable towns that do not[14].

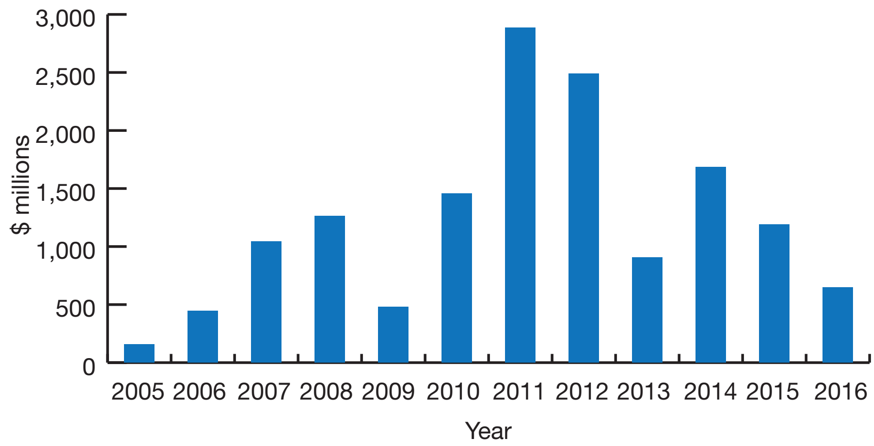

Figure 1 Global investment in next generation biofuels and biochemicals. (Source: Bloomberg New Energy Finance[17].)

Yet biofuels in the United States and across the globe have progressed little over the past decade—in sharp contrast to other renewable energy technologies. Expansion of global production of biofuels has leveled off, policy support has weakened, and research and development (R&D) funding has decreased and/or narrowed in many countries. Cellulosic biofuel investment and expectations have decreased markedly, although the rationale for their use is widely accepted and in some ways stronger than a decade ago.

Past and present

Between 2000 and 2010, the first-generation ethanol industry grew by tenfold in the United States and 2.6-fold in Brazil. In the middle of that decade, the world started paying a great deal more attention to cellulosic biofuels prompted by a sharp increase in oil prices, analyses indicating large-scale availability of low-cost, sustainable cellulosic feedstocks, and claims that the technology was ready. The Renewable Fuel Standard, created under the Energy Policy Act of 2005, provided a strong policy driver for market adoption in the United States[15], and President George W. Bush mentioned switchgrass-derived biofuels in his 2006 State of the Union address. The European Union's 28 member states implemented a 'biofuels directive' in 2003 and followed this with more comprehensive biofuels-related legislation in 2009 through its Renewable Energy Directive and amendments to the Fuel Quality Directive[16].

National governments saw in biofuels, and in particular cellulosic biofuels, a chance to contribute to rural employment and economic development and to enhance energy security. Many startup companies were formed, big companies also got in the game, and investments were made at previously unimaginable scales by both the private and public sectors. Entrepreneurs seeking to raise funds in a competitive marketplace presented their technology in the best possible light, only to be told by investors in many cases that they needed to think bigger and bolder—thereby raising the bar for the next investment pitch. Propelled by this spiral of hyperbole, expectations and reality eventually diverged.

Fast forward to the present, and six precommercial pioneer cellulosic ethanol plants have come on line[7], providing important opportunities for technology assessment and learning by doing, and global production of renewable diesel and jet fuel increased by ~30% last year (A. Zamorano, Bloomberg New Energy Finance, personal communication). Still, by any measure, the biofuels landscape today is a pale shadow of what was imagined a decade ago. In 2016, global production capacity for liquid biofuels from cellulosic feedstocks was 4.4 billion liters for thermochemically derived renewable diesel and jet fuel, and 0.7 billion liters for cellulosic ethanol (A. Zamorano, Bloomberg New Energy Finance, personal communication). These figures are dwarfed by the production capacity of first-generation biofuels—98 billion liters for ethanol produced from grains, sugarcane, and sugar beets, and 30 billion liters for biodiesel produced from oil seeds[17]. Whereas the US Renewable Fuel Standard foresaw a domestic cellulosic biofuel industry producing 4.5 billion gallons (17 billion liters) in 2016 (ref. 15), actual production was 0.16 billion gallons (0.6 billion liters) of which 98% was biogas rather than the liquid fuels originally envisioned (ref. 15 and A. Zamorano, Bloomberg New Energy Finance, personal communication). The amount of global cellulosic ethanol capacity retired last year exceeded the amount added (A. Zamorano, Bloomberg New Energy Finance, personal communication).

Many advanced biofuel startups have failed. Those that have survived are trading well below their initial public offering price; most are focusing primarily on higher value products other than fuels: Solazyme (S. San Francisco, CA, USA) changed its name to Terravia and is now focused exclusively on food products; Amyris (Emeryville, CA, USA) is active in flavors, fragrances, sweeteners, and rubber; and Ceres (Thousand Oaks, CA, USA) shifted its emphasis from cellulosic feedstocks to food and feed, and was acquired by Land-O-Lakes (Arden Hills, MN, USA). Global investment in next-generation biofuels and biochemicals is now >50% in chemicals rather than fuels, less than a quarter of its peak in 2011 (**Fig. 1**).

Diagnosis

Although widely expected circa 2008, a price on carbon did not materialize in most of the world. The nascent cellulosic biofuels industry was rocked by the global financial crisis, causing many commercially focused efforts to change abruptly from hyperventilating to holding their breath. The collapse in oil prices in 2014 was the final knockout punch to many efforts in the cellulosic biofuels space, although the weakness of the industry (as indicated by the value of publicly traded advanced biofuel companies) was already evident. And yet other renewable energy sectors—facing largely the same economic headwinds (and perhaps even more directly impacted by the low cost of natural gas)—thrived during this period. Between 2005 and 2015, global solar investment increased by an order of magnitude, and wind investment more than tripled[18]. During the second half of this decade, the cost of battery energy storage for electric vehicles dropped by about threefold[18].

So what has been different about cellulosic biofuels? Overestimation of technological readiness is part of the answer. There has been a marked tendency, encouraged by both government and private sector investors, to focus on large, expensive, stand-alone facilities rather than niche applications. Particularly in the United States, funding agencies prematurely turned away from cellulosic ethanol, although it is now clear that further development is needed to achieve cost-competitive fuel production even with oil prices at $100/barrel[7]. Amidst frequent claims that economically viable technology was in hand and investment was needed only in scale-up and commercialization, investment in new, potentially low-cost processing paradigms was generally modest; as a result, technological advancement was slower than it might have been, and policies were designed assuming that deployment, rather than technology, was the limiting factor. The impacts of a tendency to try to vault 100-foot cliffs with ten-foot poles were compounded by the very large size of investments ($250–$500 million) and relatively long duration of the design-build-operate-learn cycle in the cellulosic biofuels field. In sharp contrast, other renewable energy technologies proceeded in a stepwise fashion, recognized the need for technological advancement and invested accordingly, and benefitted from projects with lower costs and more rapid learning cycles.

There is more to it, however. Biofuels require land; as a result, their production inevitably has strong linkages to food security, rural economic development, and land-based ecological services. Biofuel advocates see these linkages as opportunities to achieve value above and beyond low-carbon energy supply, pointing to the soil fertility and water quality benefits of incorporating perennials into agricultural landscapes[19,20], the social benefits resulting from the Brazilian biofuel industry[13,14], and the potential role of biofuels in African transformation and enhanced food security[21]. Critics see these linkages as posing risks that arise to a smaller extent with other renewables, and point out that although cellulosic biofuels avoid direct competition with food markets, they do not avoid competition for land[22]. There is a basis for both perspectives, but the critical voices have spoken more loudly over the past decade, and this has contributed to weaker and less consistent policy support for biofuels compared with other renewables.

What to do?

Three key measures should be part of any effort to revitalize cellulosic biofuels. First, pursue commercial deployment in achievable, successively enabling steps, proceeding from where the industry is today; second, maximize social and environmental benefits based on examples and learning from experience; and finally, invest in innovation pursuant to alternative processing paradigms offering potential for large cost savings.

Solar and wind energy were deployed first off-grid and at the most advantageous sites. Battery technologies were employed for consumer electronics before use in hybrid vehicles, with grid storage the next horizon. Although initial applications were small, they provided important opportunities for rapid learning. A similar stepwise approach in the biofuels field involves niche applications featuring low-cost feedstock, preferably with established supply chains, and/or preexisting infrastructure. The idea is to deploy new technologies in their most advantageous applications and to de-risk technological components a few at a time, even if these applications are small relative to global energy demand and do not embody all desired features. Industry has internalized this message, as exemplified by the Raizen plant, which converts bagasse to ethanol within a larger sugarcane processing facility in Brazil; intensive efforts by several companies to convert corn fiber in the United States; and LanzaTech's conversion of waste gasses in China and elsewhere. However, governmental R&D programs and policies are in some cases not yet aligned with a stepwise deployment strategy.

Gracefully integrating bioenergy technologies into the agricultural, social, and environmental systems with which they interact is a challenge that can only be resolved by experience. With supportive policies, suitable safeguards, innovative business models, and on-the-ground projects aimed at benefitting people, planet, and profit, it is reasonable to expect progress as we replicate successes and learn from failures. Analyses aimed at anticipating the consequences of expanded biofuel production have often asked, "What would happen if biofuels were deployed without regard to climate, habitat, and social consequences?" The less often posed question "How would biofuels be deployed to achieve positive impacts?" offers different insights. However, no amount of abstract analysis is going to resolve debates over the merits and risks of biofuels or teach us how to cut with the good edge of the double-edged biofuels sword. Only experience can do that. Many investments in bioenergy are ultimately reversible[22], and the recent application of the brakes to bioenergy expansion worldwide provides ample evidence that the growth of bioenergy can be curtailed[2].

Just as battery development focused successively on lead-acid, nickel-cadmium, and then lithium ion chemistries and is now exploring new alternatives to meet the challenge of grid storage, cellulosic biofuels technology must actively look beyond existing processing paradigms. It is widely recognized that the key challenge to cost-effective production of cellulosic biofuels is the difficulty of converting cellulosic biomass into reactive intermediates, termed recalcitrance[23,24]. The recalcitrance barrier is manifested in the cost of thermochemical pretreatment and added enzymes for biological processing[7]. For thermochemical processing, it is manifested in the cost of gasification or pyrolysis, including clean-up before fuel synthesis[25,26].Although it is possible that incremental improvement of these established processing paradigms may result in cost-competitive cellulosic biofuels beyond niche applications, this is by no means certain, and there are increasing indications that innovation beyond learning by doing will be necessary. To maximize the probability of developing a robust cellulosic biofuels industry at a scale large enough to meaningfully contribute to climate and other goals, we need an aggressive effort aimed at new processing paradigms.

Targeting innovation and the role of ethanol

Innovations involving upstream technologies aimed at producing readily processed intermediates from recalcitrant cellulosic biomass—whether sugars, synthesis gas, or pyrolysis oil—address the key economic barrier to cellulosic biofuel production and are, in principle, enabling for all fuel molecules. New downstream technologies aimed at converting reactive intermediates to desired fuel molecules also have an important role to play. Innovations aimed at upstream and downstream challenges will likely be introduced one at a time to keep risks manageable rather than be commercially deployed at once. For thermochemical conversion, established downstream technologies for catalytic synthesis are available given suitably clean feed streams, and thus there are opportunities to focus innovation on the upstream piece. For biological processing, ethanol is the only liquid cellulosic biofuel for which downstream technology is established at scale, and which is cost competitive for some fuel applications. Consistent with a step-wise, risk-minimizing approach, biological production of 'drop-in' fuels should be commercialized first for easily fermented feedstocks, such as corn or sugar cane juice, before tackling production from cellulosic biomass.

Although fuel molecules other than ethanol are more readily compatible with existing infrastructure—particularly for applications, such as aviation, ocean shipping, and long-haul trucking, where biofuels are most needed for climate change mitigation—ethanol is the least expensive fermentation-derived liquid fuel molecule and is likely to remain so for the indefinite future. Ethanol is also a potential precursor for production of drop-in fuels[27]. There are no technical barriers to using higher level ethanol blends in new light-duty vehicles. Indeed, in Brazil today 'gasoline' contains ~25% ethanol, and mid-level ethanol blends (e.g., 30%) foster increased engine efficiency[28]. Heavy-duty vehicle manufacturer Scania (Södertälje, Sweden) sees ethanol as one of the most promising options for low-carbon fueling of heavy-duty vehicles for both the near- and long term (J. Strömberg, personal communication)[29].

The steps to expand ethanol markets are vastly simpler and less costly than those to expand markets for electricity or hydrogen in transportation. Yet, while infrastructure vehicle and energy storage and delivery changes to accommodate batteries and hydrogen are widely contemplated, biofuels are commonly assumed feasible only if they are infrastructure-compatible. The so-called 'blendwall' is largely the result of a lack of confidence in the merit of the ethanol supply chain and a concomitant reluctance to take the relatively modest steps needed to develop new fuel ethanol markets.

Seeing things as they are and a call to action

With swings from irrational exuberance to dismissal behind us, it is time to see cellulosic biofuels as they are. They remain an important and likely necessary component of climate change mitigation strategies, but face substantial technological challenges to achieve financial viability. They require learning by doing to maximize favorable social and environmental outcomes and to enhance competiveness with incumbent fossil fuels, which have benefitted from a century of investment and development. Near-term deployment opportunities need to be realized in a stepwise fashion, along with aggressive investment in R&D aimed at innovation and new processing paradigms. Cellulosic ethanol provides the most direct path to a low-cost platform for biological production of fuels from inedible biomass, and is the logical point of entry and proving ground for new technology aimed at overcoming the recalcitrance barrier for biological processing, but is not yet cost competitive and needs innovation to become so. As with many aspects of the climate change challenge, needed actions in the biofuels domain should be aligned with market realities, but will progress more quickly with policy support than in response to market forces alone.

In the International Energy Agency (Paris) 2 °C scenario, low-carbon biofuels need to provide about 25 exajoules by 2050 (ref. 8), which is well within conservative estimates of the resource base[6,22]. This is likely still possible, given historical precedent and today's production levels[30], but the window will not remain open for much longer unless deployment of cellulosic biofuels accelerates. Aggressive action, new approaches, and a great deal more progress in the next decade than in the last will be required. Companies wanting to be part of the new green economy need to persevere and in many cases reengage. Public and private investors need to revise their strategies. Governments need to realign policies aimed at technology development, deployment, and market support. Nongovernmental organizations need to guide and support deployment in ways that realize social and environmental benefits. All must be realistic about the need for cellulosic biofuels as well as their challenges, and there needs to be a recognition that the risks of inaction have become greater than the risks of action.

DISCLAIMER
The opinions expressed here are solely those of the author.

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The author declares competing financial interests: details are available in the online version of the paper.

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