Bonkers about biofuels

Stephan Herrera

Biofuels have been touted before, but failed to deliver. What's needed to get it right this time around?

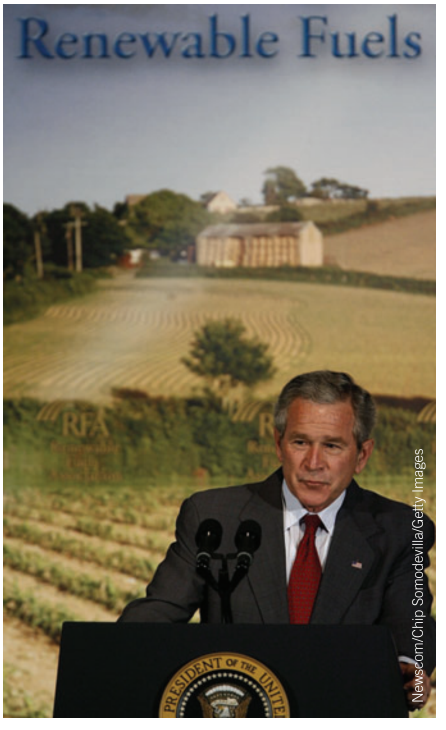
Are biofuels an idea whose time has come? Biotech industry boosters, environmental groups, farmers, automobile manufacturers and even some oil companies say that fuel made from plants, organic waste products and various other forms of biomass is now a feasible proposition. There are even predictions that the economic and technical hurdles that, in the past, have held back adoption of biofuels at gas stations and in factories have now been overcome. Nowhere has the political chorus been louder than in the United States.

This is notable for several reasons. The United States consumes more fuel, buys more cars and produces more CO_2 and SO_2 than any other nation in the world. It is also only one of two nations that refused to sign the Kyoto protocol to curb greenhouses gases (like CO_2) that contribute to global warming.

Even former oilman George W. Bush has jumped on the biofuel bandwagon. President Bush's new 'Biofuels Initiative' is a major component of his 'Advanced Energy Initiative,' which seeks to reduce America's dependence on foreign sources of oil by replacing more than 75% of oil imports by 2025 (ref. 1).

In his State of the Union address, Bush requested $150 million for the Biofuels Initiative in his FY 2007 budget—a $59 million (60%) increase from FY 2006, including boosted funding for biofuels research and development. The Biofuels Initiative aims to increase the use of nonfood-based biomass, such as agricultural waste, trees, forest residues and perennial grasses in the production of transportation fuels, electricity and other products. One specific goal of this initiative is to accelerate research and make cellulosic ethanol cost competitive by 2012, offering the potential to replace up to 30% of the US's current fuel use by 2030.

Stephan Herrera is an Editor-at-Large at Nature Biotechnology.



Newscom/Chip Somodevilla/Getty Images

US president George W. Bush addresses the Renewable Fuels Association at the Marriott Wardman Park Hotel, April 25, 2006, in Washington, DC. Bush said that corn-derived ethanol will help relieve the country's dependence on foreign oil and "is good for the country."

All this has played against a backdrop of skyrocketing oil and gasoline prices and a print and broadcast media breathlessly touting biofuel technology as an energy source that has come of age. If the United States is so bullish on biofuels, something truly tectonic is underway.

Biofuel boosters

Do biofuels deserve all this ink? Can they replace oil or are we seeing just the latest episode in a decades-long energy debate in which biofuels have had star billing but flopped before? Boosters say it's not a question of if, but rather, when. Indeed, they point to adoption rates in countries like Brazil, Sweden and Austria as evidence that biofuels are no longer just a pipedream but rather an energy source that has proved itself viable where it counts most: at fueling stations, in automobiles and at the local school and factory.

One of the biggest advantages of biofuels is that they can be produced anywhere in the world from home-grown raw materials using existing farm machinery and grain distribution systems. Brazil, for example, produces ethanol from sugarcane and biodiesel (methyl or ethyl esters) from soya and castor beans; Malaysia and Indonesia produce ethanol from palm oil; Sweden, the UK and Austria use wood to produce liquid and solid fuel (see **Box 1**); Canada uses corn and wheat; and the United States mostly uses corn kernels and corn stover (stalks that remain after corn has been harvested) (**Fig. 1; Table 1**).

Skeptics argue that even the most promising biofuels have dramatically worse yields than fossil fuels and point to the massive changes in agricultural land use and cultivation required to make biofuel production feasible. Historians are quick to point out that, despite numerous efforts and predictions during the late 20th century, biofuels have struggled to live up to their promise to meet the global need for an alternative to oil and the other dominant fuels like coal, natural gas and nuclear power.

But some of the main parameters are changing. The science and technology of producing biofuels like ethanol and biodiesel are finally reaching the point where they will soon be able to compete on both price and performance with oil-based fuels and petrochemicals. And this time around, there's backing from a US president, forward-looking oil companies like Shell (The Hague, The Netherlands) and BP (London), environmental groups from the Sierra Club on down, and a growing number

Box 1 Is wood the next-generation biofuel?

All things considered, there are several economic advantages for energy farmers focused on wood. Unlike corn, wheat, soya, rapeseed and other food crops, trees can be harvested any time of year without risk of profit-erasing damage from the weather. There is little need for environmentally harmful tillage, compaction or fertilization; in fact, trees grow perfectly well in some of the most nutrient-poor soils in the world. Coppiced trees, which are high in cellulose and show rapid growth in many habitats, can produce liquid and solid fuel just as readily in developed nations as in the developing world, where fuel is a precious commodity. Wood from poplar and willow varietals are well suited for making ethanol. The willow salix (*Salix nigra)* is particularly promising, growing quickly and abundantly when coppiced, with meager water or fertilizer requirements. Small towns, schools, buses, ski resorts and factories in Sweden and Austria have long relied upon the byproducts of the forest industry—stumps, sawdust, chips and scraps—to produce liquid and solid fuel. Some excess is pelletized and sold to the electric grid, schools and factories, for example.

Sweden will need to rely heavily upon wood-based solid and liquid biofuels to help it attain a goal of 100% energy self-sufficiency by 2020. "We are particularly focused on the role that the poplar can play in producing large quantities of liquid fuel, as it is abundant and well understood within forest biotechnology," says Mats Johnson, CEO of Umea, Sweden-based SweTree Technologies. "Sweden is quite fortunate: we have a lot of trees and a lot of scientific and industrial experience with them."

So do the US and Canada. But Oregon State University forest biologist Steven Strauss worries that the biofuel potential of trees is being overlooked because of the politics of commercial forestry and concerns about the environmental impact of trees genetically engineered for lower lignin content. Hybridization, molecular breeding and genetic engineering efforts are all under consideration to achieve more rapid growth rates and thereby improve the economics of wood-based ethanol production. For example, North Carolina State University researchers Steve Kelly and Richard Phillips, along with Vincent Chiang, are researching wood-to-ethanol techniques using transgenic trees low in lignin in a project funded by the US Department of Agriculture.

"Our preliminary results clearly point out that transgenic wood can drastically improve ethanol production economics," Chiang says. "Manipulation of hemicelluloses can give a huge boost on ethanol yield. Lignin structure and therefore chemical reactivity and increased cellulose content are the key traits we are focusing on. We already have transgenic trees with low and reactive lignin and high cellulose and are using them in our current project for ethanol production. We are also in the process of cloning the genes that could control the increase of C6 sugar–containing, and decrease of C5 sugar–containing, hemicelluloses. Currently, no efficient C5 fermenting system is available and C5 sugars, mainly xylose, are converted to furfural, which is toxic to the yeast used in fermentation. In the future, if C5 fermentation is available we then can also upregulate C5-containing hemicelluloses."

Chiang, Strauss and others point out that because of genetic variation within willows, poplars and their many hybrids, forest researchers can screen for the wood chemistry that is most amenable to producing ethanol. Thus, it is possible that a tree's cellulosic bounty might well be tapped without resorting to genetic engineering at all. A pilot project being put in place in Taupo, New Zealand by biotech startup BioJoule Technologies aims to determine whether centuries-old coppicing techniques, molecular-assisted breeding with salix and steam generated by nature's own geothermal energy are capable of producing a cost-effective, continuous-flow, salix-to-ethanol biorefinery system.

Turning tree bits into solid and liquid fuel was easily the most popular component of the World Bioenergy 2006 conference held this past May in Jönköping, Sweden. The conference attracted participants (and even a number of government energy officials) from Asia, Canada, Brazil and Ghana, although there was a notable absence of US interest. A delegation from one of China's largest energy firms used the occasion to announce a series of technology transfer agreements with Swedish firms Ena Energi AB and Harjedalens Miljobransle AB. The subject of the licenses? Turning wood into biofuel. *SH*

of manufacturers, like Toyota (Nagoya, Japan) and DuPont (Wilmington, DE, USA). With this type of momentum behind it, can the biofuel dream finally realize its potential?

Barrels and tipping points

Last July, in Washington, DC, the First International Biorefinery Workshop was convened[2]. All in all, some 300 senior-level executives from the world's largest automakers and chemical companies, as well as scientists, investors and bureaucrats from around the world (including European Commission representatives) were in attendance; alternative fuels are clearly back on political and research agendas. One month later, the US Energy Policy Act of 2005 was signed by President Bush. The new law calls for 7.5-billion gallons of ethanol and biodiesel (or nearly 6% of the US fuel consumption) to be injected into America's fuel complex by 2012 (see **Fig. 2**). Similar government mandates have also been (or soon will be) pushed through in Canada, Japan and in Europe.

Leading backers, like the Biotechnology Industry Organization (BIO, Washington, DC, USA), EuropaBio (Brussels), the Organization for Economic Cooperation and Development (Paris) and consultancy McKinsey & Co (New York), argue that the cost of producing biofuels has quietly fallen every bit as dramatically as the price of oil has climbed in recent years. Indeed, they argue that biofuels can compete with oil in the $40 per barrel range. Oil has been selling well above this range for a while as a result of several factors, including war and instability in the Middle East, falling supply and surging demand from India and China.

None of these variables is likely to change sufficiently over the next few years to bring the price of oil back down to where it was a few years ago—in the $30 per barrel range. In fact, last spring investment bank Goldman Sachs (New York) released a report to its customers in which it predicted that oil prices could stay well above $50 per barrel for at least several years.

At the same time, unlike during previous gas price spikes and supply shortages during the late 1970s, there appears to be more widespread enthusiasm now for biofuels among the oil, chemical and automotive industries. BP, Shell, Dow (Midland, MI, USA), DuPont, GM (Detroit) and Toyota have all produced print and television advertising campaigns touting biofuels.

President Bush even stated during a recent televised address to the nation that America, which consumes more oil than anybody on the planet, must cure its "addiction" to oil and turn to alternatives like "cellulosic ethanol." He

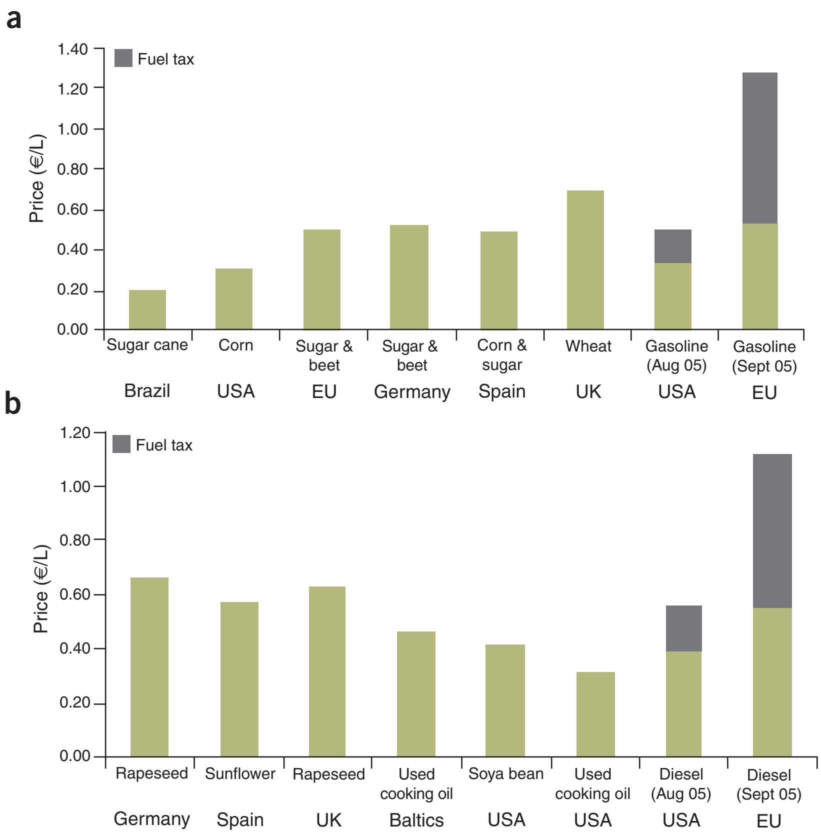


Figure 1 Relative production costs of alternative fuels in different countries. (**a**) Bioethanol. (**b**) Biodiesel. Source: Imprimatur Capital.

further proposed that the United States cut oil imports by 75% by 2025. Indeed, BIO's Brent Erickson and EuropaBio's Dick Carrez have done an excellent job selling Washington and Brussels on the idea that investing in biofuels like ethanol and biodiesel is in their interests. "A lot of people on the Hill get that if America wants energy security, it's going to have to start looking at biofuels and oil much differently [from the way] it has in the past," says Erickson.

In a recent letter to the editor in the *Wall Street Journal*, Senator Richard G. Lugar (R-Indiana)[3], who is also chairman of the powerful Senate Foreign Relations Committee, went so far as to suggest that when one factors in the true cost of oil—defending oil supplies around the world, damage to the environment and damage to national and international security interests by petro-states "made rich by the world's overreliance on petroleum"—homegrown cellulosic ethanol is nearly fully competitive with gasoline. "Unlike oil or natural gas, it is renewable, burns cleanly and makes virtually no net contribution to global warming," he wrote. "Switching to an ethanol-based transportation system, by adapting new cars to run on an ethanol-gasoline blend with inexpensive, off-the-shelf flexible fuel technology and piggy-backing on the existing gas station network, would be good policy and a great bargain for consumers."

Interest in, and support for, biofuels is clearly at an all-time high. Indeed, in January, at the BIO Pacific Rim conference on Industrial Biotechnology in Honolulu, Hawaii[4], Roger Wyse, of San Francisco-based investment bank Burrill & Co., told delegates that biofuels are a big reason that industrial biotech, in general, has reached a "tipping point."

A clear value proposition

The term 'biofuels' has become something of a catchphrase that refers to any combustible fuel produced from plants, organic waste products and biomass. More often than not, the moniker biofuels refers to ethanol or methyl/ethyl-based esters (biodiesel). The reason is simple: both of these fuels have the best shot of supplementing, if not replacing, petroleum and petrochemicals without completely rebuilding the machinery that runs on them now and the refining and transport infrastructure used to produce and distribute them. There are alternative fuels, such as bio-derived hydrogen and methane, but these still pose significant practical and technological challenges. Biohydrogen, for example, requires the invention of a practical and economic means of storage, not to mention a large improvement in the efficiency of current fuel-cell technology.

Most important of all, ethanol and biodiesel have a comparative advantage over other biofuels—most of the world's machines and transport systems weren't built for fuels like hydrogen or methane. Indeed, one of the main reasons alternative fuels of all sorts have flopped in the past, and still trigger some lingering ambivalence in industry suites today, is that their success in the past relied upon massive investments in new plants, equipment and machinery—even though ethanol and biodiesel could be used as additives to existing fuels and chemicals in place of standard hydrocarbons.

Indeed, automaker GM is already the largest producer of ethanol-powered hybrid fuel vehicles built to run on gasoline blends containing up to 85% ethanol known as simply

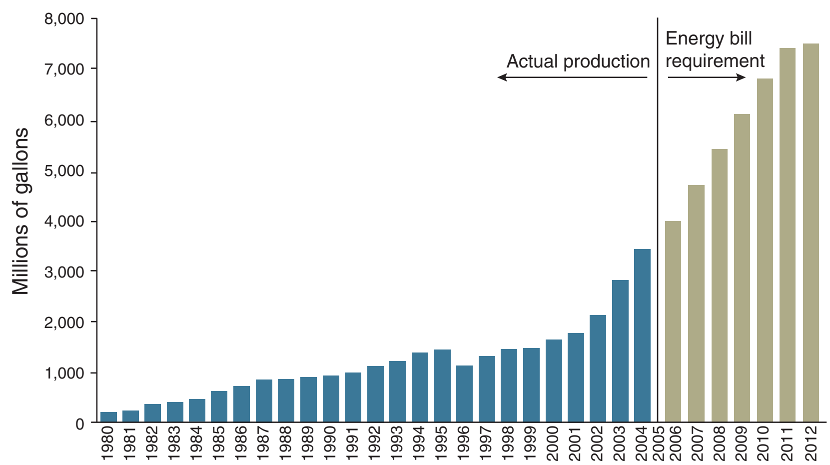


Figure 2 US production of ethanol. Source: Renewable Fuels Association.

Box 2 BTUs and bioethanol

Last year, the controversy over the real versus perceived environmental and net energy benefits of bio-ethanol reemerged[12–14]. In an article published last spring in *Natural Resource Research*, Cornell University's David Pimentel and Tad Patzek, an associate professor of petroleum engineering at the University of California-Berkeley, argued that ethanol is a net environmental and industrial loser. At issue is the disputed amount of total energy input components required to produce ethanol, such as the fuel to power the machinery needed to plant, fertilize, harvest and transport the corn typically used to produce ethanol. Add to that the fuel used in manufacturing the required fertilizers, pesticides and herbicides for the feedstock, the fuel needed to transport the feedstock to the processor and the fuel/electricity expended by the ethanol-processing plant, and Pimentel says the numbers speak for themselves. According to his calculations, ethanol takes about 1.15 BTUs (British thermal units) of input for every 1 BTU of output.

The articles followed a debate last August at an open forum entitled 'Ethanol Energy Balance' at the National Press Club in Washington. The forum was sponsored by the National Corn Growers Association. Pimentel and Tad Patzek, an associate professor of petroleum engineering at the University of California-Berkeley, argued that ethanol production from corn is a net energy loser and contributes to global warming. They also said it could never provide more than a tiny portion of the nation's fuel needs. In response, Bruce Dale of Michigan State University and John Sheehan of the National Renewable Energy Laboratory in Golden, Colorado, US asserted that Pimentel and Patzek's calculations are based on faulty data. "The most surprising suggestion in Pimentel and Patzek's new publication," they counter, "is the claim that ethanol made from energy crops—trees and grasses containing cellulose and hemicellulose sugars—requires 50% more fossil energy inputs than the fuel energy it delivers….Studies by Argonne National Laboratory and the National Renewable Energy Laboratory have demonstrated that ethanol from energy crops and even from agricultural residues like corn stover offer large fossil energy savings….That is, all of its energy needs are provided by the biomass, eliminating the need for the fossil energy that Pimentel and Patzek claim are needed to provide steam and power in the facility." Both sides do seem to agree on one thing, however—there are many other biofuels that are more energy efficient than ethanol derived from corn grain.

'E-85.' The automaker says there are now 1.1 million of these 'flex-fuel' vehicles on the road in North America (approaching 70% the total number of diesel-powered vehicles). Compared with conventional (gasoline-fueled vehicles) this is a drop in the ocean, but in the coming years, Toyota, Ford (Dearborn, MI, USA) and Volkswagen (Wolfsburg, Germany) will be accelerating the roll out of their own flex-fuel motor cars and trucks, so the total number of biofuel-ready vehicles is expected to jump tenfold in the coming ten years according to auto industry analysts.

Likewise, unlike in years past, every major chemical, automotive and oil company in the world now has an industrial biotech division focused on biofuels or are developing finished products that will, in some cases, run on them.

Achilles heel, elbow and kneecap

Major pitfalls remain, however. One bone of contention is how much energy is required to process and manufacture biofuel from feedstocks and how much energy is generated. A recent study from two researchers at Cornell University (New York) and the University of California-Berkeley[5], for example, restates the case that the production of ethanol and

Box 3 Glacial progress on Capitol Hill

The Energy Policy Act of 2005, which was signed into law last August by President George Bush, has been roundly criticized by nearly every quarter—except the oil and gas industry, which benefited from billions in credits, grants and subsidies to promote new exploration and augment some existing extraction and refining initiatives. On the plus side, the legislation did provide concrete US national goals for biofuel R&D. Refiners are mandated to double the volume of ethanol and biodiesel added to the US's fuel supply to 7.5-billion gallons annually by 2012. It also earmarks $2.9 billion over ten years for R&D/demonstration projects (to assess crop suitability for biofuels, biomass processing and development of bio-based products like corn-based plastics and soy-based lubricants), establishes a program of loan guarantees for the construction of up to four demonstration biorefineries capable of producing ethanol and other high-value products from biomass, and includes $1 billion in grants and incentives for the first commercially implemented manufacture of cellulosic ethanol.

BIO had hoped that the legislation would clear the way for major new government funding of industrial biotech R&D and infrastructure construction. In reality, the research and infrastructure funding provided is more of a pat on the back than a shot in the arm. Critics also argue that without clear focus and coordination, biofuels will not receive the solid financial and political backing that every emerging industry requires as it stumbles through the inevitable trial-and-error startup phase to a more mature state where market, management and technology risk are sufficiently predictable for the private sector to commit itself full scale. Without long-term funding commitments, benchmarks and milestones, the field will not only fail to reach its potential—at the very moment when the politics, economics and technology are in perfect alignment—but is also likely to fail to prove its long-term value to consumers. These two points could lead to public and political disenchantment and then corporate retrenchment similar to what happened in the 1970s with synthetic fuels R&D.

Biofuels boosters like those at BIO and the NRDC say that for biofuels to reach their potential they must be commercially viable by 2015. To get from here to there, however, will require further legislative action to, first, establish a clear mandate for the blending of 1.5-billion gallons of cellulosic biofuels annually by 2016; second, provide guaranteed funding for a coordinated advanced biofuels program; third, impose coordination, targeting and discipline on the Energy Policy Act of 2005 biofuels programs; and fourth, authorize and fully appropriate funding for all of the parts of a coordinated advanced biofuels program.

Box 4 Easier said than done

The largest and most advanced biorefinery in the world right now—Iogen's plant on the outskirts of Ottawa—relies upon a rather outmoded batch processing system, rather than a faster, more modern and efficient integrated processing system known as consolidated bioprocessing. Going forward, biorefineries will only be cost competitive if the production system becomes fully integrated. That means biorefineries must seamlessly combine into one continuous flow several processes currently separated in the batch process: the pretreatment of plant matter that separates solids and liquids, the biochemical enzymatic processes needed to break down this polymer dross into single-sugar monomer, the fermentation of sugar to ethanol and then, finally, the distillation of ethanol.

There is optimism that technological innovations can also improve biorefinery efficiency and bring down costs. For example, Palo Alto, California-based Genencor and Copenhagen-based Novozymes have been working to optimize the heat resistance and catalytic turnover of cellulases, enzymes required to degrade plant (cell wall) cellulose into simpler sugars in the mashing process. As a result, the cost of cellulases in the ethanol production process has fallen from $5.40 per ethanol gallon in 2000 to 20 cents per gallon last year. Other steps in the ethanol refining process might also be optimized, for instance, by enabling the separate steps in batch ethanol fermentation carried out by anaerobic microbes to be combined and run in parallel, thereby further reducing costs[11].

biodiesel from corn, soybeans and certain other agricultural crops requires more energy than it produces. Conversely, studies from the US Department of Agriculture[6,7] and the Argonne National Laboratory[8] suggest the opposite—that overall ethanol production has a positive energy yield. The debate is complicated by conflicting definitions on how energy inputs and outputs are defined and the specific crop used as a feedstock (**Box 2**). Whatever the case, it is clear that it's more efficient to produce ethanol from a sucrose-rich feedstock such as sugarcane (as in Brazil) than it is from a starch-rich feedstock such as corn (as in the United States).

Another nagging issue is that despite the fact that Brussels and Washington are mandating new laws that force manufacturers and consumers to learn to live with biofuels, these are largely unfunded mandates. What's more, neither Washington nor Brussels have created high-impact financial and other incentives for manufacturers or consumers to convert to bioenergy. At best, lethargic government leadership sends the wrong signal about bioenergy. At worst, it can trigger a backlash and lawsuits from those who feel that if there is to be a conversion to bioenergy, the government needs to pay for it (**Box 3**). And without more robust government backing and incentives, US and European companies face an uphill struggle implementing the processes and building the facilities to make biofuels a reality (**Box 4**). Iogen, the Ottawa, Ontario-based ethanol producer and easily the most widely praised ethanol producer in North America, is a leader and a survivor in large part because of Brian Foody, its tenacious and visionary founder and CEO—and because of government backing. Brazil's COSAN and Usina Cerradinho are giants in the ethanol export trade today—in large part because of government backing.

Despite the rosy estimates, there is also no guarantee that oil prices will remain at levels where biofuels are competitive. When US President Ronald Reagan took office in 1980—after three years of high gas prices, fuel shortages and public panic—the price of oil fell quickly against predictions that prices had reached a new and permanently high plateau. Forget the fact that pundits were wrong more than they were right about the permanence of oil prices; in general, when new refining capacity comes on line or if relatively cheap and clean liquefied natural gas, clean coal or nuclear power somehow overcome public and political opposition to become the fuels of choice, oil prices will surely drop as demand shifts to these alternative fuels. At the World Economic Forum in Davos, Switzerland, in January this year, Vinod Khosla, a venture capitalist who founded Sun Microsystems and is now an investor in ethanol, claims he was told by a senior Saudi oil official that it costs less than a dollar to lift a barrel of oil out of the ground and the oil industry would have no hesitation in slashing its prices if biofuels were to take off.

A final challenge is keeping expectations realistic. Last summer, the National Resources Defense Council (NRDC; New York) produced a report called *Bringing Biofuels to the Pump: An Aggressive Plan for Ending America's Oil Dependence*.[9] Its lead authors, Nathanael Greene and Yerina Mugica, state that "biofuels can play a central role in freeing us from…oil dependence and its hazards. If we follow an aggressive plan to develop cellulosic biofuels between now and 2015, America could produce the equivalent of nearly 7.9-million barrels of oil per day by 2050. That is equal to more than 50% of our current total oil use in the transportation sector and more than three times as much as we import from the Persian Gulf alone." The authors went on to claim that "biofuels could virtually eliminate our demand for gasoline by 2050…be cheaper than gasoline and diesel, saving us about $20 billion per year on fuel costs by 2050…provide farmers with profits of more than $5 billion per year."

In farming and the oil business, it's hard enough to project costs and revenues year over year. To throw out projections about what is possible with biofuels in 2050 is not just ridiculous and Utopian; it's counterproductive. If the decision by Dow Chemical last year to pull out of its Cargill Dow joint venture for producing biodegradable plastics taught us anything (*Nat. Biotechnol.* **23**, 638, 2005), it is that models and simulations designed to forecast the future cost-benefit of emerging industrial biotechnologies are doomed to revision.

Table 1 Top ten global ethanol producers

Country	Ethanol (millions of gallons)
Brazil	3,989
United States	3,535
China	964
India	562
France	219
Russia	198
South Africa	110
United Kingdom	108
Saudi Arabia	79

Source: Renewable Fuels Association and CitiGroup

Conclusions

There is no question that the United States (and the world, for that matter) needs to wean itself from oil. Energy experts, like Houston, Texas-based energy trader and author Matt Simmons, say that this time, world supply of oil has really peaked and is well on its way to decline. It is telling that about the only voices arguing that there are still large tracts of reserves to be discovered are coming from self-interested quarters. Nor does it seem likely that new technologies will enable oil to be recovered from sources that are currently economically inaccessible, as Canada's recent experience with oil sands seems to suggest.

Simmons estimates that by 2050, global energy consumption will more than double to 30 terawatts; others believe it will climb as high as 60 terawatts. Clearly, the world must find more efficient ways of conserving and consuming energy. Radical technological innovations will help get us from here to there, but a more substantive commitment to industrial and retail alternative energy sources like biofuels will be required. It will take a minimum of a decade to even begin to solve the challenges of producing that kind of power.

There are projections that create heightened expectations and there are those that merely give pause. According to *Winning the Oil End Game*, published by the Rocky Mountain Institute, a bona fide domestic biofuels industry has the potential to supply one-fourth of the country's oil demand. The report goes on to assert that "replacing fossil-fuel hydrocarbons with plant-derived carbohydrates will strengthen rural America, boost net farm income by tens of billions of dollars a year, and create more than 750,000 new jobs. Convergence between the energy, chemical and agricultural value chains will also let versatile new classes of biomaterials replace petrochemicals."

Perhaps, but who is going to pay for it and keep the industrial and political momentum moving? In Europe, where public and corporate investment in biofuel technologies is still running well behind the EU's political will to impose onerous fuel standards and biofuel requirements at the pumps, the answer is unclear. In the United States, although the political will and a modest level of funding is available for R&D, the government is well ahead of industry in funding and enthusiasm.

Biofuels are no easy solution whose rough edges can easily and quickly be smoothed out by science and money. Research-derived, evidence-based pronouncements will be useful, but results based on economic outcomes will build a more solid foundation for the biofuels industry.

Also, manufacturers, investors, consumers and governments must be willing to accept that engineering a biofuels conversion will not be inexpensive, disappointment free or swift. Brazil is both a model and a cautionary tale for this point. It took decades of massive government subsidies, private investment and public cajoling before Brazil's transport system, and much of its economy, became biofuel based. Brazil's government no longer subsidizes ethanol production and consumers no longer need to search for automobiles that run on E85 or filling stations that sell the stuff. Brazil is now the world's largest exporter of ethanol. Getting from there to here was not inexpensive, free of disappointments and missteps, or swift.

And finally, biofuels boosters must pursue and promote this conversion to biofuels on its own merits rather than by overhyping the relative political, economic and environmental advantages of biofuels over oil. Likewise, boosters—particularly those in the US—must find a way to get past the squabbling over feedstocks and resist efforts like those from the corn lobby to shackle the country to a single feedstock standard. There's nothing wrong with corn, of course, but it's not the only plant capable of producing fuel. Brazil, for example, manages perfectly well with sugarcane, China with sweet potatoes, Canada with wheat and Thailand with palm oil. Indeed, countries like China, Austria, Sweden, New Zealand, even Ghana are building their (solid and liquid) biofuels infrastructure around wood-based feedstocks (**Box 1**)[10].

Nobody can blame the entrepreneurs, scientists or engineers this time if biofuels fail. This time around, if they fail to deliver, or at least reveal their true potential, it will be because politicians, investors, factory owners, the transport industry, special interest groups and biofuels boosters lose their patience and their perspective.

1. http://www.energy.gov/news/3255.htm
2. http://www.biorefineryworkshop.com/
3. Lugar, R.G. *Wall Street Journal* (2005) Page A17, February 13.
4. http://www.bio.org/pacrim/
5. Pimentel, D. & Patzek, T. *Nat. Resour. Res.* **14**, 65–76 (2005).
6. Shapouri, H., Duffield, J.A. & Wang, M. *Trans. ASAE* **46**, 959–968 (2003).
7. Shapouri. H. *et al. Estimating the Net Energy Balance of Corn Ethanol*. Agricultural Economic Report No. 721 (US Department of Agriculture, Economic Research Service, Office of Energy and New Uses, Washington, DC, July 1995).
8. Wang, M. *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies* (Tech. Rep. ANL/ESD/TM-163, Argonne National Laboratory, Argonne, IL, 2001). http://www.transportation.anl.gov/pdfs/TA/153.pdf.
9. Greene, N. & Mugica, *A. Bringing Biofuels to the Pump: an Aggressive Plan for Ending America's Oil Dependence* (National Resources Defense Council, New York, July 2005).
10. Herrera, S. Wood-based ethanol advances on international front: Cellulosic fuels from trees gets a closer look. *Ind Biotechnol* 2:2, 101–107 (2006).
11. Lynd, L. *et al. Proc. Natl. Acad. Sci. USA* **102**, 7321–7325 (2005).
12. Peplow, M. Alcohol fuels not so green. *news@nature.com*, 1 July 2005.
13. Peplow, M. Biofuels get mixed review. *news@nature.com*, 26 January 2006.
14. Farrell, A.E. *et al. Science* **311**, 506–508 (2006).
15. Ragauskas, A.J. *et al. Science* **311**, 484–789 (2006).