A high-tech look at the fine structures of pre-treated biomass at the US National Renewable Energy Laboratory in Colorado.

DENNIS SCHROEDER/NREL

INTRODUCTION

Next generation biofuels

Proponents of biomass-based fuels push for sustainability against a steady tide of conflicting analysis, but can advanced biofuels cut the mustard?

BY PETER FAIRLEY

Sustainable, supersonic fighter jets. President Barack Obama conjured up that improbable image in the spring of 2011 to help students at Georgetown University, Washington DC, grasp why biofuels deserve a starring role in his energy strategy. Just the week before, a US Air Force pilot had throttled a fighter jet up to one and a half times the speed of sound on a 50/50 blend of petroleum-based fuel and biofuel from *Camelina sativa*, an inedible cousin of the mustard plant — powerful evidence, claimed Obama, that biofuels could help the country kick its oil habit. "If an F-22 Raptor can exceed the speed of sound using biomass," Obama half-joked, "your old beater can do the same."

Such unqualified advocacy is bold following criticisms heaped on biofuels in recent years. The rapid scale-up of biofuels, fermented or refined from foodstuffs such as corn (maize), sugarcane and soybeans, has contributed to higher food prices and deforestation. And as production of biofuels relies mainly on fossil fuels, these early deployments have done little to cut greenhouse-gas emissions. In April 2011, summing up the findings of a 14-month inquiry into the ethics of biofuels, Nuffield Council on Bioethics, a think-tank in London, said policies and targets to encourage biofuels had "backfired badly".

Yet, as Obama's speech shows, the unpopularity of biofuels is giving way to a recognition that for all their present flaws, biofuels need to be part of our energy future. Other renewable sources of energy, such as the Sun and wind, will contribute to electricity capacity, but the reality is that the vast majority of motor vehicles require liquid fuel and will do so for the foreseeable future. And any attempts to sustainably power the world's millions of motor vehicles must include biofuels.

In early 2011, organizations as diverse as the London-based financial giant HSBC, and environmental advocacy group Oceana, based in Washington DC, have endorsed biofuels use as a critical means of squaring transport, economic growth and environmental protection. If appropriately implemented, biofuels could maximize use of the waste materials of farming, forestry and city life. That approach could help save land that provides carbon sequestration and other critical environmental services.

In May, the International Energy Agency (IEA), based in Paris, laid out a 'roadmap' to ramp-up the use of biofuels from around 2% of global transport fuel today to 27% by the year 2050. Biofuels, according to the IEA, could displace enough petroleum to avoid the equivalent of 2.1 gigatonnes of carbon dioxide emission each year if produced sustainably — about as much as net carbon dioxide absorbed by the oceans.

Such estimates have convinced the IEA, Obama and others that biofuels are not only preferable to petrol (gasoline) but that, with technological advances, there is also hope for biofuels' environmental and social redemption. Biofuel advocates are counting on a new generation of advanced biofuels to maximize petroleum (crude oil) displacement and minimize side effects. "Continuing the pathway we

➲ NATURE.COM
to read the latest news and research on biofuels
go.nature.com/xxxxxxx

started in the last ten years with conventional biofuels really isn't possible," says biofuels researcher Anselm Eisentraut, lead author of the IEA's biofuels roadmap. "We need more land- and resource-efficient technologies."

The biofuels that inspire enthusiasm among advocates are to be bred and brewed from a variety of non-food materials — be they ethanol from corn stalks or other 'cellulosic plants' or even from municipal garbage, or jet fuel from dedicated energy crops such as the fast-growing *Camelina sativa*. The order of the day is to demonstrate that the required agronomy and technologies deliver at industrial scale, and that the net reduction in petroleum use and greenhouse-gas emissions are real, lasting and ethical.

FUELING A TURNABOUT

Biofuels derived from crops other than corn or sugarcane appear to be on the cusp of commercialization — again. In 2007, advanced biofuels developers were gearing up to build their first processing facilities. They expected explosive growth based in part on a surge in governmental support. For example, the US Congress had created mandates to spur cellulosic ethanol production up to about 950 million litres by 2011. But the US Environmental Protection Agency — recognizing the dearth of supply available — mandated blending of just 30 million litres of cellulosic ethanol and 57.7 million litres of corn ethanol into petrol this year. The United States "had an aggressive plan and we've done essentially nothing," says Jeremy Martin, a policy analyst at the Union of Concerned Scientists, a Massachusetts-based advocacy group pushing advanced biofuels.

A series of blows knocked the backers of advanced biofuels to the floor. Researchers studying the impact of biofuels over their entire life cycle — from crop to car — predicted surprisingly large greenhouse-gas emissions. A report by researchers at Princeton University published in *Science* in 2008 estimated that greenhouse gases caused by increased cultivation of corn for ethanol would exceed the greenhouse-gas emissions of petrol. Despite the study's explicit focus on first-generation biofuels, the unexpected magnitude of the estimates cast a pall over the entire biofuels enterprise.

Biofuels of all flavours took another hit when spiking food prices sparked food riots in Mexico in December 2007, which subsequently spread to impoverished communities throughout the developing world. Annual output of bioethanol and biodiesel had exploded from 16 million litres worldwide in 2000 to more than 100 million litres in 2010, outpacing growth in supply of corn, sugarcane and vegetable oil. Although many economists agree that biofuels contributed less to the price hikes than commodities speculators, oil prices and weather, protestors and food rioters claimed that the conversion of staple foods into biofuels distorted global agricultural markets.

As the future for biofuels dimmed, electrical vehicle technology pushed forward to fill the void. Major automakers began mass-marketing their first electric vehicles, including Michigan-based General Motors' Chevy Volt and Japanese carmaker Nissan's Leaf. Worldwide, government, industrial and private investments in developing electric vehicles and battery technology — including RMB 100 billion (US$15 billion) budgeted by Beijing — eclipsed investments in biofuels.

Advanced biofuels hold promise of an escape from their predecessors' food-versus-fuel conundrum (see 'Beyond food versus fuels, page S6). The problem is their presently higher production cost compared with first-generation biofuels and petroleum fuels. Prices for bioethanol account for its relatively low energy density; bioethanol packs only 70% the energy of petrol. And according to the IEA, the cost of producing and retailing diesel and ethanol from cellulose is about US$1.10 per litre of petrol-equivalent, or about US$ 4 a gallon. By way of comparison, corn and cane ethanol are 62-75 US cents per litre-equivalent, whereas petrol itself is about 54 US cents. Consequently, at the moment, advanced biofuels are far from competitive — but that should change. The IEA estimates that by 2050, cellulose-based biofuels will be produced for as little as 75 US cents per litre-equivalent. But bridging the gap will require continued investment, research and development.

Ground is shifting back towards biofuels, partly owing to a series of natural disasters and societal shifts.

But the ground is shifting back towards biofuels, partly owing to a series of natural disasters and societal shifts that have heightened the urgency of avoiding petroleum. Obama set his energy strategy in the context of growing instability in the oil-rich Arab world and shrinking petroleum reserves. HSBC's analysis asserts that the supply squeeze created by steeply rising demand from developing countries should be of concern to "anyone who drives a car, heats a home, or runs a factory." The BP Deepwater Horizon oil-spill disaster in 2010 prompted Oceana's call for the elimination of oil drilling in the Gulf of Mexico by 2020.

Then in 2011 came Japan's nuclear crisis, which shone a harsh light on an important source of low-carbon electricity. Major economies including China, Germany and the United States had been counting on nuclear power to help charge millions of electric vehicles. Without more nuclear and massive new investments in renewable energy, electric vehicles will fuel-up on coal-fired power, doing the environment little good.

Can entrepreneurs revive biofuels? With government financial support from the United States and Europe, several biofuels developers are likely to begin building new industrial-scale plants over the next year or so. The IEA's roadmap says that biofuels plants capable of displacing nearly 175 million litres of petrol annually have already been built, and it estimates that capacity to replace another 1.9 billion litres per year is in construction or advanced planning. The Obama administration promises federal funds to help at least four advanced biofuels plants break ground by 2013.

Many of the early movers in advanced biofuels have demonstrated pilot-scale production of cellulosic ethanol through some combination of physical, enzymatic and fermentation steps (see 'A chewy problem', page S12). Take the 50 million litre per year ethanol factory that Italian chemicals firm Gruppo Mossi & Ghisolfi began building north of Turin in April 2011, which is designed to displace about 34 million litres of petrol. The plant will mash-up straw feedstocks, then use enzymes supplied by Denmark's Novozymes to break the long-chain carbohydrates into smaller sugars for fermentation.

Mascoma, based in Lebanon, New Hampshire, plans to begin construction on a 150-million litre per year cellulosic ethanol plant in Michigan in late 2011. The company genetically engineered thermophylic microbes to secrete cellulase enzymes. "The organism produces its own enzymes, so you cut out one of the most costly components," explains Jonathan Mielenz, who heads the Bioconversion Science & Technology Group at Oak Ridge National Laboratory in Tennessee and has collaborated with Mascoma.

Another innovator is Illinois-based Coskata, which has a US$250 million federal loan guarantee to construct a cellulosic ethanol facility in rural Alabama. The plant will produce 208 million litres of ethanol per year by gasifying woody biomass. In Coskata's novel process, the carbon monoxide and hydrogen gases released by the biomass are fermented to ethanol by anaerobic bacteria. One advantage of gasifying biomass is that the process accommodates a wider variety of feedstocks than enzymatic approaches. "You can use any carbonaceous material — even rubber tires," says Mielenz. "It's much more forgiving."

These processes all consume a range of biomass feedstocks and, like oil refineries that split and upgrade petroleum into an assortment of fuels and chemicals, churn out their target fuels plus other commodities. Co-products from these biomass 'biorefineries' include solid residues that can be burned to generate steam and power or sold as animal feed; carbon dioxide that can be purified for carbonation; and glycerine for pharmaceuticals and cosmetics. Co-products boost revenues and, in some cases, provide a free and renewable source of energy to power the biorefinery. Such integration may also cut carbon emissions — a factor that first-generation biofuels producers are also now trying to exploit.

And there are novel processes and fuels on the way. Exxon, for example, has dedicated US$600 million to finance an R&D collaboration with Synthetic Genomics, based in La Jolla, California, founded by human genome entrepreneur Craig Venter, to optimize photosynthetic algae to produce refinery-ready oils (see 'A scum solution', page S15). This spring, UCLA biomolecular engineer James Liao reported three novel bioprocessing ways to make butanol — a promising alcohol-based fuel that packs about 25% more energy per litre than ethanol. In one elegant demonstration of metabolic engineering, Liao made a biofuel by fermenting proteins instead of sugars. The source of the protein is the same algae from which Exxon and others are trying to harvest oils. Liao's approach to using algae makes sense because algae are roughly two-thirds protein, and at best one-quarter oil.

Liao's discovery of unimagined routes to butanol shows that this is a "pretty exciting time" for advanced biofuels R&D, says Mielenz. "The combination of thermochemical breakthroughs and the ability to genetically modify organisms means there are many more pathways and routes that we haven't yet discovered."

DOES ADVANCED MEAN GREEN?

Will biofuels advances translate into more sustainable transportation? They could, but only if producers and policymakers sweat the details and investigate the impact of biofuels on overall energy and environmental sustainability.

Studies suggest that it should be feasible to responsibly harvest sufficient biomass to meet ambitious biofuels targets. In May 2011, the Intergovernmental Panel on Climate Change (IPCC) issued a report on renewable energy projects concluding that biomass can by mid-century sustainably provide up to 300 exajoules — more than four times the biomass needed to meet the IEA target of 27% of the worlds' transportation fuel coming from biofuels. (One exajoule is one billion gigajoules, or one billion gigawatt-seconds.)

The question is how to ensure that the biomass is harvested as the IEA and IPCC recommend — maximizing the use of farm, forestry and municipal wastes, and encouraging cultivation of dedicated energy crops away from lands that provide carbon sequestration and other critical environmental services. One way to channel the development of biofuels along the greenest path is to develop a set of standards and practices that biofuels producers comply with, either voluntarily or by mandate. For example, in March 2011 the Roundtable on Sustainable Biofuels, run by the Energy Center at EPFL in Lausanne, Switzerland, released details of a certification system for biofuels to qualify between sustainable biofuels and those that are environmentally destructive.

That proposal has plenty of company. The IEA roadmap cites no fewer than 67 initiatives underway worldwide to develop just such criteria for biofuels sustainability — a proliferation that could muddy the waters further. When it comes to determining sustainability, international methods are needed, according to the IEA's Eisentraut, to head-off confusion that might discourage producers from trying to operate sustainably. "There's a risk of creating market distortions," he warns.

The problem is a lack of consensus on how to measure environmental impacts of biofuels. The issue that most bedevils the biofuels debate is that of indirect land use changes — the main problem cited in the 2008 *Science* paper. In the classic case, cultivation of energy crops on existing farmland displaces other crops to freshly-cleared forest lands, thereby causing a release of carbon from both the forest soils and trees. Factoring such indirect effects into life-cycle assessment of biofuels' environmental impact is a controversial exercise; a variety of methodologies and data input results in a wide range of results. The verdict on the greenhouse-gas emissions from producing a volume of a given biofuel from a given source of biomass from a given land can swing from sustainable to lamentable as various knock-on effects and feedback loops are layered into the equations.

How to handle biorefinery co-products such as excess power generation is another vexing area for life-cycle modelers. Geoffrey Hammond, director of the Institute for Sustainable Energy and the Environment at the University of Bath, United Kingdom, who heads-up a Biotechnology and Biological Sciences Research Council-funded programme on cellulosic ethanol, has studied methodological impacts on life-cycle studies for ethanol derived from wheat and barley straw. "Depending on which accounting methodologies you use the total amount of greenhouse-gas emissions can vary by at least a third," says Hammond.

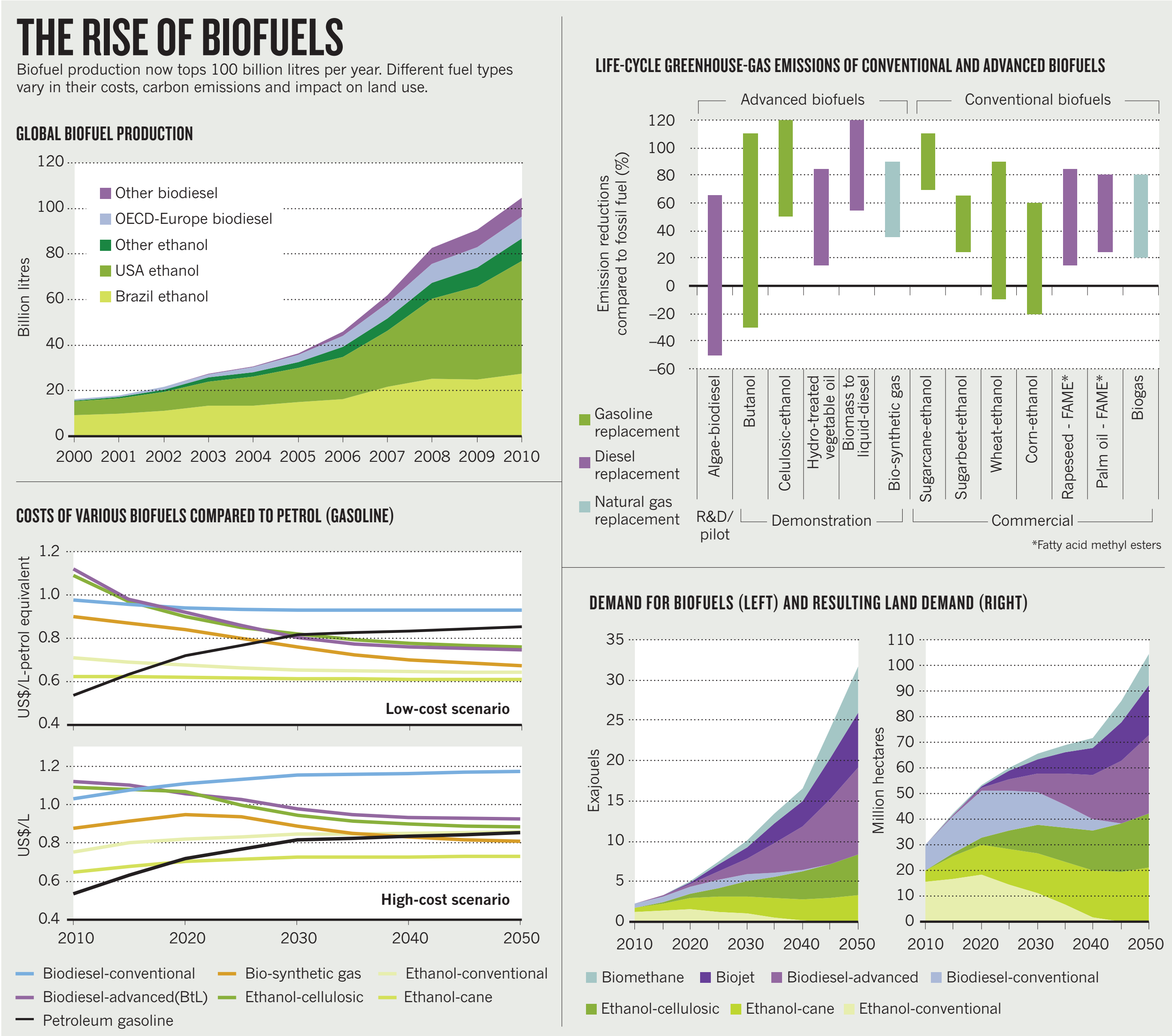
Hammond's group examined three protocols used in the United Kingdom for calculating emissions reductions and for attributing those to biofuels and biorefinery co-products. In all cases the environmental life-cycle assessment model found the straw-fed biorefineries and their ethanol to be net carbon-cutters. But the magnitude of the benefit is hard to pin down — the carbon footprint reduction ranges from a slim 9% to 38% depending on protocols.

Recent research has delivered some good news on the environmental impact of bio-fuels. Satellite analysis from Stanford University and the Carnegie Institution, Washington DC, reported in April 2011 in *Nature Climate Change,* identified a local cooling effect from planting sugarcane as an ethanol feedstock. Analysis showed that the sugarcane planted in central Brazil's Cerrado region reflects light better (higher albedo) and transpires more than the crops and pasture that the cane displaced. The net result of the conversion: a local cooling of 0.93°C. Such regional cooling could trim land-use impacts significantly by driving up agricultural productivity in arid regions such as the US southwest, says David Lobell, who studies food security at Stanford University and one of the report's authors. Extrapolating from modeling of high-albedo bioenergy crops such as switchgrass (*Panicum virgatum*) and *Miscanthus*, Lobell says that extensive plantings in the southwestern United States. could boost farm yields and thereby drive down prices for agricultural commodities. These lower prices would in turn dampen the incentive to convert forests and wilderness into farmland. "Local cooling could suppress indirect land-use change," says Lobell. "It's the kind of thing that we hadn't even thought about."

Progress in biofuels requires not just technical advances, but a level of predictability in the economic and policy terrain. Uncertainty can paralyze. The European Commission (EC) has yet to incorporate indirect land-use effects into its 2009 *Renewable Energy Directive*, which tasks European states with boosting

JOHN JAMES/ALAMY

A field of *Miscanthus,* one of several non-edible crops being used in next-generation biofuels.



SOURCE: INTERNATIONAL ENERGY AGENCY'S TECHNOLOGY ROADMAP: BIOFUELS FOR TRANSPORT, 2011.

renewables to 10% of transport energy by 2020 (see 'Fuelling politics', page S22). The directive recognizes only those biofuels whose carbon footprint is at least 35% lower than petrol (a threshold that rises to 60% by 2018). But guidance promised in December 2010 on how to handle indirect land use in the carbon footprint calculations was deferred to July, and possibly longer: "taking no action for the time being, while continuing to monitor impacts," is one option the EC is weighing up.

Regulatory paralysis freezes further incorporation of advanced biofuels into the energy supply. That worries both biofuels advocates and policy analysts, who say the status quo is untenable. "If we continue to just use fossil carbon the planet is doomed and indirect land-use changes could become fairly unimportant," says Jonathan Mielenz at Oak Ridge. "It's easy just to say biofuels are bad but the alternative is to just continue to use petroleum."

Aviation has an especially big stake in the biofuels. There is little prospect for battery-powered jetliners, so if air travel is going to become environmentally sustainable as the sector accelerates from an estimated 2.5 billion passengers worldwide in 2011 to a projected 16 billion passengers in 2050, the industry will need liquid fuels from renewable sources. The blend of refined camelina oil and petroleum jet fuel that powered Obama's F-22 Raptor may soon complete the multiyear certification process for new fuels for air travel. But commercial-scale biorefineries still remain but a figment of financiers' imaginations.

This stasis exasperates the Union of Concerned Scientists' Martin. The best way to determine how big a role advanced biofuels can play in the energy picture is to build twenty or so commercial-scale biorefineries to test the efficiency and impacts of growing energy crops, gathering and storing tonnes of biomass at a facility, and novel conversion processes, such as Mascoma's and Coskata's, to produce current and next-generation fuels. "Let's get to the first billion gallons. That will clarify a lot," says Martin.

One fact is beyond doubt: the roughly US$4 billion total pricetag in government incentives that Martin estimates is needed is a pittance compared to the subsidies now lavished on food-based fuels, which garner more than US$5 billion each year from the US government. If there is any consensus emerging around biofuels, it is that this set of funding priorities will need to change. Only then can vehicles powered by contemporary biomass, rather than plants long since dead and buried, have a chance to deliver the world to a cleaner and safer future. ■

Peter Fairley *is a science journalist in Victoria, British Columbia.*