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Decarbonizing Transport: What Role for Biofuels?

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The USA, Brazil, and the European Union (EU) account for most production and consumption of biofuels, almost all of this still consisting of first-generation bioethanol and biodiesel (Table 16.1). These fuels, which can be made from various feedstocks, cost more than petroleum, with the exception of ethanol produced in Brazil from sugarcane, and output would be near-negligible without government subsidies. These have been available in a number of countries since the oil crises of the 1970s, and production has increased, with ups and downs, since that time.

"Advanced" biofuels made from cellulosic biomass—agricultural residues ordinarily left in the field or inedible bioenergy crops such as switchgrass—or possibly from algae or bacteria might avoid or at least reduce competition with supplies of food needed to feed a swelling world population, but whether their promise will be fulfilled remains uncertain. Development of cellulosic biofuels has been disappointingly slow, and costs appear to be higher than anticipated. "Third-generation" fuels made from sources such as algae remain subjects of fundamental research, their future prospects unknowable.

Over the years, rationales for government support have shifted, with policymakers deemphasizing "energy security" and stressing the potential of biofuels for reducing emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) that drive climate change, emissions that

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Table 16.1 Biofuels production, 2014 (billions of US gallons)[a]

	Ethanol	Biodiesel	Total[b]
USA	14.4	1.24	15.0
Brazil	7.0	0.9	7.9
EU-28	1.4	3.1	4.8
World	*24.7*	*7.9*	*33.8*

Source: Renewables 2015 Global Status Report (2015) (Paris: Renewable Energy Policy Network), p. 129; based primarily on data from F.O. Licht

[a]Figures for production differ from those for consumption because of cross-border trade, which varies depending in part on prices in various parts of the world

[b]Includes renewable diesel (also known as green diesel) and biojet

stem mostly from combustion of fossil fuels—coal, oil, and natural gas. How big a difference biofuels might make in reducing GHG emissions over the next few decades remains uncertain. This question—the prospective contribution of biofuels to mitigation of climate change—is central to the discussion following.

1 Biofuels and Climate Change

Climate science is extraordinarily complex. Even so, three statements can be made with confidence. First, there is no sign of moderation in the climate dynamics driven by the release of GHGs into Earth's atmosphere (Blunden and Arnd 2015). Second, there are only two routes to mitigation, large GHG reductions or climate modification through geoengineering. GHG reductions have been preferred because no one has any real grasp of the risks, potentially very large, posed by geoengineering (National Research Council 2015). Third, in part because low-probability but potentially calamitous climate events cannot be ruled out, (Weitzman 2009) and also because the "ordinary" dynamics of climate change seem if anything to be accelerating, very large reductions in GHG emissions will be needed within the next two to three decades to begin slowing atmospheric warming and its consequences, such as sea level rise.

Climate change poses extraordinarily difficult issues for governance, and transport the knottiest set of technical issues (Box 16.1). The nature of these problems has been recognized for many years, and biofuels have often been viewed as part of the solution. Thus in the 1990s, an EU white paper found that "Specific measures are needed to help increase the market share of *liquid biofuels* from the current 0.3% to a significantly higher percentage" (European Commission 1997, p. 16). A few years later, EU authorities declared that "Greater use of biofuels for transport forms a part of the

Box 16.1 Degrees of malignity

Climate change has been called a wicked, or malign, problem (Levin et al. 2012). The appellation sets GHG reduction apart from control of ozone-depleting chlorofluorocarbons (CFCs) under the Montreal Protocol, an agreement that served as something of a model for the Kyoto Protocol. One indication of the disappointing outcomes of the Kyoto treaty: the Montreal Protocol, negotiated in the 1980s and silent on climate change, nonetheless has resulted in greater GHG reductions (Velders et al. 2007).

Differences begin with the narrow scope of the CFC problem. Scientific evidence widely accepted as conclusive linked a small number of chemicals used chiefly as refrigerants and aerosol propellants to readily apparent dangers such as heightened risks of skin cancer. A handful of firms produced CFCs, and at least one had substitutes in development. By contrast, GHGs implicate the entire world economy, or nearly all of it: hundreds of thousands, perhaps millions of firms, and an uncountable number of technologies. The far more complicated science of global warming, moreover, creates many opportunities for opponents to sow confusion and misunderstanding. At the same time, personal risks seem, to many, ill-defined and distant, certainly compared to malignant melanomas linked with ozone depletion, feared alike by politicians, corporate executives, and ordinary citizens.

The briefest look at the major sources of energy-related GHGs—electric power generation; buildings (residential and commercial, with their electrical and other energy loads); industry, goods production especially; and transport—will find the last of these heading almost any sort of malignity ranking. Technical solutions can be envisioned for the others. Nuclear power releases only incidental GHGs; Brazil gets three-quarters of its electricity from hydropower, and Norway even more; solar and wind energy continue to expand. Green design principles, well known and steadily improving, can cut building energy consumption to quite low levels. Much the same is true for many energy-intensive industrial processes, such as papermaking and cement production. Even if transition pathways seem to stretch interminably into the future, they can be marked out. Not so for transport. Oil still provides over 95% of transportation energy, and even as other uses for oil decline, markets for transport fuels (and for petrochemicals) continue to expand. Alternatives such as electrification pose stubborn technical and transition problems, and the probability of some sort of "game changing" technical fix, the transportation equivalent of, say, solar photovoltaic cells, seems essentially nil.

Table 16.2 Biofuels as percentage of all transportation fuels, 2014[a]

Brazil	22–23%
USA	8.3%
EU-28	4.5–5%
World	*3.5+%*

Sources: Brazil—production estimate based on *Petrobras 2030 Strategic Plan* (2015) (Rio de Janeiro: Petróleo Brasileiro S.A., February), 26, and *Brazil: Biofuels Annual*, GAIN Report No. BR14004 (2014) (Washington, DC: Department of Agriculture, USDA Foreign Agricultural Service, July 25), 7 and 15; USA—consumption, from *July 2015 Monthly Energy Review*, DOE/EIA-0035(2015/07) (2015) (Washington, DC: Energy Information Administration, July 28), 63, 151–52; EU-28—consumption estimate based 2012 figures in *EU Energy in Figures* (2014) (Luxembourg: European Commission), 112; World—production/consumption estimate based on 2013 figures in *Renewables 2015 Global Status Report* (2015) (Paris: REN21 Secretariat), 35

[a]Estimated share of bioethanol and biodiesel production/consumption

package of measures needed to comply with the Kyoto Protocol" (EU 2003, p. 42). Binding targets followed for all member states and consumption, supplied in part by imports, rose. Even so, biofuels account for no more than around 5% of EU consumption (Table 16.2). And while community-wide emissions from other major GHG sources have declined since 1990, those from transportation have risen by more than 15% (European Commission 2014, p. 33).

Transport accounts for nearly one-quarter of energy-related GHG emissions worldwide (Edenhofer et al. 2014). Serious efforts at mitigation of climate change require substantial reduction in GHG release from this sector. Yet it is not clear how this might be accomplished. As the EU example indicates, even when governments make strong commitments to decarbonization, the sector proves resistant. There is no obvious way to reduce CO_2 and other GHG emissions from transport except through partial and piecemeal shifts in modes (e.g., heavier reliance on high passenger-volume transit systems in urban areas), platforms (new generations of higher-efficiency aircraft that burn less fuel, hence emit less CO_2 per passenger mile), and diversification of the technologies embodied in road vehicle fleets (such as battery-electric power trains). This sort of transition pattern resembles that in other major GHG-emitting sectors, such as electric power generation. The difference is that *none* of the prospective transport technologies, with the possible and still uncertain exception of biofuels, holds out the promise of near-total decarbonization, as associated with solar or wind power. The central questions in this essay, then, can be narrowed to a focus on GHG emissions from transportation, and especially road vehicles. This was not, however, the original thrust of government policies.

2 Policy Rationales

As of 2015, more than 60 countries had adopted policies of one sort or another to encourage biofuels production and consumption (REN21 2015; Clark 2015). They divide into three main categories. Financial incentives such as tax preferences, which take many forms, aim to erase the cost/price disadvantages of biofuels noted in Box 16.2, as do price guarantees. Indirect subsidies such as consumption mandates—in place in around 30 countries in 2015—require suppliers to blend biofuels with gasoline or diesel fuel in some generally small percentage. The effect is to create a guaranteed market fenced off from competition with petroleum and therefore insensitive to price, an indirect subsidy. Many governments also fund research and development (R&D); topics range from yield-enhancing cultivation practices for first-generation bioenergy crops to long-term, fundamental research.

Broadly speaking, the search for energy security in the wake of the 1973–74 Arab embargo and the 1979 Iranian Revolution drove the original push for biofuels. Facing gasoline shortages and seeking to stretch supplies, governments in a number of countries added bioethanol and biodiesel to lists of energy interests gifted with policy favors.

Oil markets have become far more resilient since the 1970s (Kilian 2008). Even so, energy security remains a popular political trope. National economies differ greatly in their dependence on imported oil and vulnerability to price fluctuations. Even so, the essential point is simple enough: global biofuels production, now about 2.2 million barrels per day, is insufficient to offset even a supply interruption comparable to that during the 1991 Gulf War, when Iraq's production fell from about 3 million to 0.3 million barrels per day. And this, like other production declines before and since, did not result in a price shock remotely comparable to those experienced in the 1970s

Box 16.2 First-generation bioethanol and biodiesel

Many types of biomass can be processed into liquid (or gaseous) fuels of many types. Processes for making bioethanol from corn (maize) or sugarcane resemble those for alcoholic beverages, some form of milling followed by distillation. Biodiesel, the other first-generation biofuel, is likewise easy to make from oilseeds or organic wastes. For both these fuels, purchased feedstock accounts for up to two-thirds of total costs, sometimes more, depending on crop prices. For both these fuels too, leaving aside sugarcane ethanol in Brazil, costs exceed those for petroleum at generally prevailing crude oil prices (Cazzola et al. 2013). A price on carbon would alter the picture, and a sufficiently high price would obviate subsidies governments have put in place; so would oil prices in the range of, say, \$200 per barrel.

Both first-generation biofuels also have technical limitations. They differ chemically from petroleum, which can result in instability (e.g., decomposition over time) and, more seriously, renders them incompatible with most existing vehicles and infrastructure (pipelines, tanks, and pumps) except in low-percentage blends with petroleum (Alic 2013). Ethanol, on the other hand, has compensating advantages in boosting octane and reducing smog-creating tailpipe emissions. And while biomass can be processed into hydrocarbons chemically indistinguishable from petroleum—biogasoline and “renewable” or “green” diesel—this requires further refining steps at added cost.

Historically, a plantation economy, Brazil, is uniquely favored for bioethanol, with abundant land suited to growing cane sugar (two crops per year in some places), ample rainfall (at least until the 2014 drought), and large numbers of low-wage agricultural laborers who hand-harvest the cane—labor that in the eyes of some continues to be grievously exploited (McGrath 2013). In the 1970s, the military government then ruling Brazil in essence dictated creation of a biofuels industry. Since those years, inflation-adjusted production costs have decreased by a factor of three—low enough that Brazilian bioethanol can compete with petroleum even at oil prices below \$50 per barrel (Mendes Souza et al. 2015, p. 495).

(Blanchard and Gali 2007). Unless biofuels output were to greatly increase—and there are no guarantees that large increases would be sustainable, for reasons discussed below—and costs were to come down to levels competitive with petroleum, biofuels will not have much effect on oil markets.

Governments frequently voice additional justifications for biofuels policies, such as rural development and job creation. These too are dubious as policy rationales. Rural development is a common watchword among politicians; yet even in countries that take it seriously, bioenergy crops, while providing supplemental income for some farmers, will probably never be very profitable for smallholders. Most, if able to grow higher valued-added crops, whether strawberries or coffee beans or flowers—or biofeedstocks for specialty chemicals—can expect to do better than by trying to compete with commercial growers of commodity bioenergy crops. Not only do large concerns dominate agriculture in many parts of the world, multinational corporations (MNCs) dominate downstream production. US-based Archer Daniels Midland reportedly operates the world's five largest bioethanol facilities (REN21 2015), and Abengoa, a major biofuels supplier based in Spain, gets more than 85% of its revenues outside its home country. (Abengoa, under severe financial pressure, sought protection from its creditors at the end of 2015). Even in Brazil, for many years a partially closed economy, MNCs (including Abengoa) account for a substantial, and rising, share of output (Damaso et al. 2014). Big MNCs have market power to bid down feedstock prices, and with subsidies tilted toward biorefiners rather than growers, generally reap the bulk of the rewards.

The benefits of job growth have frequently been overstated too. While any new biorefinery will hire workers locally, the numbers tend to be modest. Biorefineries on average are small, their capacity limited by shipping charges for low-value biomass (Alic 2015). Most employ only a few dozen people. Although indirect jobs such as driving trucks add to those inside the plant, other work meanwhile vanishes, albeit elsewhere and not necessarily in equal numbers. Gains in Iowa, for instance, may be offset by losses in North Dakota or Louisiana (or perhaps the Brazilian state of São Paulo). Politicians will always brag of jobs created, saying nothing of net effects. The latter cannot in any case be estimated with much accuracy, being small differences in large aggregates displaced geographically and temporally. For such reasons, and again leaving aside local impacts, the figures put forward for creation of "green jobs" seldom have much credibility (Berck and Hoffmann 2002). This leaves reductions in GHG emissions—possible but not guaranteed—as the primary reason, looking ahead, for government support of biofuels. Yet even as this rationale has gained prominence, concern over the full range of impacts has risen.

3 Assessing Impacts

Because growing plant matter takes up CO_2 from the atmosphere, substituting biofuels for fossil fuels can lower *net* GHG emissions, but only *if* removals of CO_2 exceed emissions elsewhere over the entire life cycle and along the entire supply chain, from land clearing for new cultivation through to processing and final consumption. Many imponderables cloud life-cycle analysis (LCA), and not all LCAs include the full range of environmental effects, those beyond GHG emissions themselves. These are many and can be large (Davis et al. 2009). Increased production of cultivated biomass, for example, normally means more usage of fertilizer, and fertilization releases large volumes of nitrous oxide, a warming agent some 300 times more powerful than CO_2. And because grasslands and forests serve as major terrestrial carbon sinks, clearing additional land for cultivation releases large amounts of CO_2, whether through burning or slow decomposition. Many years may then pass before cumulative GHG reductions from displacement of fossil fuels overtake the initial CO_2 release (Elshout et al. 2015).

Published LCA figures, not surprisingly, span wide ranges and often prove controversial. Even for LCAs restricted to GHG emissions from first-generation biofuels, which have been intensively studied, "the range of uncertainty can be larger than the average expected benefit," creating "a risk that such fuels provide no benefit or even produce higher rates of greenhouse gas emissions than oil products" (International Transport Forum 2007, p. 2). Box 16.3 provides further discussion.

The US Congressional Budget Office (CBO) has presented a useful comparison of GHG estimates (only) gathered from several sources. These show emissions for corn ethanol relative to gasoline that range from decreases of nearly 50% to large increases (CBO 2014, pp. 24–5). Sugarcane ethanol and biodiesel do better, with GHG reductions generally in the range of 50% or more. Both these fuels also offer superior energy balances—the ratio of the energy available in the final fuel to that consumed in cultivation, processing, and so on. Estimates for second-generation cellulosic ethanol tend to be still more favorable. Made from the inedible cell walls of plants including byproducts such as corn stover (postharvest remnants ordinarily left in the field) and woody energy crops, cellulosic fuels have the additional advantage of reducing or eliminating upward pressure on food prices. The estimates CBO presents for corn-stover ethanol range from small GHG decreases relative to gasoline to reductions of more than 100%. The necessary caution: there is as yet little empirical data for input into LCA analysis of cellulosic ethanol; processing technology has proven unexpectedly recalcitrant, with production underway in only a handful of mostly small plants (Alic 2015).

Box 16.3 Life-cycle analysis

Not all environmental impacts associated with biofuels are as obvious as, say, soil degradation and water pollution through runoff, and many assessments slide over non-GHG impacts of all types: "From a representative sample of LCA studies on biofuels, less than one third presented results for acidification and eutrophication and only a few for toxicity potential (either human toxicity or eco-toxicity, or both), summer smog, ozone depletion or abiotic resource depletion potential, and none on biodiversity" (UNEP 2009, p. 17).

Besides neglect of non-GHG impacts, two additional factors contribute to the wide range of published LCA estimates. Reliable empirical data for input and calibration of computer models remains scarce, especially as concerns biomass growth, which takes place under vastly different conditions from place to place and time to time. Agrochemical applications vary widely, for example, and less than average rainfall one year may mean more than usual irrigation, consuming extra energy and depleting aquifers. Second, because of the opacity of LCA models and the many assumptions they embody, "it is much too easy to use a model to generate, and thus seemingly validate, the results one wants" (Pindyck 2015, p. 8).

In recent years, indirect land-use changes, which take place when farmers bring new land under cultivation, have been especially contested. Demands on arable land—as terrestrial carbon sinks; for bioenergy crops; for growing food to feed growing population, in poorer countries especially—lead to sharp conflicts. At the same time, agricultural land goes in and out of production constantly, and for many reasons. In recent years, for example, much land in countries including Indonesia has been clear-cut for crops such as palm oil, sold both for biodiesel and as an ingredient in food products and cosmetics. How much palm oil goes for biodiesel and how much for food depends on market prices determined by supply and demand. For such reasons, indirect land-use changes cannot be linked to biofuels production in meaningful ways—another major unknown in trying to assess long-term sustainability (Finkbeiner 2013).

There is no real question, conversely, that expanded cultivation of bioenergy crops exerts upward pressure on food prices (Wright 2014). In the USA, biorefiners have recently taken as much as 40% of the corn crop and food prices have risen broadly; much corn is sold as livestock

Box 16.3 (continued)

feed, and more costly feed means more costly chicken and beef, while corn syrup is a common sweetener in processed foods. Even in a country as wealthy as the USA, rising food prices mean hardship for some, and arguably contribute to unhealthy diet choices.

Algae and other advanced biofuels could skirt at least some of the liabilities sketched above. Their promise cannot as yet be judged with any confidence. There are thousands of possibilities, relatively few of which have been explored in much depth, so that projected costs, net GHG emissions, and effects on land and water usage represent little more than informed speculation (National Research Council 2012).

4 The Transport Dilemma: Personal Vehicles

If biofuels are to make much difference for mitigation of climate change, it will be through replacement of petroleum fuels for road vehicles. Cars and trucks account for over 70% of GHG emissions from transportation, far exceeding those from waterborne shipping and aviation, each in the range of 11% (Edenhofer et al. 2014). The world stock of cars and trucks (plus buses, motorcycles, etc.), now around 1.2 billion, is expanding rapidly (OICA 2015). By midcentury, the total will probably exceed 2 billion, and could reach 3 billion. Much of the growth will be in developing countries, driven by rising levels of disposable income. Market projections suggest increases over the period 2010–2030 of perhaps 80% in Brazil, more than 200% in China, and as much as 600% in India, compared with no more than 20–30% in the USA and Europe (International Council for Clean Transportation 2013, p. 11). No one expects such forecasts to be accurate; still, the relative rates of growth should be indicative.

New vehicles sold in wealthy country markets incorporate many GHG-reducing technical advances to meet increasingly strict regulatory standards for fuel mileage, CO_2 emissions, or both. These include hybrid, battery-electric, and, soon, fuel cell-electric power trains, along with modified conventional power plants (and transmissions) of several types. At the level of the vehicle system, lighter weight and reductions in aerodynamic drag, friction and rolling resistance, and auxiliary loads (heating, air conditioning, power steering, and brakes) yield further gains. Even though battery costs for electric vehicles, to take one example, have been declining quite rapidly (Nykvist and Nilsson 2015), all this comes at a price, one that markets in poorer countries will not easily support. Most developing countries have no fuel mileage or CO_2 standards; others, including China and India, have proposed, announced, or put in place standards. Even so, these standards tend to be less stringent than those in the USA and EU (to hold down costs), and future enforcement could prove lax.

The world fleet, at the same time, turns over slowly. The average age of vehicles worldwide is around 15 years. Millions of older vehicles remain in use more-or-less indefinitely, often passed on to developing country markets as used cars or trucks. Under any scenario, then, it will take many years to replace today's vehicle stock with newer low-GHG types, or with alternatives suited to dense urban conurbations. After all, even in affluent markets, sales of vehicles incorporating more advanced, and expensive, technologies have been slow. Nissan's battery-electric Leaf is the world's best-selling car of its type; the company no doubt lost a considerable sum on each Leaf built in 2014—about 60,000. And even 600,000 battery-electric vehicles per year would not make much difference for GHG emissions, which are largely displaced to fossil fuel power plants (with exceptions for nuclear-dependent France and a few countries with abundant hydropower); in the USA, for instance, electric vehicles may increase CO_2 emissions compared to hybrids and even conventional vehicles, depending on region and time of day of charging (Graff Zivin et al. 2014). To be sure, if self-driving battery-electrics eventually replace large numbers of personally owned vehicles in cities, energy consumption and emissions per passenger mile would decline; battery-electrics save energy through higher overall efficiency than conventional vehicles; self-driving vehicles save additional energy through more nearly optimal route planning and, eventually, lower levels of congestion; and sharing of such vehicles reduces GHG emissions per passenger mile still further. Yet most future megacities will be relatively poor, at least initially, with infrastructures ill-suited to such innovations (and perhaps to electrified transit systems as well).

The great majority of vehicles entering the world fleet over the next decade, at least, will continue to run on gasoline or diesel fuel (product development cycles in the auto industry run half a dozen years or more, and longer still for engineering work on innovations that count as more than incremental). Greater numbers of such vehicles traveling more miles means increasing volumes of tailpipe CO_2 at a time when fast action is needed to control climate change. There is only one way to reduce CO_2 from such vehicles—change the fuel. Policymakers are right to ask whether and by how much biofuels could hold down life-cycle GHG emissions from transportation.

5 Comparing Policies: Brazil, the USA, the EU

Path dependent policy outcomes reflect institutional, political, and administrative structures, which, for biofuels, interact with technological advance and the dynamics of national economies and the international economy. Corn ethanol in the USA illustrates. A myriad of subsidies and incentives at federal and state levels, built up over the years under the influence of agribusiness interests, has meant that essentially all gasoline (or gasohol) contains 10% corn ethanol, even though this is the least desirable of all biofuels in terms of GHG emissions and energy balance. If US policies reflect interest group politics, Brazil, under military rule at the time, made sugarcane ethanol part of the country's fuel mix by government fiat. In much of Western Europe, meanwhile, popular support for environmental protection slowly moved biofuels onto policy agendas. The rest of this section offers a rather impressionistic view of policies in the Brazil, the USA, and the EU, without attempting to be exhaustive.

In late 1975, when Brazil's ProÁlcool, or National Alcohol Program (Programa Nacional do Álcool) took effect, the country's offshore oil reserves had yet to be discovered and imports made up around 80% of consumption. When oil prices skyrocketed, so did the country's trade deficit. Even so, ProÁlcool, which included measures such as subsidized loans for construction of biorefineries and guaranteed purchases of their outputs, should not be taken simply as a response to energy shock. Rather, the program was conceived and implemented as part of Brazil's long-running economic development strategy, its version of the import substitution industrialization (ISI) policies widespread in Latin America after the Second World War (Meyer et al. 2013). With measures such as import barriers to shield domestic firms from MNC competition and local content rules requiring foreign-owned investors to procure inputs from domestic suppliers, ISI policies aim to enhance indigenous capabilities. ProÁlcool built on earlier measures directed at MNC auto firms that wished to sell into South America's biggest market. Despite policy stumbles and market shifts, the program retains its overall shape and thrust (Box 16.4).

In the USA, in some contrast to Brazil, weak and divided government and sharply clashing private interests leave energy policy incoherent to the extent that it is easy to argue no such thing exists. Congressional committees and subcommittees jostle one another for oversight and control, scattering administrative responsibilities among major and minor agencies and subagencies with vague or overlapping charters and little provision for coordination. Such

Box 16.4 Ethanol in Brazil and flexible-fuel vehicles

Brazil's economic development policies spurred rapid growth of domestic auto production starting in the late 1950s. By the midpoint of the following decade, MNCs including General Motors and Volkswagen were buying nearly all their parts and components from local firms (Teitel and Thoumi 1986). At the time ProÁlcool took effect, Brazilian engineers employed by MNCs and domestic suppliers had no trouble developing power trains suited to ethanol.

In the mid-1980s, oil prices began to fall and Brazil's balance of payments improved. With cheap gasoline again available, ethanol subsidies were cut, output flattened, and Brazilians who had purchased ethanol-only vehicles could not always find fuel; as a result, sales of gasoline-only vehicles rose sharply (Goldemberg and Horta Nogueira 2014). The government, by then democratically elected, responded with legislation mandating 22% ethanol in gasoline, and several years later required automakers to produce flexible-fuel vehicles able to burn gasoline or ethanol in essentially any proportions. The key feature of these flex-fuel power trains, again developed by locally owned suppliers and the Brazilian employees of MNC automakers and parts firms: an exhaust sensor that detects the alcohol content of the fuel based on products of combustion and a control system that adjusts fuel injection volumes accordingly.

Since 2003, many new cars sold in Brazil, and in some years most, have been able to run on either gasohol (the mandate is now 27% ethanol) or straight ethanol. Consumers choose which fuel to buy based on prices at the pump, set by government depending on oil prices and on available supplies of ethanol, which vary regionally, seasonally, and with demand for sugar as a food product. Brazil now exports considerable quantities of both fuel ethanol and sugar.

Automakers also produce flex-fuel vehicles in the USA, but sales have been modest, despite tax incentives, in part because retailers have not made high-alcohol fuels (e.g., E85, 85% ethanol and 15% gasoline) widely available. No more than 3000 of nearly 160,000 US fuel outlets sell E85, and they do not always price it below gasoline to compensate for lower energy content (Pouliot and Babcock 2014). Brazil remains alone in having a large market for high-ethanol fuels and flex-fuel vehicles.

a setting gives private interests abundant openings to press for measures, or interpretations, they prefer. The record since the time of the First World War, when mechanization on land and in the air as well as at sea made energy in the form of oil a major national security concern, reads as a grab-bag of measures with something for nearly everyone: coal and oil first, joined later by natural gas, then in the 1950s by nuclear power, and since the 1970s by renewables.

Biofuels policies grew by accretion. Midwest farming interests retain great influence in Washington even though agriculture now accounts for only around 1% of economic output. Corn is big business in Iowa, the state routinely leading all others in production. Iowa's early presidential caucuses attract national attention. Hopefuls endorse corn ethanol subsidies almost universally, regardless of their views on economic affairs more generally. When Barack Obama entered the White House in 2009, he named Thomas Vilsack, two-term Iowa governor and a former rival for the Democratic Party's nomination, Secretary of Agriculture. Well into President Obama's second term, Vilsack, a tireless ethanol booster, continues in the position.

Lacking much in the way of party discipline, legislation results only when coalitions come together, perhaps fleetingly, in Congress. More than in most countries, US policymaking can be considered a garbage can, into which flow "independent, exogenous streams" bearing "problems, solutions, decision-makers, and choice opportunities" (Olsen 1991, p. 92). On occasion, the cooks manage to serve up a stew, or a menu of stews. The laws that encapsulate current US biofuels policies—the 2005 Energy Policy Act; the 2007 Energy Independence and Security Act; and the 2008 Food, Conservation, and Energy Act (the title given that year's farm bill)—total some 1500 pages. These laws, with a few subsequent modifications, established a complicated structure of tax incentives for biofuels, some now expired, consumption quotas, some unrealistic and unenforced, plus ancillary measures such as import duties on bioethanol, aimed at sugarcane ethanol from Brazil and also now expired (Yacobucci 2012). The mélange is grossly inefficient in an economic sense, far more costly than would be such alternatives as a price on carbon (Holland et al. 2011).

In 2006, with petroleum prices on the rise, President George W. Bush deplored the nation's "addiction" to oil in his State of the Union address, and went on to register his support for biofuels: "We will increase our research … in cutting-edge methods of producing ethanol, not just from corn but from wood chips and stalks or switch grass. Our goal is to make this new kind of ethanol practical and competitive within 6 years" (Government Printing Office 2006, p. 150). It did not happen. Congress established quotas mandating production of "advanced biofuels" such as cellulosic ethanol beginning in 2009—made from feedstocks of the sort to which Bush had referred—with quantities stepping upward through 2022. Given assured markets, written into law, perhaps 200 companies, large and small, announced R&D and investment plans. Process development for cellulosic ethanol proved much more difficult than expected, estimated production costs rose, and a number of high-profile bankruptcies followed (Alic 2015). In the absence of production capacity, the mandated quotas could not be met. Congress had charged the Environmental Protection Agency (EPA) with administrating the quotas, including discretion to adjust them. EPA had no choice but to cut those for advanced biofuels year by year to token levels.

Regulations covering automobile fuel economy and GHG emissions provide a further illustration of the incoherence common in US governance. Amendments to the Clean Air Act (CAA) in 1970 made EPA responsible for tailpipe emissions. A few years later, at the time of the first energy crisis, Congress wrote the first Corporate Average Fuel Economy (CAFE) standards into law, assigning them to a subagency of the Department of Transportation, the National Highway Traffic Safety Administration (NHTSA). In 2007, following years of administrative and legal proceedings, the Supreme Court finally ruled that EPA had authority under the CAA and amendments to regulate GHGs from road vehicles. Since tailpipe CO_2 depends almost entirely on fuel economy, hence on CAFE standards, EPA and NHTSA then had to find ways to coordinate their actions likely to be found acceptable under existing laws and decades of sometimes strained interpretations and court decisions—all under the watchful eyes of environmental groups, affected industries, Congress, and also the White House Office of Management and Budget, which, ever since Ronald Reagan's presidency, has intervened frequently but erratically in environmental rule-making, nearly always to weaken (or delay) them (in Republican and Democratic administrations alike) (Heinzerling 2014).

In contrast to the opacity of so much that goes on in Washington, the early agenda-setting stages of EU policymaking feature steams of green papers, white papers, and other more-or-less technocratic documents intended to inform, reflect, and build consensus—or not, since seemingly endless discussion and debate sometimes leads to nothing, or to stalemate, or to toothless compromise. At the culmination of one such process, EU legislation adopted in 2009 will require each member state, by 2020, to get at least 10% of "final energy consumed in transport" from renewable sources (EU 2009). Amendments pending as of mid-2015 would cap the contribution of first-generation biofuels at 7%, reflecting rising concerns over land use and sustainability.

6 Conclusion: The Future of Biofuels

At the time of the 1970s oil crises, when governments began to promote biofuels, only a few skeptics foresaw their limitations. These are real, and a good deal of the early enthusiasm had dissipated well before oil prices began their most recent decline. Investment continues, especially in South America (Argentina, Colombia) and Asia (China, Indonesia), but the worldwide trend has been sharply downward: global annual biofuels investments have dropped from nearly $30 billion in 2007 to about $5 billion in 2014 (UNEP 2015, p. 15). The International Energy Agency projects only slight increases in output over the next few years, from 2.2 million barrels per day currently to perhaps 2.4 million barrels in 2020 (IEA 2015, p. 6).

In the longer term, how much of the global market for transport fuels might bioenergy supply? With sustainability a criterion, most estimates cluster not too far from 20% (REN21 2014, p. 41; Department of Energy 2015, p. 422). Such estimates depend on assumptions that begin with acreage that might be available for bioenergy crops without encroaching on agricultural land needed to feed a world population expected to exceed 11 billion by century's end, on ongoing technological advances in producing cellulosic ethanol, and on overall demand for fuel, which will depend on variables including vehicle efficiency improvements and changing patterns of transport usage. Perhaps needless to say, large uncertainties attach to most of these factors. There seems little reason today to go beyond the view expressed some years ago by the UK Royal Society: "Biofuels have a limited, but potentially useful, ability to replace fossil fuels, largely due to technical and economic constraints" (Royal Society 2008, p. 62). If anything, the constraints seem to tightening, particularly those rooted in land use and competition with food crops (Johnson et al. 2014).

Over the longer term, prospects for biofuels hinge on radical innovation. Many possibilities remain to be explored: genetic engineering of algae; bacteria; perhaps "solar fuels," hydrocarbons made by removing CO_2 from the atmosphere (or perhaps from the flue gases of fossil fuel-burning power plants) and, with energy inputs from sunlight, combining the carbon in the CO_2 with hydrogen from water to yield synthetics chemically interchangeable with petroleum. Yet while incremental innovations of the sort ongoing with cellulosic ethanol can often be predicted, radical advances cannot, and policymakers should not assume that research spending will pay off: innovations, quite simply, cannot be forced into being. Still, if transport emissions cannot in one way or another be reduced, much of the crude oil still in the ground will sooner or later be burned and Earth will continue to warm, with results that no one can predict—but which will almost certainly be enormously disruptive for billions of people, especially those in low-income countries with limited capacity to adapt.

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