

Chapter 26

Getting the carbon out of transportation fuels

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Transport is currently responsible for 13% of global greenhouse gas (GHG) emissions and it contributes 23% of global carbon dioxide emissions from fuel combustion (International Energy Agency, 2008). Global transport-related carbon dioxide emissions are expected to increase by 57% in the period 2005–2030, making this the fastest growing sector globally. At the same time, there is broad consensus in science and politics that global GHG emissions must be reduced by more than 80% from 1990 levels by 2050 to avoid perilous global warming. It is clear that the transport sector will need to be central to mitigation efforts. One important contribution towards this goal can be to reduce the carbon content of fuels or, more generally, vehicle propellants. In this essay, we investigate the potential of biofuels and electric mobility to decarbonize car transportation. As with most areas of a sustainable energy economy, large improvements are possible, but they require a ‘systems science’ approach that works across disciplines and considers traditional vehicles approaches and stationary power. Science, technology, policy, economics, and cultural awareness must be utilized in concert.

Innovations in response to challenges: from lead to carbon

During the late 1970s and early 1980s, the highest-profile environmental issue in the vehicle and fuel industries was the establishment of a ban on lead additives in petrol – encapsulated by the slogan *get the lead out*. After initial uncertainty and some opposition based on the fear that prices would rise and vehicle performance would suffer, the transition to unleaded fuels proved remarkably easy and effective. Between 1970 and 1987 the average blood-lead level in the US population dropped by 75%, and the blood-lead levels of up to two million children were reduced to below toxic levels every year as leaded petrol use was curtailed.¹ In direct response to the reduction in atmospheric lead the IQ levels of previously lead-exposed urban children increased (Thomas, 1995).

The US Congress also enacted the Corporate Average Fuel Economy (CAFE)² regulations, a sustained effort to raise average vehicle efficiency standards in response to the 1973 Arab oil embargo. This measure increased vehicle mileage standards by more than 25%. Such examples demonstrate that ambitious, yet achievable, targets can be codified, enforced, and adjusted as technological, economic, and environmental needs change. These targets set a precedent for what is possible. In other words, technological innovation combined with economic and environmental necessity is altering the landscape of vehicle efficiency. Today’s innovation is reminiscent of the effort to *get the lead out*, only this time the goal is to *get the*

¹ <http://www.thenation.com/doc/20000320/kitman>

² <http://www.nhtsa.dot.gov/cars/rules/cape/overview.htm>

carbon out of transportation fuels. One policy measure that supports ambitious emission-reduction targets is the low-carbon fuel standard.

The low-carbon fuel standard is a simple and elegant concept that targets the amount of GHGs produced per unit of energy delivered to the vehicle; i.e. the vehicle's so-called 'carbon intensity'³. In January 2007, California Governor Arnold Schwarzenegger signed Executive Order S-1-07,⁴ which called for a 10% reduction in the carbon intensity of his state's transportation fuels by 2020. Eight months later, a coalition that included one of the authors (DMK) and other researchers at the University of California and non-governmental groups responded with a technical analysis⁵ of low-carbon fuels that could be used to meet that mandate. The report relies upon life-cycle analysis of different fuel types, taking into consideration the ecological footprint of all activities included in the production, transport, storage, and use of the fuel.

If a low-carbon fuel standard were established, fuel providers would track the 'global warming intensity' (GWI) of their products and express it as a standardized unit of measure – the grams of carbon dioxide equivalent per megajoule (gCO₂e/MJ) of fuel delivered to the vehicle. This value measures not only direct vehicle emissions but also indirect emissions, such as those induced by land-use changes related to biofuel production. The global warming intensity also provides a common frame of reference to compare propellants as diverse as petrol and electricity. Before discussing the GWI of biofuels and 'electromobility', let us contrast the low-carbon fuel standard with current policies on biofuels.

Problematic biofuel policies

Unfortunately, the first biofuel policies were developed before the true impact of global warming was known, with the main examples coming from the USA and EU. In the USA, two current policies promote biofuels: a USD 0.51 tax credit per gallon of ethanol used as motor fuel, and a mandate that up to 7.5 billion gallons (5–6% of total US fuel demand) of 'renewable fuel' be available at US petrol stations by 2012. The EU aims that by 2020 biofuels will account for 10% of fuels used in the transport sector.⁶

Government policies to promote biofuels intend to improve environmental quality (for example, to reduce the impact of global warming) and aim to support agriculture and to reduce petroleum imports. In practice, however, current government

³ Our team published a paper and an open-access life-cycle model, called 'EBAMM', which has been widely used to assess the carbon impacts of a broad range of fuels (Farrell *et al.*, 2006).

⁴ <http://gov.ca.gov/executive-order/5172>

⁵ http://www.energy.ca.gov/low_carbon_fuel_standard/UC-1000-2007-002-PT1.PDF

⁶ <http://www.euractiv.com/en/transport/biofuels-transport/article-152282>

biofuel policies tend to function most directly as agricultural support mechanisms, involving measures such as subsidies or mandates for the consumption of biofuels. By contrast, the environmental impacts of biofuels, and more specifically the GHG emissions related to fuel production, are often not measured, let alone used to adapt financial incentives or to guide government regulation. Yield maximization for a number of agricultural staple crops often involves high levels of fossil-fuel inputs (e.g., for fertilizers), further complicating the mix of rationales for biofuel support programmes. It is important to apply a fairly broad framework on biofuel policies to avoid repeating past mistakes.

Sustainability and economic path dependency. The biofuel industry has been growing rapidly and can be very profitable when world oil prices are high. Government policies to further subsidize, mandate, and otherwise promote biofuels are being implemented, and more are proposed. Given the large investments in research and capital that continue to flow into the biofuels sector, it is time to carefully assess the types and magnitudes of the incentives that are meant to mitigate global warming. By engaging in this analysis, we can reward sustainable biofuel efforts, and avoid the very real possibility that the economy could be further saddled with the legacy costs of short-sighted investments.

Global warming impact. Biofuels are often proposed as a solution to environmental problems, especially climate change. However, biofuels can have a positive or negative global warming impact relative to petrol, depending on the precise production pathway (Farrell *et al.*, 2006), as we will discuss in the next section. To distinguish between these two cases, and the myriad of other feedstock-to-fuel pathways, as illustrated in Figure 1, clear standards, guidelines, and models are needed.

Development of novel biofuels. Many new fuels, feedstocks, and processing technologies are now emerging, and numerous others are under consideration (Tilman *et al.*, 2006; Gray, 2007; Stephanopoulos, 2007). These are being developed as biofuel technologies per se; they are not merely adaptations of pre-existing agricultural production methods. If these developments can be managed to achieve high productivity while minimizing negative environmental and social impacts, the next generation of biofuels could avoid the disadvantageous properties of a number of current biofuels (e.g., low energy-density, corrosiveness, and poor performance at low temperatures).

A transparent set of data on what we wish biofuels to provide, as well as clear and accessible analytic tools to assess different fuels and pathways, are critical to efforts aimed at providing appropriate incentives for the commercialization of cleaner fuels. This entire analysis, however, needs further elaboration.

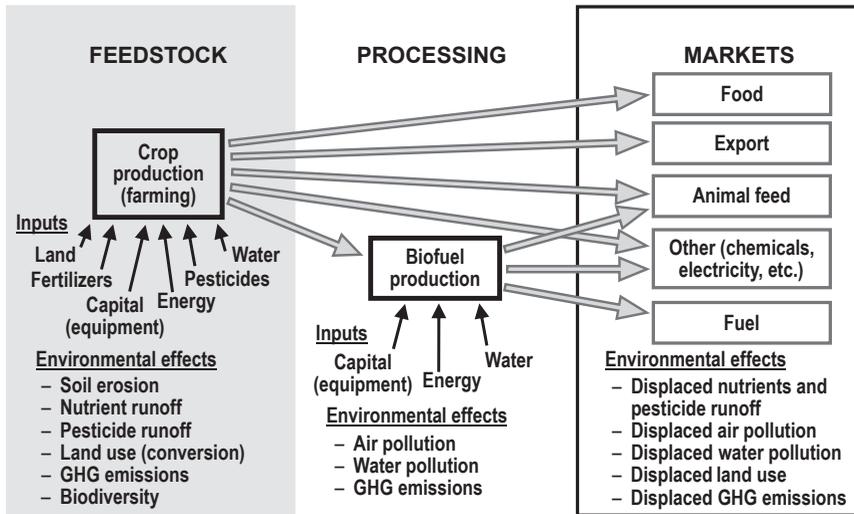


Fig. 1. Simplified general biofuel pathway with inputs and environmental impacts. Many effects are displaced; i.e., they occur at different locations due to market-mediated forces. (Source: adapted from Kammen *et al.*, 2008).

What is the carbon impact of biofuels ... and of other new fuels?

Biofuels and related GHG emissions are a contentious issue, both in the political and research arenas. A variety of different GHG emission values have been reported, ranging from a 20% increase to a 32% decrease when switching from petrol to ethanol in the United States (Farrell *et al.*, 2006). Our group developed EBAMM (The ERG Biofuel Meta-Analysis Model; Farrell *et al.*, 2006; Kammen *et al.*, 2008) to compare and reconcile these different values. A major reason for inconsistencies was the choice of different system boundaries; i.e., the choice of which processes to include in biofuel GHG emission accounting, and which to exclude. Harmonization of boundaries – for example, excluding emissions induced by human labour but including the displacement of GHG emissions by energy-valuable co-products of ethanol – brings the GWI of the different processes closer together. Any significant remaining uncertainty is mostly due to the unknown and not-well-studied effect of lime application (lime is added to correct the pH of acidic soils; it is applied only once, and it is crucial to account for GHG emissions over the full yield period). According to the updated EBAMM,⁷ ethanol produced using a carbon-dioxide-intensive refining process (e.g., a lignite-powered ethanol plant) has a marginally better GWI than petrol (i.e., 91 gCO₂e/MJ instead of 94 gCO₂e/MJ), while average

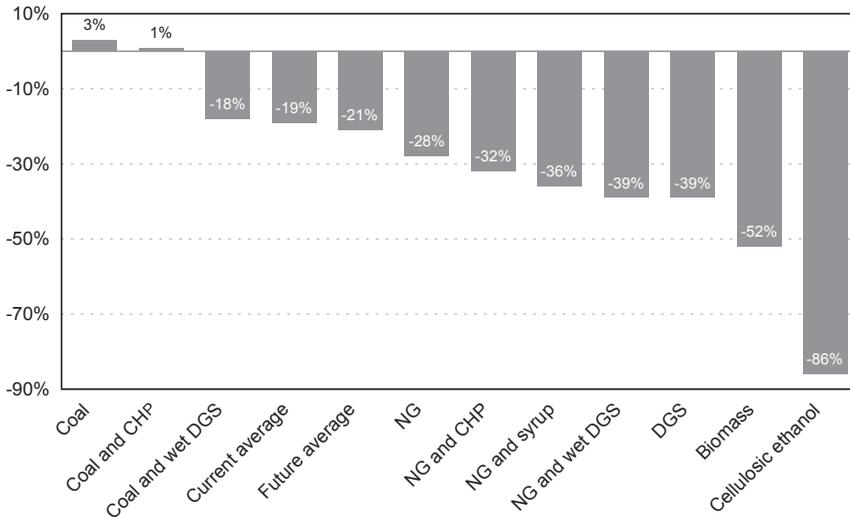
⁷<http://rael.berkeley.edu/ebamm>

ethanol production has a GWI of 77 gCO₂e/MJ. Biofuel generated by harvesting cellulose from switch grass is projected to have a GWI of only 11 gCO₂e/MJ.

The EBAMM meta-analysis points out that not only specific processes but also agricultural practices largely determine the GWI. The fuel used to power the biorefineries is decisive for the absolute climate change impact. Coal-powered biorefineries barely reduce GHG emissions (but shift emissions from petroleum to coal, thus reducing energy dependency in OECD countries). Natural-gas-powered biorefineries are already having a positive net effect; i.e., fewer GHG emissions than when using petrol. The highest potential in terms of GHG emissions is, however, in cellulosic ethanol. Figure 2 summarizes the variability across different biorefinery processing scenarios (Wang *et al.*, 2007).

From this discussion, it is already clear that there is substantial need to evaluate each fuel using a detailed life-cycle analysis. However, land-use changes further complicate matters. Recent studies indicate that expanding biofuel production induces large GHG emissions from land-use change for biofuels, in particular when biofuel production competes with other land uses such as the production of food. Indirect effects are difficult to evaluate but highly significant. Commodity substitutability and competition for land transmit land-use change across global markets; for example, when US ethanol production increases the global corn price, making it profitable to clear rainforests for additional corn or crop production in Brazil. These market-mediated land-use change emissions are separated from the biofuel production process by several economic links, as well as by physical distance.

A critically important new study finds that such indirect land-use changes induce GWI above petrol emissions on a century time-span (Searchinger *et al.*, 2008). If grassland is converted to crops, both land conversion (e.g., by fire) and land cultivation cause significant emissions. For example, if one acre of land is devoted to bioethanol production, which involves the conversion of 0.6 acres of forest and 0.24 acres of grassland to agricultural land, then 30 metric tonnes of carbon dioxide are released. One acre produces approximately 400 gallons of ethanol per year, saving one tonne of carbon dioxide annually. Hence, the GHG payback time is 30 years (CARB, 2009). Searchinger *et al.* (2008) estimate that GHG payback time is over 150 years in some cases. In particular, expansion of US bioethanol production will cause previously uncultivated land to be utilized for crop production, both in the USA and elsewhere (primarily in Brazil, China and India). Hence, there will be significant loss of pristine grasslands and forests, as well as lost opportunities for carbon sequestration on idle arable land. It is generally recognized that there are significant GHG emissions related to indirect land-use changes. While the extent of this effect is disputed, as 1) model assumptions cannot easily be verified, and 2) the system is highly complex; deforestation, for example, is multi-causal (there are also local drivers of deforestation). The following factors produce major uncertainty:



CHP = combined heat and power; DGS = distiller grains and solubles; NG = natural gas

Fig. 2. Comparison of the GWI of different biofuel refineries compared to petrol. Note that land-use effects are not part of this analysis. Taking resource supply (cellulosic biomass versus corn) into account, cellulosic ethanol appears as the ultimate ethanol option, reducing GHG emissions by 86% in comparison to petrol – if it can be produced for a competitive market. (Source: adapted from Wang *et al.*, 2007)⁸

- Carbon emission factors related to agro-ecological zones and new land (i.e., the precise location of biofuel production, and the carbon content of the land prior to conversion to biofuel plants);
- Future land-use trends, such as the total global demand on food production, which itself depends on population growth;
- Policies and competition for different land-use types (e.g., the existence and effectiveness of rainforest protection measures).

Another issue is the accounting of time. To obtain a GWI, most studies averaged the total indirect emissions over the total fuel produced during a production period and add these to the direct emissions. This straight-line amortization has been proposed for the Californian LCSF (Arons *et al.*, 2007; CARB, 2009). Hence, a unit of GHG emissions released today is treated as though it had the same consequences as one released decades in the future. Annual GHG flows are, in general, a poor proxy for economic costs; most climate change costs are imposed by GHG stocks in the atmosphere. Furthermore, consideration of long timeframes involves assumptions

⁸ These assessments from 2007 do not fully capture the concerns raised by Searchinger *et al.* (2009) about the generally far smaller than previously thought benefits of many biofuel-to-transportation fuel (liquid or via electricity) pathways. Further analysis is needed to chart the actual benefits of these technology/fuel systems.

about technological innovation and land-use changes over that timeframe, including post-cultivation changes in land use. A proper accounting of time, recognizing the physics of atmospheric carbon dioxide decay, significantly worsens the GWI of any biofuel that causes land-use change in comparison to fossil fuels (O'Hare *et al.*, 2009). The key point is that a lot of emissions appear due to land-use changes at the beginning of biofuel cultivation, while emission savings occur later. Emissions occur front up, and as a result, cumulative warming – global warming produced by emissions within a fixed analytical horizon (e.g. 50 years) – and associated damages in the near-term are more severe than future ones.

Biofuel production has also been criticized for competing with global food supply (Runge and Senauer, 2007), and for raising global corn prices as a consequence. For the world's poor a marginal price increase can have devastating effects. The corn required to fill the fuel tank of a SUV with bioethanol contains enough calories to feed one person for a year; the SUV driver will often pay more for the corn (indirectly as fuel) than people in poor countries can afford. From a narrow market perspective, the starvation of the poor can in fact be an efficient market outcome, making bioethanol policies in the USA and EU even more questionable. To understand the relevance of policies in specific world regions, we should note that, for example, 40% of global corn (maize) production is in the USA.

One way out of this problem is to decouple biofuel cultivation, first from food production by using waste products (second generation) and, in the long run, from land-use; for example, by relying on biofuels produced from algae (third generation). Currently, these technologies are not cost-effective, but significant research and money is being invested.

Overall, major uncertainties about the sustainability of current biofuel production persist. Indirect land-use change effects are too diffuse and subject to too many arbitrary assumptions to be useful for rule-making. To ascertain a minimum environmental quality of biofuels, a suggested low-carbon fuel standard can include evolving minimum criteria related to GHG emissions, for example as identified by Börjesson (2009). One could start by placing restrictions on biorefineries, requiring improved agricultural practices, such as conservation tillage, and in a few year's time allow only biodiesel and biofuels of the second generation. The Roundtable on Sustainable Biofuels⁹ develops criteria according to which a third party could perform a life-cycle assessment of biofuels and certify the fuels according to established standards.¹⁰

⁹The Roundtable on Sustainable Biofuels is an international initiative that brings together farmers, companies, governments, non-governmental organizations, and scientists who are interested in the sustainability of biofuel production and distribution.

¹⁰<http://cgse.epfl.ch/page65660.html>

Electromobility

Biofuels represent a minor modification in vehicle propulsion. Electromobility is a more radical and rapidly evolving technological change that dates back to the nineteenth century. Electromobility not only requires a different propellant but also different vehicle technology (an electric motor) and storage system (for example, a battery). There are two main advantages of electromobility:

1. An electric motor has 70–80% well-to-wheel efficiency¹¹ and, hence, is far superior to the combustion engine (with 15–25% well-to-wheel efficiency).
2. In principle, it is a straightforward process to get the carbon out of electromobility by increasing the deployment of renewable energies for electricity generation.

A significant challenge for large-scale electromobility is battery technology. Current batteries need to be improved in terms of storage capacity but also in terms of cost. All-electric cars must be relatively light in order to reduce overall energy demand. Altogether, the electricity used by a battery-powered electric vehicle in California has a GWI value of 27 gCO₂e/MJ (Lemoine *et al.*, 2008; Kammen *et al.*, 2009), a considerable improvement on petrol and ethanol. Other comparable technologies, based on the current electricity mix and different storage media – such as compressed air or hydrogen – have at present a worse GWI than petrol (Creutzig *et al.*, 2009).

The evaluation of the GWI of electric cars is not a trivial issue. Rather than the GHG emissions of the average power plant, it is the marginal power plant (added when there is additional electricity demand) that must be evaluated in terms of climate change impact. Potentially, car batteries can be used for demand management (for example, cars can be charged by wind energy at night, when there is no other electricity demand; see also the chapter by Joachim Luther on smart loads, this volume). Electromobility is not merely synonymous with electric cars, but also includes smaller vehicles such as electric bikes. For OECD countries, electric bikes are still relatively exotic. However, in China – by 2009 the world's largest market for cars – more electric bikes than conventional cars are sold.

It is important to consider the full spectrum that lies between conventional petrol-operated cars and all-electric cars. For example, average fuel savings in the USA can easily be doubled (and fleet emissions halved) by deployment of existing technological advances, weight reductions and a reasonable market penetration of hybrid vehicles (American Physical Society, 2008). In contrast, plug-in (hybrid) electric vehicles (relying on battery for short distances and petrol for longer distances) are

¹¹ Well-to-wheel efficiency is the percentage of the primary energy that is used for powering the car.

expected to contribute little to total emission savings until 2030. In the case of urban transportation, even more can be gained. If inner-city transport switches from cars to non-motorized transport and electromobility, urban transportation can be effectively decarbonized.

Beyond fuels

Car transportation emissions can be factorized into vehicle distance travelled, fuel efficiency, and carbon content. In this chapter, we mostly discuss the carbon content of fuels. There is, however, a need to reduce transportation emissions drastically, and both other factors will have to contribute. Fuel efficiency can be increased through better technologies and by reducing the weight of vehicles. There is huge potential to decrease average vehicle weight, particularly in the USA (Schipper, 2007). Vehicle distance travelled can be reduced by appropriate land-use policies (e.g., transit-oriented development), and by demand management (e.g., by parking management and city tolls). Pricing mechanisms, such as city tolls, are efficient ways of addressing all social costs of motorized transportation (both those internal to the transportation system such as congestion, and environmental costs such as air pollution and GHG emissions), and are most effective in joint extension of public transit (Creutzig and He, 2009). The greatest GHG mitigation potential lies in policies that address vehicle distance travelled.

Outlook on international carbon fuel measures

Equipped with detailed measurements that relate directly to the objectives of a low-carbon fuel standard, policymakers can set standards for a state or nation, and then strengthen them over time. The standard applies to the mix of fuels sold in the region, so aggressively pursuing cleaner fuels permits a certain percentage of more traditional, dirtier fuels to remain, a flexibility that can facilitate the introduction and enforcement of a new standard.

California introduced a low-carbon fuel provision (specifying the low-carbon fuel standard from 2007) in April 2009, mandating emission reduction of 10% from the entire fuel mix by 2020 (CARB, 2009). The regulation also requests lifecycle emissions scores for biofuels that include indirect pollution from the conversion of forests to farm land for cultivation of corn and other fuel-feedstock crops. The US Environmental Protection Agency (EPA) proposed a revised Renewable Fuel Standard in May 2009,¹² mandating total renewable fuel volume requirements and GHG

¹² <http://www.epa.gov/otaq/renewablefuels/#regulations>

emission reduction targets for different biofuel categories ranging from 20% to 60%. An evaluation of full lifecycle emissions was also proposed. The American Clean Energy and Security Act of 2009 (ACES, also known as the Waxman-Markey Act), which was approved by the US House of Representatives but is still up for debate by the Senate, includes a mandate for the EPA to *exclude* any estimation of international indirect land-use changes due to biofuels for a five-year period.

The EU acknowledges criticism of its biofuel targets. It has confirmed its 10% 'green fuel' target by 2020, but this includes not only biofuels but all renewable energy used in transport, such as electric vehicles powered by renewable sources. Furthermore, it has clarified that biofuels must offer at least 35% GHG emission savings, a value that will be incrementally increased to 60% by 2017. Indirect land-use emissions, however, are not included in the formula to calculate overall GHG performance.

The appeal of a low-carbon fuel standard is that it establishes performance levels and opens the transportation fuels market to new competitors, not allowing the government to lock in on preferred programmes (such as biofuel subsidies) or technologies. Liquid fuel providers who produce and sell diesel fuel, petrol, or biofuels – as well as electricity providers who 'fuel' plug-in hybrid vehicles with electricity generated by renewables – can all now compete equally for transportation spending. Competition and market forces are tremendously useful in encouraging innovation that brings down costs.

All of this momentum is pushing a steady evolution to cleaner fuels, but there is no reason to stop at eliminating GHG emissions. As described above, there are other ramifications of fuel usage that we can measure and need to improve. The impacts of biofuel production, for example, range from excessive water use to erosion of formerly fallow land, to competition with food production. A natural next step is to evolve from a low-carbon fuel standard to a *sustainable* fuel standard.

Finally, a lurking issue is how fuel standards will more generally interact with the prices for carbon emissions that are likely to be established in a number of regions. Europe has already enacted a carbon trading scheme. California and the New England/mid-Atlantic region of the USA have begun to work out regional frameworks, likely based around a 'cap and trade' system, and several other regional markets may evolve in the USA. The Waxman-Markey Act aims to introduce US-wide cap-and-trade. If these carbon pricing projects are successful, the use of sector-specific regulations will likely need to evolve, both to address areas where the carbon price is too low to induce real change, and to focus on ecological and cultural sustainability issues, as the idea of a 'sustainable fuel standard' implies.

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