Spotlight

Biofpr Biofuels Bioproducts & Biorefining

The need for biofuels as part of a low carbon energy future

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Abstract: The question of whether the world needs biofuels is approached by examining the feasibility of doing without them. Even with aggressive reductions in travel growth, shifts to mass transport modes, strong efficiency improvements, and deep market penetration by vehicles running on electricity and hydrogen, there remains a large demand for dense liquid fuels in 2050 (80% of transportation fuel) and even in 2075 (50%). This demand is due largely to aviation, ocean shipping, and long-haul trucking. Acknowledging the significant uncertainties involved in such projections and the challenges faced by all candidate technologies and fuels, we conclude that it will likely be difficult to achieve a low-carbon transport sector without widespread use of biofuels, and that aggressive efforts to develop sustainable, low-carbon biofuels alongside other options are warranted. © 2015 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

There is a notable lack of consensus about whether biofuels could or should contribute to future energy supply on a scale large enough to meaningfully impact global energy challenges. This communication summarizes our analysis of the magnitude of the gap between anticipated transport energy demand and the anticipated supply from low-carbon energy options other than biofuels. We focus on scenarios that achieve very low net carbon dioxide (CO_2) emissions, reflecting the consensus that deep reductions are needed to avoid radical changes to the world's climate with great attendant risks.[1] Acknowledging substantial and unavoidable uncertainty, we consider energy futures out to 2075, since the entire energy system must be nearly fully decarbonized by then in order to limit global temperature increase to about two degrees,[2] and because this allows enough time for a full transition to near-zero-carbon fuels.[1] The research presented here extends and deepens analysis presented in the International Energy Agency (IEA) Energy Technology Perspectives 2012,[1] which two of the present authors were involved in developing.

Substantial reductions in CO_2 emissions from the transport sector can be achieved by increasing vehicle and modal efficiency, reducing travel demand, and changing travel patterns toward more efficient modes. However, achieving deep CO_2 reductions will also require a shift to very low-carbon energy carriers, of which the three most likely to play a prominent role are electricity, biofuels, and hydrogen. For all three, life-cycle carbon emissions vary

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from near zero to relatively high levels on a 'well-to-wheels' basis, depending on the energy source and supply chain. All three also require significant infrastructure changes and technological innovation. For electrical energy storage, key challenges include providing very low-carbon electricity generation and improved battery technology. For hydrogen, challenges include low-carbon production, installation of a hydrogen transmission and distribution system, and on-vehicle storage and conversion (mostly likely using fuel cell systems). For biofuels, land-use challenges will need to be addressed along with achieving technologies to produce fuels from biomass feedstocks sustainably and cost-effectively at a very large scale. These considerations make transportation one of the most challenging sectors to reconcile with a low-carbon future. Transportation cannot, however, be neglected since it is responsible for about 25% of global energy use and dramatic growth in the size of the world's vehicle fleet, travel activity, energy use and CO_2 emissions is anticipated.[1]

Scenario framework

The IEA Energy Technology Perspectives presents three energy scenarios, related to 6, 4, and 2 degree centigrade increases in mean global atmospheric temperature compared to preindustrial levels – denoted 6DS, 4DS, and 2DS, respectively.[1] The 6DS results from 'business as usual' assumptions. The 4DS reflects a range of policies being applied that are currently under consideration by governments around the world that results in a flattening but not significant reduction of CO_2 in the future. The 2DS requires deep CO_2 reductions and is developed as a backcast from a given 2050 target, showing combinations of changes in travel patterns, vehicle technologies and fuels that reduce CO_2 sufficiently without specifying the policies necessary to bring these changes about. The ETP 2DS includes an extension to 2075 that reaches zero net carbon emissions for energy production, distribution, and use, primarily through a transition to electricity, hydrogen, and biofuels from renewable feedstocks, along with widespread use of nuclear power and carbon capture and storage. Here we extend the IEA 2DS scenario by examining in more detail implications for fuel consumption by transport mode and fuel type, quantifying continued anticipated liquid fuel use in 2050 and 2075 and the reasons for this, and describing obstacles to achieving a low-carbon future without biofuels.

For transport, the ETP 2DS includes a substantial cut in travel growth compared to the 4DS, as well as modal shift. By 2050, passenger travel growth by car and air is cut by about 25% globally, with about half shifted to mass transit modes (bus and rail) and half avoided through better land use, information systems (e.g. teleconferencing), and other measures. For freight, half of all air and truck travel growth is shifted to rail. Overall these changes in travel patterns result in a 20% reduction in energy demand in the 2DS compared to the 4DS in 2050 and 2075. As a result of technology-driven efficiency increases, average energy intensity of the stock in all modes worldwide is at least 40% less in 2050 than in 2005, mainly from incremental improvements to internal combustion engine road vehicles, trains, ships and jet aircraft.

In addition to demand reduction and increased efficiency, the 2DS includes a rapid penetration of electric vehicles, plug-in hybrid vehicles, fuel cell vehicles, and biofuels. For light-duty vehicles, this means a strong trend toward electrification after 2015 and rapid adoption of fuel cell/hydrogen vehicles after 2025. For trucks a shift toward fuel cells and hydrogen increases dramatically after 2030 and is substantial by 2050. Further electrification and hydrogen use in road vehicles occurs by 2075. Rail systems are nearly completely electrified by 2050. The implied rates of technology change in 2DS are dramatic. For example, among passenger light-duty vehicles (PLDV), electric/plug-in hybrid vehicle sales nearly double each year through 2020, increasing from 40 000 in 2011 to 7 million. Growth rates slow thereafter but the absolute increase continues to be dramatic, reaching sales of 30 million in 2030 and over 100 million by 2050 – more than half of new PLDV sales worldwide in that year. Except for plug-in hybrids, internal combustion engine vehicles are in steep decline by 2050 and are completely phased out by 2075 (Fig. 1).

There are some notable exceptions in the 2DS from the drive toward electrification and hydrogen use in vehicles. For long-haul trucks and especially for large ships and aircraft (the heaviest and longest-travelling modes), electricity and hydrogen do not penetrate very significantly to 2075 and advanced, low-carbon biofuels dominate. Reasons for this are explored below.

Analytical background

The ETP 2012 presented the overarching picture with respect to energy use and CO_2 emissions out to 2075, but this paper takes a 'deeper dive' in presenting and interpreting the fuel-related results, especially with regard to its modal distribution. The transportation chapter of ETP 2012 did not draw particular attention to the large amount of liquid fuels still in the transportation system even in 2075. The ETP 2DS is very ambitious with respect to transport CO_2 mitigation and ramps up all plausible (and where

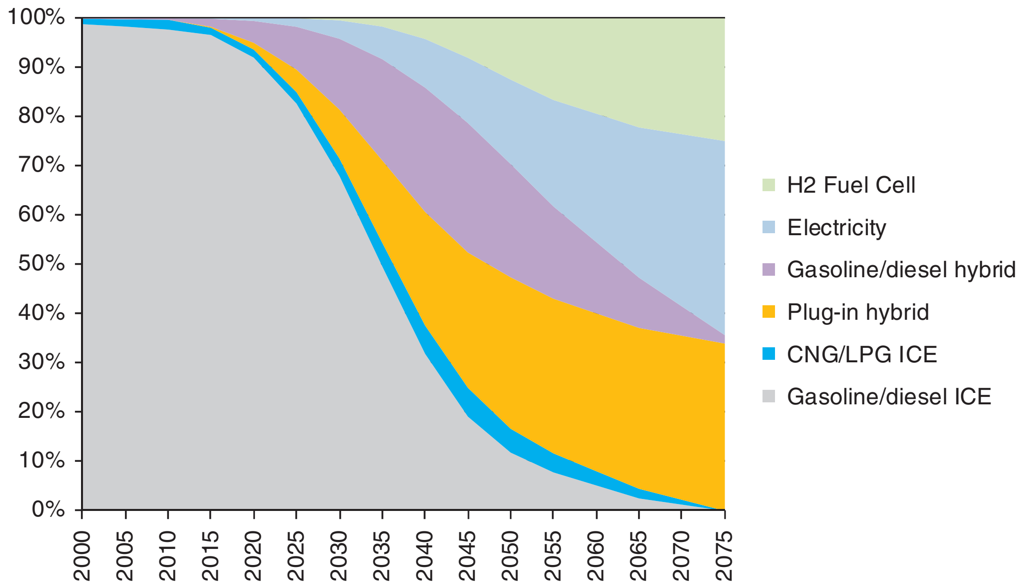


Figure 1. Technology shares of global light-duty vehicle stocks to 2075, 2DS.

possible cost-effective) CO_2 reduction options. With the rates assumed in ETP (such as for fuel efficiency improvement, reduction in travel growth, modal shift, and uptake of electricity and hydrogen), a substantial amount of liquid fuel use is still projected, and a fuller elucidation of this picture is developed here. In particular, we dissegrate the 2DS scenario into greater modal detail and present the ETP results in a way that makes the role of biofuels more apparent than has been shown previously. We also review other studies that have conducted similar types of projections.

The biofuel production levels herein can be interpreted as the minimum amount of biofuels necessary to achieve a two degree transportation scenario (2DS) after all other strategies are adopted. It is possible that a two-degree scenario could be achieved with less CO_2 reduction from transport and more from other sectors; this could lead to reductions in biofuels, but would more likely result mainly in a slowing in the rate of electricity and hydrogen uptake, since these are among the most expensive options. In any case, we present scenario details to better illuminate the role of biofuels in this scenario.

Energy use and CO_2 emissions

Whereas transport energy use nearly doubles by 2050 in the 4DS, demand remains roughly constant in the 2DS. (Fig. 2(a)). Well-to-wheel transport CO_2 emissions (Fig. 2(b)) rise from 8 Gt in 2010 to nearly 13 Gt in 2050 in the 4DS, but instead drop by 25% to about 6 Gt in the 2DS, and further decrease to just over 2 Gt in 2075, if total energy system net

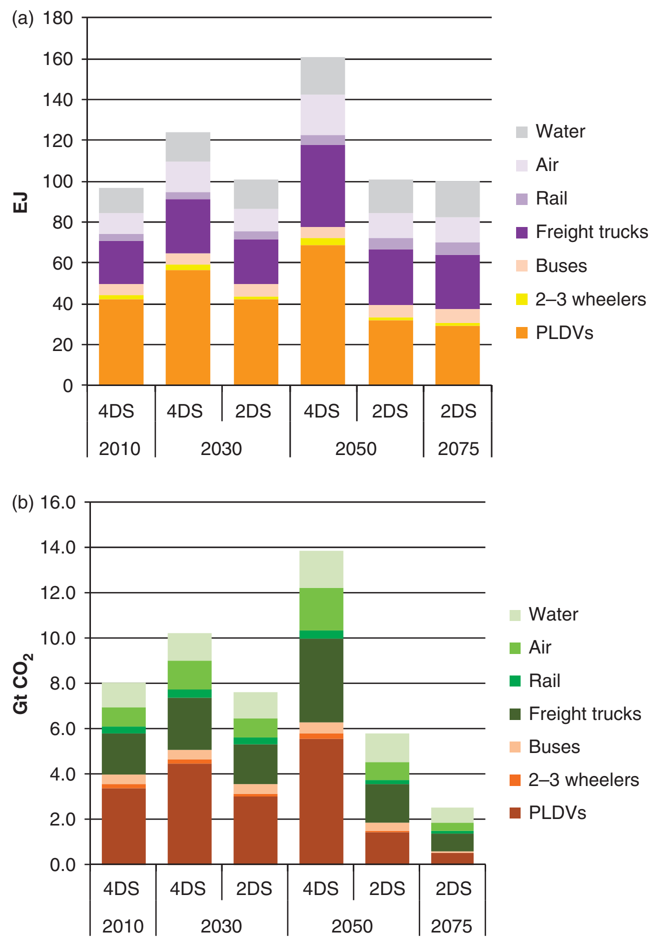
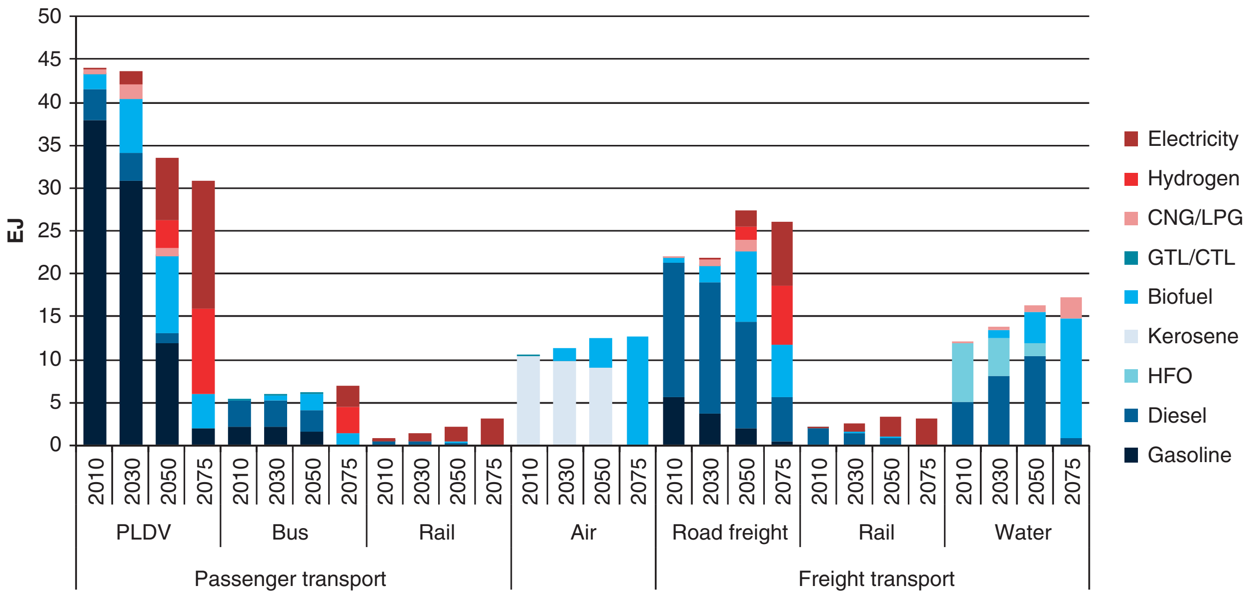


Figure 2. (a) Energy use by scenario and mode. (b) CO_2 emissions by scenario and mode (well-to-wheel).



Note: CNG/LPG = compressed natural gas/liquid petroleum gas, GTL/CTL = gas-to-liquid/coal-to-liquid, HFO = heavy fuel oil.

Figure 3. Global energy use in 2DS by mode and energy carrier, selected years.

emissions are to reach zero by 2075.[1] While travel shifts and especially efficiency improvements are important to 2050, the changes between 2050 and 2075 mostly reflect ongoing shifts to electricity, hydrogen and biofuels along with ongoing decarbonization of these fuels.

Figure 3 presents a breakdown for the energy provided by various fuels and energy carriers as a function of transportation mode and time for the 2DS. The combined contribution of electricity and hydrogen in 2075 is quite high: 80% for PLDV, 70% for busses, 100% for rail, and 50% for road freight.

Notwithstanding the very large contribution of electricity and hydrogen depicted in Fig. 3, the aggregate contribution of biofuels is substantial (Fig. 4). By 2075, biofuels provide 100% of aviation fuel, nearly three-quarters of shipping fuel, and over a third of fuel for road freight (trucks). Out of a transportation sector total of 103 EJ for the 2DS in 2075, biofuels are the largest contributor at 43 EJ or about 42%. If this gap were made up by a mix of fossil fuels similar to that otherwise still used in the 2DS, those fuels would emit approximately 4GT of carbon over and above the 2.5 GT emissions in the 2DS scenario from transport.

Even with aggressive reductions in travel growth, shifts to mass transport modes, strong efficiency improvements and deep market penetration by energy carriers other than biofuels, direct use of electricity and the use of hydrogen

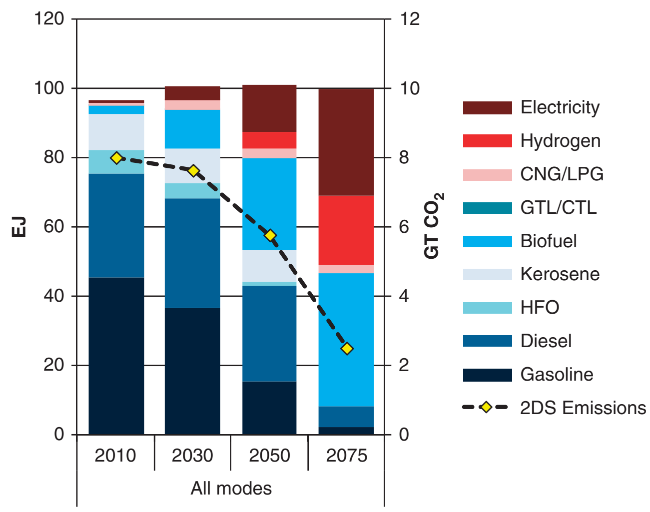


Figure 4. Transport energy use by fuel and year, displaced CO_2 emissions by fuel and year, and total CO_2 emissions from all sectors for the 2DS.

account for about 20% of transport energy in 2050 and about half in 2075. Thus about 80% of transport energy in 2050 and 50% in 2075 remain to be decarbonized.

This low-carbon transport 'gap' arises because the technical and economic challenges associated with use of electricity and hydrogen are greater for some transport applications than others. Light duty passenger vehicles and trains are the easiest targets for these low-carbon energy carriers while buses and urban freight trucks may also be amenable,

[1]Negative emissions occur from using biomass-derived electricity together with carbon capture and storage (CCS) in the power sector.

given relatively short distances travelled per day (buses have been an attractive mode for testing fuel cell systems). Long-haul trucks are much more challenging, given their typically very high daily driving levels and the need to store the respective low carbon energy under weight and volume restrictions. For the same reason ocean shipping and planes appear likely to be the hardest to decarbonize.

Discussion

Will so much energy-dense liquid fuel really be needed in 2050 and 2075 in a very low carbon transport system? There are certainly a number of technological breakthroughs that could change this picture. Much higher energy density batteries (or other storage systems) could be a game changer, for example allowing long-haul electrified trucks. But energy densities would have to improve by nearly an order of magnitude to match the long-haul capabilities of diesel fuel and diesel engine powered trucks of today, and recharging these high capacity batteries within acceptable time limits also poses a serious technological problem. Similarly, even with liquid (cryogenic) hydrogen storage, fuel cell trucks would need at least triple storage volume capabilities to meet current long haul trucking ranges. Another possible innovation is electrified roadways, either using induction charging in roadbeds or catenary systems (overhead electrical lines tethered to trucks). But fully developing such systems would require large infrastructure investments.[3] Inductive wireless "dynamic" charging on roadways is in a relatively early stage of research and development, and is not expected to play a significant role for at least 1–2 decades.

Without new technology breakthroughs, it appears very unlikely that battery electricity will play a major role for ships and aircrafts, given range and power requirements. Hydrogen could however provide adequate characteristics for at least some types of shipping and aircraft. For aircraft, hydrogen would likely need to be stored as a liquid and used with jet engines. For ships, it could be liquefied or pressurized and would likely be used with fuel cell systems and electric engines. The weight (mass) of hydrogen required to deliver a given amount of energy is less than half that of liquid petroleum fuels like kerosene, a particular advantage for aircraft.[4] However, since the volumetric energy storage density of liquid hydrogen is much lower (about 75%) than the energy density of jet fuel, radical aircraft redesign would be needed to accommodate fuel tanks up to four times larger for a similar range (or aircraft ranges would need to be greatly reduced). The major compromises in aircraft performance this would entail have led many analysts to conclude that hydrogen is not currently a serious fuel for medium-to-long haul aircraft,[4,5] which account for the vast majority of aviation fuel use. In contrast, premium drop-in biofuels for planes already exist and have been shown to provide performance equal to petroleum jet fuel. In addition, they require no equipment modifications, though the biofuels themselves may be expensive, at least in the near-to-medium term.

Hydrogen appears more viable for use in ships than in aircraft, given the possibility of storing large amounts of liquid hydrogen without major compromises to ship functionality. Hydrogen would most likely be used with solid oxide fuel cells to generate electricity to turn propellers. These are efficient though expensive, and still in development.[6] A major obstacle here is cost – ships currently use very cost-effective diesel engines with low-cost residual and marine diesel oil. Replacing such a system with a hydrogen/fuel cell system for the sake of CO_2 emissions could be extremely costly on a dollar per tonne CO_2 basis. In contrast, biofuels can be used to replace residual fuel oil using relatively simple conversion technology (e.g. pyrolysis) and only minor (if any) engine modifications.[7]

How do the IEA transport scenarios compare to other studies? Another recent energy futures study, the Global Energy Assessment,[8] projects fractions of transportation energy provided by liquid hydrocarbons in 2050 that are very similar to the IEA projections. In particular, the IEA and GEA studies both feature substantial biofuel use in trucks, ships and aircraft by mid-century. Dale *et al.*[11] recently compiled results from five global low-carbon energy studies for 2050, included in addition to the IEA and GEA studies, scenarios developed by ECOFYS/World Wild Life Fund, and data drawn from the IPCC 5th assessment. Bioenergy averaged 25% of primary energy supply in these studies, and all anticipate a need for liquid biofuels. In contrast, Jacobson and Delucchi,[9,10] project an energy system that is eventually 100% supplied by wind, water and solar power. They argue that the technical and cost barriers preventing electricity and hydrogen from widespread use in all modes can be overcome. However, they do not present a detailed examination of the complex issues associated with using (and transitioning to) these energy carriers for trucks, ships or aircraft.

Regarding the potential for biofuels to meet the energy requirements in these scenarios, a recent comprehensive review by Creutzig *et al.*[12] finds high agreement for a technical potential of bioenergy up to 100EJ, medium agreement for a potential between 100 and 300 EJ, and low agreement above 300 EJ. These values are large relative to the ~40 EJ low carbon transport gap in the ETP 2012 scenario. However, the technical potential for bioenergy to be produced on this scale in a sustainable manner does not mean that this will necessarily occur.

As with electricity and hydrogen, scaling up use of transport biofuels entails tremendous challenges. While end-use and distribution infrastructure are smaller obstacles for biofuels than for hydrogen or electricity and batteries, biofuels face distinctive challenges related to scale, feedstock supply, issues related to land-use, and policies required to ensure sustainable production. Yet with new discoveries of fossil hydrocarbon resources reducing pressure on the supply side, closing the low carbon transport gap identified herein is made more difficult and there is a substantial risk that it may not happen. Clearly, taking biofuels off the table increases this risk.

Conclusions and policy implications

Achieving deep CO_2 reductions in the transportation sector will require a shift to very low-carbon energy carriers, of which the three most likely to play a prominent role are electricity, hydrogen and biofuels. Even with aggressive reductions in travel growth, shifts to mass transport modes, strong efficiency improvements and deep market penetration by energy carriers other than biofuels, electricity and hydrogen are anticipated to account for about 20% of transport energy in 2050 and about half in 2075 under an ambitious carbon mitigation scenario. Thus about 80% of transport energy in 2050 and 50% in 2075 remain to be decarbonized.

This low–carbon transport 'gap' arises because the technical and economic challenges associated with use of electricity and hydrogen are greater for some transport applications than others. Light duty passenger vehicles and trains are most easily powered by low carbon energy carriers other than biofuels, urban freight trucks are more challenging but likely doable. Long-haul trucks are much more challenging, and ocean shipping and aviation are the most challenging of all. The underlying reason for this ranking is simple and unlikely to change: Energy storage is more difficult, less space-efficient, and more expensive for electricity and hydrogen compared to liquid hydrocarbons, and this becomes a greater liability as weight and distance travelled increase.

Acknowledging the significant uncertainties involved in such projections and the challenges faced by all candidate technologies and fuels, we conclude that it will likely be difficult to achieve a low-carbon transport sector without widespread use of biofuels. Until the feasibility and viability of other fuel options becomes established over the full range of transportation applications, simultaneous aggressive technology development and deployment strategies for sustainable, low-carbon biofuels alongside these other fuel options is the only responsible path.

Much has been written about the risks of large-scale production of biofuels in ways that are not sustainable. Our analysis highlights a second risk: that sufficient sustainable biofuel production will not happen and as a result a low-carbon energy future will be harder to achieve. Preoccupation with the first risk could result in constraining the growth of all biofuels, exacerbating the second risk. Preoccupation with the second risk could result in advancement of unsustainable biofuels, exacerbating the first risk. A policy balance is needed that targets aggressive development and deployment of sustainable biofuels. In this context, it is desirable to avoid pendulum swings between being too permissive to too restrictive. Biofuels policy must take a realistic view toward the likely need for large volumes of sustainable, low-CO_2 biofuels for transportation. This means developing policies that tilt the table toward land use practices that achieve environmental and social benefits, and away from those that do not. Establishing robust and internationally accepted methodologies to quantify life cycle greenhouse gas emissions of biofuels as well as developing international codes and standards related to sustainable production practices are important steps towards a global policy framework to incentivise sustainable biofuel production and discourage negative land-use change and food security related effects at the same time.

Development of low-cost technology for processing cellulosic biomass remains a critical and as yet unrealized goal, although progress is being made. Accelerating such development is an important objective for research, development, and demonstration with governments playing an important role for some time to come. Finally, linking low-cost technology for making reactive intermediates from cellulosic biomass with production of the full range of fuel molecules, particularly middle distillate type fuels for heavier, long-distance transport modes, is an important objective.

Acknowledgements

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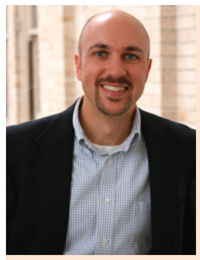

Luke Tonachel

Luke Tonachel is the Director of the Clean Vehicles and Fuels team and a senior analyst for the Natural Resources Defense Council (NRDC). Since joining NRDC in 2004, his focus has been on reducing the environmental impacts of the world's transportation demands by advocating for policies that develop and commercialize cleaner, more efficient vehicles and non-petroleum fuels. Mr. Tonachel has authored and contributed to numerous nationally-recognized reports and analyses covering vehicle electrification, improved vehicle efficiency and other oil and emissions reduction opportunities. Mr. Tonachel holds a bachelor's degree in mechanical engineering from the University of Rochester. He gained hands-on experience with energy systems and propulsion plants as an engineering officer while serving aboard a cruiser in the United States Navy. After the Navy, Mr. Tonachel developed business skills as a software product manager and then returned to school, receiving his Masters in Public Policy from University of California, Berkeley in 2004.

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