When Comparing Alternative Fuel-Vehicle Systems, Life Cycle Assessment Studies Should Consider Trends in Oil Production

Timothy J. Wallington, James E. Anderson, Robert D. De Kleine, Hyung Chul Kim, Heiko Maas, Adam R. Brandt, and Gregory A. Keoleian

Summary

Petroleum from unconventional reserves is making an increasingly important contribution to the transportation fuel supply, but is generally more expensive and has greater environmental burdens than petroleum from conventional sources. Life cycle assessments (LCAs) of alternative fuel-vehicle technologies typically consider conventional internal combustion engine vehicles fueled by gasoline produced from the average petroleum slate used in refineries as a baseline. Large-scale deployment of alternative fuel-vehicle technologies will decrease petroleum demand and lead to decreased production at the economic margin (unconventional oil), but this is not considered in most current LCAs. If marginal petroleum resources have larger impacts than average petroleum resources, the environmental benefits of petroleum demand reduction are underestimated by the current modeling approaches. Often, models include some consequential-based impacts (such as indirect land-use change for biofuels), but exclude others (such as avoided unconventional oil production). This approach is inconsistent and does not provide a robust basis for public policy and private investment strategy decisions. We provide an example to illustrate the potential scale of these impacts, but further research is needed to establish and quantify these marginal effects and incorporate them into LCAs of both conventional and alternative fuel-vehicle technologies.

Keywords:
consequential LCA
economic effects
greenhouse gas (GHG) emissions
industrial ecology
transportation
unconventional oil

Introduction

The desire for improved energy security and reduced greenhouse gas (GHG) emissions has led to policies that mandate more-stringent fuel economy standards and encourage alternative fuels and vehicle technologies. These alternative fuel-vehicle combinations include biofuels in internal combustion engine vehicles (ICEVs), natural gas in compressed natural gas vehicles (CNGVs), electricity in plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), and hydrogen in fuel-cell electric vehicles (FCEVs). Life cycle assessment (LCA) is the dominant approach for evaluating the environmental performance of alternative fuel-vehicle technologies.

The LCA community has been debating the merits of two different life cycle approaches for evaluating the effect of policy and large-scale technology deployment (Mason Earles and Halog 2011; Soimakallio et al 2015). Though definitions differ, attributional LCA (ALCA) can be described as the “traditional” approach to LCA whereby material and energy inputs and outputs are quantified and attributed to a product or service typically by utilizing average data and standard unit process representations. On the contrary, consequential LCA (CLCA) seeks to assess the net change in environmental
outcomes based on the introduction of a product or policy. In CLCA, marginal inputs and outputs are desirable and indirect changes to other product systems are considered.

Plevin and colleagues (2014) concisely put forth a viewpoint that CLCA has the capability to provide better information to decision makers, particularly in areas of policy. There is some debate in the LCA community about the constructs of CLCA and ALCA and their relative value to decision making (Anex and Lifset 2014; Suh and Yang 2014). However, the inclusion of indirect land-use change (ILUC) in most contemporary biofuel LCA analyses, including that from regulating agencies, signals a significant shift from attributional to more consequential approaches for fuel-vehicle assessment. Thus far, biofuels analysis has been perhaps the most significant and developed area for CLCA. We argue that the inclusion of consequential effects in vehicle analysis enhances our understanding of environmental outcomes, but doing so for only biofuels can create a false comparison. To be consistent, a more comprehensive consequential approach is needed in evaluating petroleum and other alternative fuels, but this has not been common practice.

Rising oil prices over the last decade have led to increased petroleum production from “unconventional” and depleted reserves, which account for an increasing fraction of gasoline and diesel fuel supply (IEA 2013). Despite significant declines in global oil prices observed in 2014, unconventional production is expected to remain a key source of petroleum capacity growth (IEA 2015). There are an estimated 400 billion barrels of proven unconventional reserves available for extraction, and trillions of barrels of oil in place that could become economic with future technologies (IEA 2013). Characteristics of these resources include: energy-intensive extraction (e.g., Canadian oil sands); extreme environments (e.g., ultra-deepwater); and/or depleted or lower-quality reservoirs (e.g., tertiary recovery, infill drilling, or production from tight reservoirs). A growing body of research has demonstrated that fuels produced from unconventional reserves are generally more expensive to develop and have greater environmental burdens than fuels from traditional petroleum sources (Unnasch et al. 2009; IEA 2013; Jordan 2012; Brandt 2012; El-Houjeiri et al. 2013; Boland and Unnasch 2014; Van den Bos and Hamelinck 2014; Gordon et al. 2015; Nduagag and Gates 2015; Cai et al. 2015). These insights need to be reflected in future fuel-vehicle assessments.

To date, LCAs of fuel-system systems (e.g., Samaras and Meisterling 2008; Stephan and Sullivan 2008; Elgowainy et al. 2010; Anair and Mahmassani 2012; MacPherson et al. 2012; Joseck and Ward 2014; Hawkins et al. 2013; Luk et al. 2015) have largely not accounted for three crucial trends in petroleum production. First, few life cycle studies of alternative fuels evaluate the implications of the petroleum resources that are being displaced and their respective environmental impacts. Instead, comparisons are typically made to conventional gasoline produced from an average petroleum slate. Second, LCA studies do not consistently include market-based analysis across conventional and alternative fuels. Some market-based effects (e.g., land-use change for biofuels) are considered, but others (e.g., decreased petroleum production at the margin) have been neglected. Third, temporal trends in the environmental impacts of fuels are typically neglected. This ignores the general increase in impacts over time for depletable resources, such as petroleum, and the general decrease in impacts over time of alternative fuel technologies attributable to policy and technological learning. In this article, we explore these trends and their implications for transportation sustainability studies.

Unaccounted for Petroleum Trends in Fuel-Vehicle Studies

The first challenge in proper accounting of the costs and benefits of alternative fuels and vehicles lies in a simplistic comparison to petroleum products from typical pathways (Burnham et al. 2012; Wang et al. 2011). Studies supporting U.S. and European regulations use this approach when modeling displacement of “baseline” fuels, such as gasoline or diesel produced from the average mixture of petroleum processed in that region’s refineries and consumed in ICEVs.

This assumption is problematic because of mounting evidence that the variation in emissions between different crude petroleum resources can be larger than the reductions in emissions required by regulation. For example, figure 1 shows the distribution of carbon intensities (CIs) across refinery petroleum sources from recent studies for California and the European Union (EU) (CARB 2012; ICF 2013). The range between the least and most carbon-intensive petroleum sources used in these regions is approximately 30 and 15 grams carbon dioxide equivalent per megajoule (g CO₂-eq/MJ), respectively. Also, note that for California, the maximum CI (32 g CO₂-eq/MJ) is 3 times greater than the average (10 g CO₂-eq/MJ). These differences are significantly greater than the reductions in fuel CI required by regulations in these regions (~10 g CO₂-eq/MJ).
The second challenge we note is a lack of consistency in including economics-based marginal effects in fuel LCAs. In the case of biofuel LCAs, it has become common practice to include the consequential effect of iLUC (Searchinger et al. 2008; Plevin et al. 2010). However, no such effort is applied to petroleum markets analysis. Given the emergence of unconventional oil sources and their generally higher production costs, including market effects is key to understanding environmental benefits of alternative fuels. Oil market effects will drive disparate environmental impacts if two conditions hold: (1) different oil resources have different environmental impacts and (2) there is some correlation between the marginal production cost of a petroleum resource and its environmental impact. The first condition is illustrated in figure 1. The second condition has not been rigorously studied, but is logical. Oil resources can be expensive for two key reasons: high capital (fixed) costs and high marginal (variable or per-barrel) costs. Real-time production decisions are always driven by marginal costs of production, because capital costs are sunk at the time of field development. Some unconventional oil resources are expensive because of high capital costs (e.g., deepwater fields with development costs of the order of billions of dollars), whereas some unconventional oil resources have high operating costs (e.g., thermal oil recovery requiring steam generation).

We argue that unconventional resources with high per-barrel costs will tend to have higher GHG emissions than resources with low per-barrel costs (conventional or unconventional). This is because of high energy costs in some unconventional oil resources (e.g., energy-intensive Canadian oil sands). Other resources may have a combination of high operating and capital costs, in which case low prices will affect decisions to reduce investment in the medium to long run. This effect has been observed in recent reduced investment in Canadian oil sands and U.S. tight oil resources (IEA 2015). This evidence suggests that decreased unconventional oil production represents a significant consequential effect for alternative fuel-vehicle technologies.

To illustrate this concept, we present a first-order assessment of the importance of upstream GHG emissions assumptions for petroleum in figure 2. We considered the production of reformulated gasoline using the range of values from the 10th to the 90th percentile for the upstream GHG intensity of petroleum feedstocks in California refineries in 2010. We compared the effect on results for the ICEV and alternative fuel-vehicle technologies based on Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) 2014. The median (i.e., 50th percentile) CI value is used to represent conventional oil whereas the 90th percentile value represents marginal oil inputs. The 10th percentile value can be thought of as oil from easy-to-extract reserves and CI is provided for reference. The left-most bar shows the conventional well-to-tank (WTT), tank-to-wheels (TTW), and well-to-wheels (WTW) GHG emissions (g CO₂-eq/mile) for a conventional mid-size gasoline ICEV with fuel economy of 23.4 miles/gallon (10.1 liters/100 kilometers). The WTT GHG emissions for the baseline gasoline-fueled ICEV are 106 g CO₂-eq/mile, including an upstream GHG burden of 9.6 g CO₂-eq/MJ, which is the median value for average crude oil entering California refineries. The upstream burden for the 10th and 90th percentile CI values is 6.4 and 21 g CO₂-eq/MJ, respectively. The other bars show the GHG emissions for alternative fuel-vehicle technologies, also from GREET, calculated using an ALCA approach, except that the WTT portion for E85 includes approximately 28 g CO₂-eq/mile for (consequential-based) land-use change effects.

The range in the GHG emission results illustrates the importance of upstream GHG intensity of petroleum fuel as a parameter in WTW analysis. Making the assumption that future petroleum-fueled vehicles (ICEVs, E85, hybrid electric vehicles, and PHEVs) contribute to the demand for marginal petroleum fuels and that these marginal fuels are more likely to be among those with the highest CI, the red diamonds in figure 2 show an approximation of the WTW emissions using fuel derived from these oil sources. For all fuel-vehicle systems, the additional GHG burden is proportional to each technology’s petroleum fuel use. For non-petroleum-fueled powertrains (CNGVs, BEVs, and FCEVs), the results are virtually unchanged as a result of the very minor amount of petroleum consumed in these fuel pathways, but the GHG improvement relative to ICEVs
becomes larger than in the conventional case. This illustrates the potentially large effect of the treatment of marginal petroleum demand on assessments of alternative transportation technologies. These arguments also apply for many technologies that improve the efficiency of conventional vehicles (e.g., improved engines and transmissions, improved aerodynamics, and lightweighting). Any technology that reduces petroleum consumption can displace marginal crude petroleum.

The third major challenge is the inconsistent application of time trends and potentially decades-long amortization of impacts. The energy intensity of crude oil production tends to increase with depletion (Brandt 2011) as a result of increased work of lifting of fluids as an oil field depletes. Thus, whereas a given oil field may initially have low CI, the average CI over its production life will be higher than a “snapshot” analysis performed at initially high productivity. This trend, coupled with the independent shift to unconventional resources noted above, leads to the important conclusion that the CI of both average and marginal petroleum resources is likely to increase over time. Biofuel LCAs have long included amortization of land-use impacts over an extended period of time, but we are not aware of such impacts in crude oil LCAs.

In contrast to petroleum, evidence suggests stable or downward trends in GHG burdens for oil substitutes in the United States (electricity, ethanol, and natural gas). The GHG burden of the U.S. electricity mix (in terms of g CO₂-eq/kWh) is declining, reflecting the increasing use of natural gas and renewables in lieu of coal (EIA 2015), which, in turn, increases the GHG benefits of electric vehicles. An increasing contribution from cellulosic biofuels (e.g., as mandated in the U.S. Renewable Fuel Standard) and process improvements in corn ethanol production make it likely that the CI of ethanol will continue to decrease in the future (Farrell et al. 2006). Shale gas production is increasing in the United States, and recent assessments indicate comparable, or slightly lower, GHG emissions compared to conventional natural gas (Burnham et al. 2012). Hence, including temporal trends for alternative fuel-vehicle technologies is likely to reinforce their benefits beyond those illustrated in figure 2.

Discussion

Additional research is needed to understand and quantify marginal effects for conventional and alternative fuels. Open questions include the relevant time frame(s) for petroleum supply-demand considerations given the long time frame for climate change. For example, do near-term reductions in petroleum demand simply delay, but not prevent, the consumption of marginal petroleum over the relevant time frame? Or can such a delay buy time for eventual changes in technology or climate policy, such that less unconventional petroleum is ultimately extracted? It is also important to understand the short- and long-term elasticities of petroleum supply (e.g., for various conventional and unconventional oil sources) and demand curves (e.g., for different market segments) in the relevant time frame(s), and how these will impact GHG emissions.

Such analyses should be undertaken to inform life cycle and other energy system models currently used to drive transport policy (e.g., the U.S. Department of Energy National Energy Modeling System). Because these models currently neglect differentiation of crude petroleum sources, policy decisions are being made without complete information. Given that the scale of this effect is comparable in magnitude to the reduction targets of these policies, any policy decision made without marginal crude petroleum considerations is possibly neglecting a first-order effect.

Acknowledgments

The authors thank Sandy Winkler (Ford), John Ginder (Ford), Mike Tamor (Ford), Ole John Nielsen (Copenhagen University), Chris Knittel (MIT), and Jim Bushnell (U.C. Davis) for helpful discussions.

References

Anair, D. and A. Mahmassani. 2012. State of charge: Electric vehicles’ global warming emissions and fuel-cost savings across the United States. Union of Concerned Scientists Report. www.ucusa.org/assets/documents/clean_vehicles/electric-Carglobal-Warming-Emissions-Report. Accessed 21 January 2016.

Anex, R. and R. Liptat. 2014. Life cycle assessment: Different models for different purposes. Journal of Industrial Ecology 18(3): 321–323.

Boland, S. and S. Unnasch. 2014. Carbon intensity of marginal petroleum and corn ethanol fuels. Life Cycle Associates Report LCA, 6075. 83.

Burnham, A. R. 2012. Variability and uncertainty in life cycle assessment models for greenhouse gas emissions from Canadian oil sands production. Environmental Science & Technology 46(2): 1253–1261.

Burnham, A. R. 2011. Oil depletion and the energy efficiency of oil production: The case of California. Sustainability: Science Practice and Policy 3(10): 1833–1854.

Burnham, A., J. Han, C. E. Clark, M. Wang, J. B. Dunn, and I. Palou-Rivera. 2012. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environmental Science & Technology 46(2): 619–627.

Cai, H., A. R. Brandt, S. Yeh, J. G. Englander, J. Han, A. Elgowainy, and M. Q. Wang. 2015. Well-to-wheels greenhouse gas emissions of Canadian oil sands products: Implications for U.S. petroleum fuels. Environmental Science & Technology 49(13): 8219–8227.

CARB (California Air Resources Board). 2012. Detailed California-Modified GREET Pathway for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) from average crude refined in California. Sacramento, CA, USA: California Environmental Protection Agency, Air Resources Board, Stationary Source Division. www.arb.ca.gov/regac/2011/lcf2011/carbob.pdf. Accessed 21 January 2016.

EIA (Energy Information Administration). 2015. Figure 7. Electric power generation. Monthly energy review April 2015. No. DOE/EIA-0035(2015/04). Washington, DC: EIA.

El-Houjeiri, H. M., A. R. Brandt, and J. E. Duffy. 2013. Open-source LCA tool for estimating greenhouse gas emissions from crude
oil production using field characteristics. Environmental Science & Technology 47(11): 5998–6006.

Elgowainy, A., J. Han, L. Poch, M. Wang, and A. Vyas. 2010. Well-to-wheels analysis of energy use and greenhouse gas emissions of plug-in hybrid electric vehicles. trid.trb.org.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O’Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. Science 311(5760): 506–508.

Gordon, D., A. Brandt, J. Bergerson, and J. Koomey. 2015. Know your oil: Creating a global oil-climate index. The Carnegie Endowment for International Peace, March 11. http://carnegieendowment.org/2015/03/11/know-your-oil-creating-global-oil-climate-index. Accessed 28 July 2015.

Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. 2013. Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of Industrial Ecology 17(1): 53–64.

ICF International. 2013. Independent assessment of the European Commission’s Fuel Quality Directive’s “Conventional” Default Value. Fairfax, VA, USA: ICF International.

IEA (International Energy Agency). 2013. Resources to reserves, oil & gas technologies for the energy markets of the future. Paris: IEA.

IEA (International Energy Agency). 2015. Medium-term oil market report 2015: Market analysis and forecasts to 2020. Paris: IEA.

Jordaan, S. M. 2012. Land and water impacts of oil sands production in Alberta. Environmental Science & Technology 46(7): 3611–3617.

Joseck, F. and J. Ward. 2014, March 25. Cradle to grave lifecycle analysis of vehicle and fuel pathways. Washington, DC: U.S. Department of Energy.

Luk, J. M., B. A. Saville, and H. L. MacLean. 2015. Life cycle air emissions impacts and ownership costs of light-duty vehicles using natural gas as a primary energy source. Environmental Science & Technology 49(8): 5151–5160.

MacPherson, N. D., G. A. Keoleian, and J. C. Kelly. 2012. Fuel economy and greenhouse gas emissions labeling for plug-in hybrid vehicles from a life cycle perspective. Journal of Industrial Ecology 16(5): 761–773.

Mason Earles, J. and A. Halog. 2011. Consequential life cycle assessment: A review. The International Journal of Life Cycle Assessment 16(5): 445–453.

Nduagu, E. I. and I. D. Gates. 2015. Unconventional heavy oil growth and global greenhouse gas emissions. Environmental Science & Technology 49(14): 8824–8832.

Plevin, R. J., M. O’Hare, A. D. Jones, M. S. Torn, and H. K. Gibbs. 2010. Greenhouse gas emissions from biofuels’ indirect land use change are uncertain but may be much greater than previously estimated. Environmental Science & Technology 44(21): 8015–8021.

Plevin, R. J., M. A. Delucchi, and F. Creutzig. 2014. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. Journal of Industrial Ecology 18(1): 73–83.

Samaras, C. and K. Meisterling. 2008. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy. Environmental Science & Technology 42(9): 3170–3176.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319(5867): 1238–1240.

Soimakallio, S., A. Cowie, M. Brandio, G. Finnveden, T. Ekvall, M. Erlandsson, K. Koponen, and P.-E. Karlsson. 2015. Attributional life cycle assessment: Is a land-use baseline necessary? The International Journal of Life Cycle Assessment 20(10): 1364–1375.

Stephan, C. H. and J. Sullivan. 2008. Environmental and energy implications of plug-in hybrid-electric vehicles. Environmental Science & Technology 42(4): 1185–1190.

Suh, S. and Y. Yang. 2014. On the uncanny capabilities of consequential LCA. The International Journal of Life Cycle Assessment 19(6): 1179–1184.

Unnasch, S., R. Wiesenberg, S. T. Sanchez, A. Brandt, S. Mueller, and R. Plevin. 2009. Assessment of direct and indirect GHG emissions associated with petroleum fuels. Life Cycle Associates Report LCA-6004-3P.2009. Boston, MA, USA: New Fuels Alliance.

Van den Bos, A. and C. Hamelinck. 2014, November 12. Greenhouse gas impact of marginal fossil fuel use. Utrecht, the Netherlands: Ecofys.

Wang, M. Q., J. Han, Z. Haq, W. E. Tyner, M. Wu, and A. Elgowainy. 2011. Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. Biomass and Bioenergy 35(5): 1885–1896.

**About the Authors**

Timothy Wallington is senior technical leader of environmental sciences at Ford Motor Company in Dearborn, MI, USA. James Anderson is a technical expert in fuels science at Ford Motor Company. Robert De Kleine is a life cycle research analyst at Ford Motor Company. Hyung Chul Kim is an LCA specialist at Ford Motor Company. Heiko Maas is a research engineer at Ford Motor Company in Aachen, Germany. Adam Brandt is an assistant professor of energy resources engineering and center fellow, by courtesy, at the Precourt Institute for Energy, at Stanford University, Stanford, CA, USA. Gregory A. Keoleian is director of the Center for Sustainable Systems and the Peter M. Wege Endowed Professor of Sustainable Systems at the School of Natural Resources & Environment, and a professor in the Civil and Environmental Engineering Department at the University of Michigan, Ann Arbor, MI, USA.