Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers

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Summary

Life cycle assessment (LCA) is generally described as a tool for environmental decision making. Results from attributional LCA (ALCA), the most commonly used LCA method, often are presented in a way that suggests that policy decisions based on these results will yield the quantitative benefits estimated by ALCA. For example, ALCAs of biofuels are routinely used to suggest that the implementation of one alternative (say, a biofuel) will cause an X% change in greenhouse gas emissions, compared with a baseline (typically gasoline). However, because of several simplifications inherent in ALCA, the method, in fact, is not predictive of real-world impacts on climate change, and hence the usual quantitative interpretation of ALCA results is not valid. A conceptually superior approach, consequential LCA (CLCA), avoids many of the limitations of ALCA, but because it is meant to model actual changes in the real world, CLCA results are scenario dependent and uncertain. These limitations mean that even the best practical CLCAs cannot produce definitive quantitative estimates of actual environmental outcomes. Both forms of LCA, however, can yield valuable insights about potential environmental effects, and CLCA can support robust decision making. By openly recognizing the limitations and understanding the appropriate uses of LCA as discussed here, practitioners and researchers can help policy makers implement policies that are less likely to have perverse effects and more likely to lead to effective environmental policies, including climate mitigation strategies.

Introduction

The concept of life cycle thinking has become widely accepted as a paradigm for assessing the environmental effects of products and services. This is evidenced by the adoption of life cycle assessment (LCA) in regulations (U.S. Environmental Protection Agency [USEPA] 2010; European Parliament 2009), product certifications (British Standards Institute [BSI] 2008), and sustainability standards (e.g., Roundtable on Sustainable Biofuels, rsb.org). LCA is also commonly used to describe the climate-change mitigation benefits associated with alternative products and services, both in the academic literature (Farrell et al. 2006; Lipman and Delucchi 2010; Wang et al. 2012) and, importantly, in reports targeting policy makers (Chum et al. 2011; Fulton et al. 2009; Berndes et al. 2010; Bird et al. 2011).

Climate-change mitigation policies are generally motivated by a desire to avoid adverse effects of climate change. In most LCAs, climate effects are defined as the weighted sum of the life cycle greenhouse gas (GHG) emissions (GHGEs) of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), where the weights are given by the 100-year global warming potentials (GWPs) (Forster et al. 2007) of each gas. The total life cycle CO_2-equivalent GHGEs (LC-CO_2-eq-GHGE) are then

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expressed per functional unit of the product or service being assessed (e.g., grams [g] of LC-CO_2-eq-GHGE per mile of travel by a vehicle using a biofuel).[1] We will refer to this per-functional-unit LC-CO_2-eq-GHGE metric as the *global warming intensity*, or GWI.

In LCA terms, GWI is a midpoint indicator—an estimate of emissions intensity, not of the harm caused to humans and the environment. As commonly used in standards, regulations, and policy guidance reports, GWI serves as a proxy for the climate-related damages of using a product system, and a difference in GWI between an alternative and incumbent product is treated as a proxy for climate-change mitigation benefits.[2] However, because of numerous simplifications inherent in conventional estimates of GWI, it is difficult to ensure that even the sign of this proxy is correct.

The aims of this article are to show that policy makers can be misled by the characterization of attributional LCA (ALCA) results as describing climate-change mitigation potential, and that a more appropriate use of LCA would be to support the development of policy interventions that are robust to uncertainty. We focus on LCA of energy systems, because this is the subject of the standards, regulations, and reports noted above. We make the case that LC-CO_2-eq is not an adequately complete or even meaningful measure of climate change impacts.

The Semantics of Life Cycle Assessment

Although many studies purport to estimate life cycle environmental effects, there is no universally accepted, precisely defined, single method for conducting an LCA (International Organization for Standardization [ISO] 2006b; Finkbeiner 2009) and thus the precise meaning of "life cycle environmental impact" can differ from study to study. Even when following the fairly specific guidance of the Handbook of the International Reference Life Cycle Data System (ILCD) (European Commission–Joint Research Centre–Institute for Environment and Sustainability [EC-JRC-IES] 2010), the operational definition of LC-CO_2-eq-GHG depends on subjective choices regarding system boundaries, data sources, aggregation methods, treatment of coproducts, and more (Van der Voet et al. 2010; Hoefnagels et al. 2010; Malça and Freire 2010; Wardenaar et al. 2012; Reap et al. 2008b; Suh et al. 2004; Finnveden 2000; Heijungs and Guinée 2007; Cherubini et al. 2009). Given this definitional latitude, LCA results of the same nominal target can span a wide range.

This problem arises, in large part, because there is no way to directly measure GWI; what constitutes a life cycle must be assembled in a model. In practice, many elements of a life cycle model are known only approximately, for several reasons: The activities and subsystems of the life cycle are complex and have not been described in detail; input-output (IO) flows are not directly measured in the ways needed for LCA; the inputs are commodities that cannot be traced to specific producers; production practices are not revealed as a result of concerns over intellectual property; some suspected or known potential sources of GHGEs have not been characterized or measured; available measurements of GHGEs are based on only a subset of the full range of technologies, operating conditions, and environmental conditions in the real system; and there is not enough historical or cross-sectional experience to precisely formulate how IO flows scale with changes in the use of the final commodity of interest. GWI estimates thus are different from estimates of, say, tailpipe emissions from automobiles: GWI is the result of a complex and uncertain[3] model, whereas estimates of tailpipe emissions are based directly on well-established, widely agreed-upon emission-testing procedures (DeCicco 2012). Because of this, and because energy systems are global and their primary climate effects result from emissions of global pollutants with long-lasting effects, GWI cannot be directly observed or validated.

Attributional Versus Consequential Life Cycle Assessment

To further complicate matters, there are two different frameworks for performing LCA: attributional and consequential. Most LCA tools and databases (Finnveden et al. 2009) and published studies (Zamagni et al. 2012; EC-JRC-IES 2010, 70) rely on ALCA, which tracks energy and material flows along a product's supply chain and during use and disposal or recycling. This "accounting" perspective includes all flows throughout a process chain, regardless of their relevance to a change in the modeled system (Tillman 2000). ALCA represents the average operation of a static system irrespective of economic or policy context. Although ALCA does not model impacts as a function of changes in production, the result of an ALCA is commonly presented as an estimate of the effect of increasing or decreasing system output.

In contrast to attributional LCA, consequential LCA (CLCA) estimates how flows to and from the environment would be affected by different potential decisions (Curran et al. 2005). In CLCA, only those elements of a system that are affected by the decision at hand are included in the analysis; other elements are irrelevant (Tillman 2000; EC-JRC-IES 2010). Whereas ALCA is static, context independent, and average, CLCA ideally is dynamic, context specific, and marginal.

Although the appropriate uses of ALCA and CLCA are still debated in the LCA literature (for a summary, see Finnveden et al. 2009), many researchers have concluded that the key difference is that CLCA estimates the effects of a specific action (e.g., a GHG mitigation policy), whereas ALCA does not (e.g., Earles and Halog 2011; Reinhard and Zah 2011; Whitefoot et al. 2011; Curran et al. 2005; Ekvall and Andrae 2006). For example, the ILCD (EC-JRC-IES 2010), recommends the consequential approach for analyses that will inform policy making and the attributional or accounting approach only in contexts where no decision is to be made based on the results of the analysis.[4]

Because CLCA is designed to estimate the effect of a decision or action, it can, in principle, serve as a guide to mitigation potential. In practice, however, methods to identify market-mediated effects and marginal processes are incomplete and model results are scenario dependent (Dumortier et al. 2011; Khanna and Crago 2012). As with ALCA, CLCA results vary with subjective methodological choices made by the modeler, such as how exactly to model consequences, for example, whether to use partial or general economic models and how these models are configured and parameterized (Khanna and Crago 2012). By expanding the scope of the analysis (e.g., including global energy markets) and introducing dynamic relationships among system elements, CLCA introduces an additional level of structural model uncertainty (Schmidt 2008; Sathre et al. 2012). Because of this, CLCA is more useful for examining alternative scenarios to understand the range of potential environmental outcomes than for predicting a single most-likely outcome (Zamagni et al. 2012; Delucchi 2011b; Ekvall et al. 2007; Sathre et al. 2012).

We note that these issues of methodological ambiguity, data gaps, and the subjectivity of LCA have persisted for decades (e.g., Udo de Haes 1993; Ehrenfeld 1997; Hertwich et al. 2000; Finnveden 2000; Suh et al. 2004; Reap et al. 2008b), and we do not attempt to resolve them here. A newer issue, and the subject of the remainder of this article, is the appropriate use of LCA to inform climate policy.

The Challenges of Estimating Climate-Change Mitigation Benefits

In principle, the climate-change mitigation achieved by an action should be estimated as the difference in some relevant measure of the state of the climate in hypothetical worlds with and without the action, including all changed processes or climate-forcing factors within and outside the supply chain. In the case of a policy targeted at a particular technology, the climate-change mitigation benefit of the policy should be estimated as the total climate-change impact resulting from the policy-induced use of the new technology system minus the total climate-change impact estimated for a baseline scenario without the policy. To build a practical model based on these principles, however, requires simplifying assumptions, concerning, for example, how the expanded use of a new technology affects the use of the incumbent technology, the interactions of these technologies with the broader economy, and the choice of the climate-change metric itself (Tol et al. 2012; Deuber et al. 2013).

A Simple Representation of Life Cycle Assessment Modeling of Climate-Change Impacts of Energy Systems

A simple formal representation of the LCA problem will help make more concrete some of the implicit and explicit simplifying assumptions mentioned above. Consider a stylized economy with four product systems (S): systems S_1 and S_2 produce gasoline and fuel ethanol, respectively; system S_3 produces natural gas; and system S_4 produces food.

For each system S_n, we estimate the LC-CO_2-eq-GHG emissions[5] (variable E_n) by multiplying some total activity or service-provision level (variable L_n; e.g., one kilometer [km] of travel) by an LC-CO_2-eq-GHG emission factor per unit of activity (variable GWI_n, e.g. CO_2-eq per km of travel). Finally, consider two scenarios, A and B, which differ only with respect to a policy that explicitly promotes the use of S_2—ethanol, in our example. We designate the respective scenarios with superscripts A and B.

In scenario A, total LC-CO_2-eq-GHG emissions—the metric of interest (the sum of all E_n, here designated E^A)—is given by the product of activity and emissions per unit of activity, summed for all systems:

$$E^A = L_1^A \cdot GWI_1^A + L_2^A \cdot GWI_2^A + L_3^A \cdot GWI_3^A + L_4^A \cdot GWI_4^A = \sum_{n=1}^{4} L_n^A \cdot GWI_n^A$$

In scenario B, *in general*, total emissions is similarly given by:

$$E^B = \sum_{n=1}^{4} L_n^B \cdot GWI_n^B$$

The difference between these two expressions is the total LC-CO_2-eq-GHGE effect of the policy that distinguishes A from B:

$$\Delta E^{A,B} = \sum_{n=1}^{4} L_n^A \cdot GWI_n^A - \sum_{n=1}^{4} L_n^B \cdot GWI_n^B$$

Note that in our general representation of E^B, all of the variables are potentially different than for scenario A, even though the policy that distinguishes A from B explicitly targets S_2 and hence directly affects only S_1 and S_2. But, *a priori*, we have no reason to believe that the policy affects only S_1 and S_2.

In the terms of this simple representation, the application of ALCA to estimate $\Delta E^{A,B}$ requires three implicit or explicit assumptions:

1. The policy does not even indirectly affect the total activity level within the targeted systems S_1 and S_2; that is, $L_1^A + L_2^A = L_1^B + L_2^B$.
2. Nor does it affect any energy and nonenergy activities outside of the directly affected systems S_1 and S_2; that is, $L_3^A = L_3^B$ and $L_4^A = L_4^B$.
3. Nor does it affect the GWI of any system; that is, the GWIs are independent of the activity level L, and so $GWI_n^A = GWI_n^B$ for systems $n = 1$ through 4.

For example, in the case of a policy promoting biofuels for light-duty vehicles (LDVs), a typical application of ALCA presumes that the policy does not affect the price and quantity of LDV usage (assumption 1), does not affect the price and usage of any related energy or nonenergy commodities (e.g., natural gas use as a substitute for oil or agricultural commodities affected

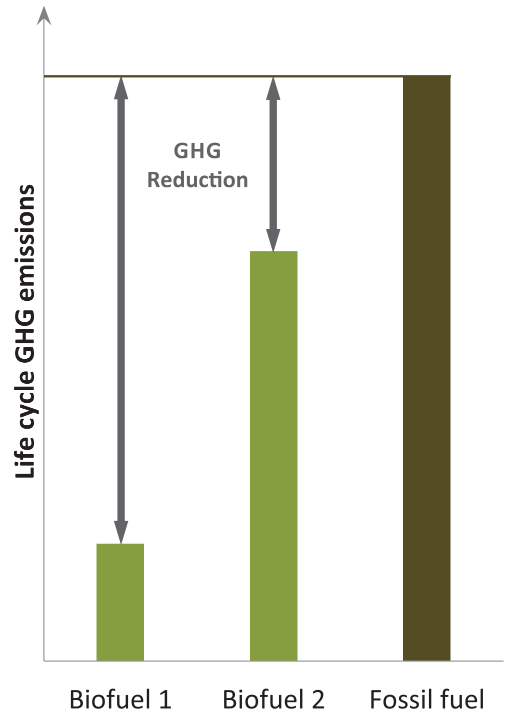

Figure 1 A typical comparison of the life cycle greenhouse gas (GHG) emission of biofuels and a fossil fuel implying (incorrectly) that the actual GHG savings from using the biofuels is simply the difference between their respective GHG emissions and that of the fossil fuel, estimated using attributional LCA.

by the production of the biofuel feedstock; assumption 2), and does not thereby cause changes in the use of inputs or technology that would lead to differences in GWIs (e.g., efficiency of gasoline-fueled LDVs; assumption 3).

With the above assumptions, and with the driving change in activity defined as $\Delta L = L_1^A - L_1^B = L_2^B - L_2^A$, it is easy to show that the climate-change mitigation benefit of the policy now simplifies to $\Delta E^{A,B} = (GWI_1 - GWI_2) \cdot \Delta L$. That is, the climate change mitigation effect becomes simply the difference in the GWIs of the two services multiplied by some scalar. Put another way, the common interpretation of ALCA results assumes that the complete system S_2 that produces a unit of service substitutes for the complete system S_1 that produces a unit of the same service, and that this substitution is valid at any scale and has no indirect effects. Expressed as a percentage change in emissions relative to S_1, the mitigation effect of the policy promoting S_2 reduces to $\frac{\mathrm{GW}I_1 - \mathrm{GW}I_2}{\mathrm{GW}I_1}$ or $1 - \frac{\mathrm{GW}I_2}{\mathrm{GW}I_1}$. This is arguably the most common interpretation of comparative LCA results. The European Parliament, for example, uses this form to define the GHG savings from biofuels in the Fuel Quality Directive (European Parliament 2009). Similarly, this approach to estimating the GHG mitigation effect is implied by graphical figures (e.g., figure 1) that compare the GHG ratings of fossil and alternative energy systems. To sum up to this point, analyses that report climate-mitigation effects based on ALCA generally have assumed away all indirect and scale effects on CO_2-eq emission factors and on activity within and beyond the targeted sector. Unfortunately, as we discuss below, there is no theoretical or empirical basis for treating indirect and scale effects as negligible (Arvesen et al. 2011).

System-Boundary Truncation

The choice of system boundary determines which processes and activities are included in an LCA, with potentially large effects on the results of the analysis (Reap et al. 2008b). Here, we examine system-boundary issues in various forms of LCA.

System-Boundary Truncation in Attributional Life Cycle Assessment

Although ALCA studies are generally described as representing the complete life cycle of a product "from resource extraction through manufacture and use to disposal" (Owens 1997), this is never the case in practice: Data gaps and practical limitations inevitably demand truncation of the system boundary resulting in omissions of 20% to 50% (Lenzen 2000) and a "systematic underestimation" of environmental effects (Majeau-Bettez et al. 2011). Of course, some omissions can result in an undercounting of sequestration, such as carbon storage under perennial crops (Anderson-Teixeira et al. 2013). Thus, even without considering indirect effects, it would be inappropriate to claim that ALCA provides a complete representation, or that the cut-off error in two life cycles being compared is either similar or negligible.

System-Boundary Truncation in Consequential Life Cycle Assessment

CLCA also suffers from truncation errors resulting from practical difficulties in identifying and including all affected processes (Zamagni et al. 2012). Some CLCA studies attempt to identify a single marginal producer and affected product (Schmidt and Weidema 2008), whereas others employ economic models to project market-mediated effects (Kløverpris et al. 2008). Modeling the entire global economy in detail is infeasible: In practice, economic models can provide either a detailed representation of a portion of the economy (i.e., partial equilibrium models) or a coarse representation of the entire global economy (i.e., general equilibrium models) (Khanna and Crago 2012; Kløverpris et al. 2008).

Issues with Hybrid Process Economic Input-Output Life Cycle Assessment

Economic IO LCA (EIO-LCA) has been applied to address the truncation problem in ALCA (Suh et al. 2004). EIO-LCA data represent average emissions per dollar expended in each economic sector, allowing EIO-LCA models to estimate the total emissions associated with a product, within the bounds of a given IO table (Reap et al. 2008b). Although EIO-LCA offers more extensive coverage (at coarser resolution) than does process-based LCA (Heijungs et al. 2006; Hendrickson et al. 2006), its monetary basis may fail to include environmentally important nonmarket activities, such as product use and disposal (Majeau-Bettez et al. 2011). Of course, EIO-LCA is only useful for product systems represented in the available IO data, and this data is not easily augmented. As with ALCA, EIO-LCA does not reflect marginal effects or out-of-supply chain effects resulting from price changes, and environmental effects are treated as linear with expenditures (Hendrickson et al. 2006). Combining EIO and process LCA models can reduce the truncation error in an ALCA framework; however, this combination does not transform an ALCA into a change-based analysis.

Alternative Proxies for Climate-Change Effects

The discussion above regards which processes are included in the LCA. In terms of the portrayal of LCA results as representing climate-change mitigation benefits, two additional issues are (1) which climate-forcing factors are included and (2) how these factors are aggregated into a single metric.

As noted in the "*Introduction*," the LCA community generally uses 100-year GWP values to convert non-CO_2 gases to aggregate these into a single CO_2-eq value. It is important to recognize that there is a vigorous debate over the appropriateness of using GWPs to estimate climate impacts (Tol et al. 2012; Manning and Reisinger 2011; Shine 2009; Smith and Wigley 2000a; Smith and Wigley 2000b; Delucchi 2011a). A variety of alternatives exist to define an equivalence between CO_2 and a non-CO_2 emission based on metrics, such as radiative forcing, temperature change, and discounted social cost (Tol et al. 2012; Deuber et al. 2013; Delucchi 2011a), and each alternative requires value-based judgments about key parameters, such as time horizon, the point in time to measure temperature, and discount rate (Moura et al. 2013). The choice of which metric to use and how to parameterize it produces a range of equivalency factors (see, e.g., Boucher et al. 2009; Moura et al. 2013; Deuber et al. 2013); which to use for a given purpose is a political decision, not a scientific one.

Missing Climate-Change Impacts

Because there are no widely accepted GWPs for several pollutants that are known to significantly affect climate, the climate forcing resulting from these pollutants is generally not included in LCAs. Since these are emitted in significant, varying quantities from different energy systems, LCAs that track only CO_2, N_2O, and CH_4 omit potentially important climate impacts. Recent scholarship has begun to address additional climate-forcing phenomena, including emissions of aerosols, such as black carbon and sulfate (Fuglestvedt et al. 2010; Galdos et al. 2013), indirect GHGs—substances that affect the residence time of GHGs (Brakkee et al. 2008), as well as albedo change (Bright et al. 2012; Anderson-Teixeira et al. 2012), but few published LCAs incorporate any of these, and none, to our knowledge, include all of them. Preliminary analyses indicate that in some biofuel scenarios, these non-GHG forcings can be of the same order of magnitude as climate forcing from carbon emissions resulting from land-use change (Delucchi 2010).

Although these exclusions are correctable within the context of conventional LCA, they cast further doubt on most published estimates of climate-change mitigation capacity of alternative energy systems.

Importance of Choice of Baseline

The climate-change mitigation effect of producing and using more or less of a product depends on the particulars of the assumed baseline. For example, the GHG mitigation achieved using a waste-to-fuel system depends, importantly, on the alternative fate of the waste; whether it would have otherwise been sequestered in a sanitary landfill with zero emission or left to decompose and emit methane largely determines the net effect on GHG emissions (Chester and Martin 2009), but ALCA does not consider counterfactual uses of inputs, so it cannot account for this. ALCA frequently does include an *implicit* counterfactual for final products, but this typically is not handled explicitly. For example, the climate-change mitigation benefit of a biofuel is commonly estimated as the difference in life cycle GHG emissions between the biofuel and the corresponding petroleum fuel. This estimated benefit is treated as though it were a property of the biofuel production system: Simply make more of this fuel and GHG emissions will be reduced by the estimated amount. However, context matters: A policy promoting a low-GWI biofuel in one region may result in a shuffling of low- and high-GWI biofuels so that the reductions in one region are balanced by the increases in the other. The actual mitigation effect of an action will vary with the political/economic/technological/social context, none of which are represented in ALCA.

Assumption of Perfect Substitution

As shown in the section "A *Simple Representation of Life Cycle Assessment Modeling of Climate-Change Impacts of Energy Systems*," the comparison of ALCA results to estimate climate-change mitigation benefits implicitly assumes perfect substitution of one product for another, and that activity and emission levels scale linearly with the quantities required for meaningful levels of climate-change mitigation, with no indirect effects. For example, an ALCA-based conclusion that corn ethanol "reduces GHGs by *X*%" (e.g., Farrell et al. 2006) or a figure showing ALCA results labeled "well-to-wheel GHG emission reductions for biofuels" (e.g., Wang et al. 2011) suggest not only that some consumer uses the biofuel instead of, say, gasoline, but that the use of the biofuel results in the avoidance of the entire life cycle of a functionally equivalent quantity of gasoline, with no indirect or scale effects in any system anywhere in the world, at any time. Not only is the consumption of the gasoline avoided, but the corresponding quantity of petroleum is assumed not to be produced, transported, or refined.

In reality, however, there is no perfect substitution, and there *are* indirect and scale effects. Continuing our example, a policy such as a biofuel mandate expands the global fuel supply. Within the policy region, the relative prices of fuels may augment or reduce the fuel replacement effect (Rajagopal and Plevin 2013). The greater use of biofuel and reduced use of gasoline in the policy region shifts the global demand curve for gasoline inward, resulting in a reduction in the global price of gasoline and petroleum relative to the baseline without the policy (USEPA 2010; Rajagopal et al. 2011; de Gorter 2010). The actual changes in consumption and production are determined by the relative supply and demand elasticities with respect to price as well as the relative strengths of the effects inside and outside the policy region. Economic theory provides a means of estimating these effects; simply assuming that producing a biofuel suppresses production of an equal quantity of petroleum-based fuel is "clearly wrong" (York 2012).

Presentation and Interpretation of Life Cycle Results

The limitations of ALCA have been widely discussed in the literature (see, e.g., Reap et al. 2008a, 2008b), and some academics and practitioners recognize that ALCA is not designed to answer the question of whether a change in energy system use results in climate-change mitigation benefits. However, presentations of LCA results generally do not acknowledge these limitations and therefore risk misleading people who use the results. Consider, for example, figure 1, showing a typical presentation and interpretation of LCA results (see, e.g., Chum et al. 2011, figure 2.10). In this figure, several fuels are presented in a bar chart, with each bar indicating one fuel's GWI, estimated using ALCA. Vertical arrows labeled "GHG Reduction" indicate the difference between the biofuels' GWI and that of the fossil fuel.

How should we interpret this sort of chart? The point we wish to make is that there is an important difference between interpreting this type of figure to mean, on the one hand, that (for example) "the GWI of sugarcane ethanol is 80% lower than that of gasoline," and on the other, that "the use of sugarcane ethanol reduces emissions (or climate-change impacts) 80%, compared to the use of gasoline." The former accurately reflects the results of the analysis without interpretation, whereas the latter interprets this difference as a prediction of real-world impacts, implying that the bars reflect consequences, rather than merely an accounting of process emissions, and that biofuels perfectly substitute for gasoline, without affecting its price or other consumption in any way. But, neither of these implications can be deduced from an ALCA.

Many reports for policy makers compile results from several LCA studies and combine these into bars that represent the range of results from studies of the same nominal system. Composite figures such as these are generally difficult to interpret. Because the phrase "life cycle GHG emissions" is subject to interpretation, values from different studies are generally incommensurable without previous harmonization (Heath and Mann 2012; Brandão et al. 2012; ISO 2006a, 11; Chiaramonti and Recchia 2010). Properly interpreting any LCA result requires understanding the specific methods, assumptions, and data used in the analysis (Plevin 2009; Farrell et al. 2006), yet the reader encountering a composite figure generally does not have access to the required information.

Some biofuel studies present ALCA results while acknowledging that some emissions—often from indirect land-use change (ILUC)—are omitted (e.g., Fulton et al. 2009; Berndes et al. 2010). Though it is commendable to recognize this potentially large missing element, the figure nonetheless suggests that (1) subtracting one ALCA result from another produces a useful estimate of GHG reductions—other than the "missing" ILUC, that is, that there are no other indirect or scale effects, (2) adding attributional and consequential results is appropriate conceptually, and (3) some useful conclusions can be drawn from the figure, even though some of the fuels compared are missing important emissions that may change the sign of the comparison. Presenting a figure with a long list of disclaimers in the text violates the reasonable expectations that a figure means what it says, thus the figure is misleading.[6]

The Way Forward: Consequential Analysis to Aid Robust Decision Making

Decision making is a forward-looking process that requires selecting among alternative actions based on their expected outcomes (Lasswell and Kaplan 1950). Decision making is best supported by an analysis that anticipates the effects of the decision, which, as we (and others) have argued, requires the use of CLCA (Tillman 2000; Zamagni et al. 2012; Finnveden et al. 2009; Ekvall et al. 2005; Weidema 2003; EC-JRC-IES 2010). However, because of the large, unavoidable uncertainty associated with even the best, practical CLCA models, it is not enough to just use CLCA instead of ALCA; we also must use LCA models differently, as discussed below.

The Nature of Uncertainty in Life Cycle Assessment

Expanding the analytic scope of LCA to incorporate markets and other complex system dynamics—for example, by relying on partial or general equilibrium modeling—broadens and changes the nature of the uncertainty in LCA results (Ekvall et al. 2007). With ALCA, the computational structure is simple: the sum of the products of activity levels and emission/use factors. When ALCA is properly applied (i.e., to *attribute* emissions, not to predict the effects of a decision) uncertainty is mainly parametric, that is, the activity levels and emission/use factor may be imperfectly known. CLCA also involves substantial parametric uncertainty while adding the scenario dependence and uncertainty inherent to all projections of the future. Moreover, complex, multifaceted, interdisciplinary problems, such as estimating the net climate effects of alternative policies, engender multiple perspectives and evaluation frameworks, yielding divergent outcomes that can be equally plausible (Sarewitz 2004). In fact, the more comprehensive the consideration of consequential effects, the more uncertain are the results (Creutzig et al. 2012), with the result that no model should be expected to produce a single, definitive quantitative assessment of environmental outcomes (Finnveden 2000; Hertwich et al. 2000; McKone et al. 2011; Delucchi 2010).

It is important, however, to recognize that the greater uncertainty associated with CLCA is not a valid reason to retreat to ALCA to estimate climate-change mitigation benefits. ALCA is less uncertain precisely because it uses a simple model—so simple that it fails to answer the policy questions that have motivated its application. The uncertainty associated with CLCA represents the true limits of scientific knowledge with respect to estimating the full environmental effects of an action.

The Role of Life Cycle Assessment in Decision Making

The scenario dependence discussed above suggests that a CLCA may generate as many distinct numerical results as there are scenarios. A policy or decision based on any single scenario may produce an undesirable outcome under another scenario. However, basing a decision on the relative performance of alternative policies under a wide range of plausible scenarios can produce decisions that are more resilient to the uncertainties examined (Groves and Lempert 2007; Hall et al. 2012). For example, if a robustness analysis indicates that ILUC emissions for some biofuels are uncertain, but large, in some plausible scenarios, whereas other alternatives (e.g., solar-electric power) have very low emissions under all conceivable scenarios, a policy maker may decide that the more robust solar-electric power is preferable. Once identified, some risks can be more easily avoided than precisely quantified (Fritsche et al. 2010; Gawel and Ludwig 2011; Wicke et al. 2012). LCA can therefore produce useful information and support decision making, even when there is substantial uncertainty.

Recommendations

Despite the long-standing discussion in the literature of the limitations of LCA, many published LCA results are not properly qualified. As Ehrenfeld (1997) noted, the limitations of an analytical method may be known as the method is first developed, but, over time, the caveats are omitted and "the method itself takes on a truthlike character." With the advent of LCA-based public policy, it is essential that we remember these caveats and avoid promoting the use of LCA beyond its methodological limits. To avoid misleading policy makers (and readers in general), we recommend the following for LCA practitioners and researchers, peer-reviewed journals, and analysts producing reports for policy makers.

The value of LCA studies will be increased if *LCA practitioners and researchers* consider carefully and systematically the questions they are attempting to answer and ensure that the form of LCA used is appropriate to answer those questions. Specifically, acknowledging methodological limitations (e.g., that ALCA is not predictive; that subjective choices, including the choice of functional unit, system boundaries, and handling of coproducts strongly determine the results of comparisons) will avoid misunderstandings that could lead to inappropriate use of LCA results. Knowledgeable LCA consumers will be aware of these limitations, but many readers, including most policy makers, will not be. LCA practitioners and researchers should use ALCA only for normative analyses (e.g., when allocating responsibility for environmental harm), sensitivity analyses, and to gain a qualitative understanding of a production system.

Peer-reviewed journals should ensure that published LCA studies refrain from unsupported claims, such as "using product X results in a Y% reduction in GHG emissions compared to product Z," because this sort of claim is valid only in the extremely unlikely case that all market-mediated effects, excluded climate forcings, nonlinear scaling effects, and system-truncation effects are negligible. Instead, journals and reviewers should insist that discussions of LCA results clearly acknowledge empirical, methodological, and conceptual limitations, with general qualifying statements. For example: "We estimate that the ALCA rating of product X is Y% lower than that of product Z, though this does not imply that producing more of X results in a Y% reduction. To infer the actual climate impact of an action affecting the use of X and Y requires a change-based (consequential) analysis."

Analysts producing summaries of published LCA results for policy makers can avoid potentially misleading conclusions by recognizing that ALCA may not be the appropriate method to answer the question at hand. They should also state clearly that LCA study results are generally not comparable without substantial harmonization, and that *post facto* harmonization is not always possible.

By clearly identifying the limitations of LCA results, and drawing only conclusions that respect these limits, LCA practitioners, analysts, and journals will provide policy makers with a more accurate assessment of the state of scientific knowledge and thereby assist in the crafting of more-effective, robust environmental policies.

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Notes

1. Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference.
2. There are examples of this throughout the policy-oriented reports and the academic literature, with statements such as, "In using LCA to determine the climate change mitigation benefits of bioenergy, the [attributional] life cycle emissions of the bioenergy system are compared with the emissions for a reference energy

system." (Bird et al. 2011). Similarly, bar charts of ALCA results with labels such as, "well-to-wheel GHG emission savings with respect to conventional gasoline and diesel fuel" (Fulton et al. 2009, figure 2.17). We note that this criticism applies to the authors' own previous works (e.g., Farrell et al. 2006; Lipman and Delucchi, 2010).

3. It is important to distinguish among (1) misuse of a method, (2) subjective choices in the implementation of the method, and (3) uncertainty in parameter values or model form. Most problematically for users of ALCA, the application of ALCA to estimate a change resulting from an action is a misuse of the method, because ALCA is not structurally capable of estimating actual changes. Setting that aside, within the context of ALCA, subjective choices are not always revealed (e.g., in figures presented in a report for policy makers), resulting in uncertainty from the users' perspective regarding the accuracy or relevance of the results to the problem at hand.
4. We would put this differently. ALCA should not be used to inform decisions about the real-world impacts of policy actions. It can, however, guide *normative* (as opposed to descriptive) considerations, such as how to *equitably* allocate impacts, costs, or benefits. It also can be used as a diagnostic tool to perform sensitivity analyses, and it even reasonably can be used as a source of information to aid in general decision making.
5. In our example, we use LC-CO_2-eq-GHG emissions as a proxy for climate change effects—not because it is a particularly good proxy, but because it simplifies the presentation: GWP-weighted emissions are additive by definition, assuming the emissions all occur simultaneously.
6. As one example of many found in the literature, Berndes and colleagues (2010) present a fairly standard barchart (their figure 8) showing ranges that "reflect variations in performance as reported in literature," noting that "possible LUC emissions are not included." The ranges in the literature usually result from different choices of system boundaries, allocation methods, proxies, and so on, and, as such, are commonly estimates of different definitions of the "life cycle GHG emissions." About ILUC, they write: "Despite the significant uncertainties involved in the quantification of LUC emissions it can be concluded that LUC can significantly influence the GHG emissions benefit of bioenergy—in both positive and negative directions." This statement acknowledges that a comparison of the results shown in figure 8 would be misleading. Their figure 10 shows GHG savings from different biofuel pathways, using the simple subtraction of biofuel LC-GHGs from petrofuel LC-GHGs. "The green 'biofuel use' bars show GHG savings (positive) from biofuel replacement of gasoline and diesel," but this is not a valid interpretation for all the reasons discussed in this article.

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