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**FY2010 LCA Milestone Report  
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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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# 1 Introduction

One barrier to the full support and deployment of alternative energy systems and the development of a sustainable energy policy is the lack of robust conclusions about the life cycle environmental impacts of energy technologies. A significant number of life cycle assessments (LCA) of energy technologies have been published. However, the results reported for certain technologies vary greatly, thus clouding the overall synopsis and limiting the utility of LCA to inform policy. To date, little attention has been given to analyzing the large body of previously published results in a way that can reduce the uncertainty and variability in as-published estimates of life cycle environmental impacts and increase their value to decision makers.

Methodological inconsistencies (e.g., inconsistent system boundaries, the use of outdated data, variations on similar energy process chains, and even simple differences in reporting of results) contribute to the variance in results between studies and hinder meaningful comparison. Many methodological inconsistencies between previously published LCAs can be aligned, a process termed “harmonization,” thereby increasing their collective value by enabling proper comparison and more generalized conclusions. Farrell et al. (2006) demonstrated that, given a set of high-quality and fully documented LCAs, one can *ex post facto* harmonize the methods (e.g., system boundaries) of multiple studies with dissimilar as-published results. This process can reduce variability and uncertainty, yielding a more robust understanding of the true life cycle burdens. Harmonization can also help to identify where gaps in our understanding of the life cycle environmental burdens of energy technologies remain and can usefully be filled by new research. However, not all sources of inconsistency are amenable to harmonization (e.g., consequential vs. attributional LCAs) and this process requires a set of studies providing detailed results and considerable effort to accomplish.

For some combinations of technology and estimated environmental impacts where variability in as-published estimates are small, simply conducting a statistical meta-analysis on the as-published estimates of impacts could yield sound, policy-relevant results. In cases where methodological inconsistencies produce results with significant variability, greater efforts to reduce inconsistencies and glean robust conclusions could be warranted. Focusing on the latter case, this report describes the background of this research issue and provides guidance on how best to carry out harmonization of previously published LCA results and provide consistency for collaborators on the LCA Harmonization project and those wishing to conduct similar analyses. An example is made of an ongoing effort to harmonize estimates of GHG emissions from previously published LCAs of electricity generation technologies. It is also true that not all sources of inconsistency among studies ought to be harmonized, but this report leaves the decision to the analyst about which dimensions of incongruity are appropriate to harmonize based on the specific context of the research question.

## Background

There are two broad types of LCAs: consequential and attributional. Consequential LCAs track the impact of a particular action (e.g., the production of X (typically large) MWh by a given electricity generation technology) across the full range of potential, system-level effects in comparison to an alternative, baseline scenario. They include evaluation of both the direct and indirect effects this action has in terms of changes in production of the primary product, its substitutes and competitors, ad infinitum, within the broader, often global, economic-social

system, recognizing that there are environmental consequences (good or bad) to all of these changes. Therefore, consequential LCAs require a very broad system boundary, much broader than typical attributional LCAs. Consequential LCAs are appropriate for analyzing the impacts of policy-level decisions, which typically introduce large-scale and long-term system changes. The assessment of feedback across multiple systems tends to lead to studies that are highly complex. Partially owing to this complexity, consequential LCAs are not amenable to comparison with attributional LCAs or even other consequential ones.

In contrast, attributional LCAs analyze the direct effects of a system over a fixed period of time (Plevin 2009). They seek to attribute all of the environmental impacts of a system, with less concern for the realistic implementation or comparison to existing scenarios. System boundaries of attributional LCAs are fundamentally different from consequential LCAs. Due to the reduced complexity and relative methodological congruity, attributional LCAs lend themselves better to comparison. Because most published literature is attributional, leveraging the results of existing LCAs for harmonization is limited to a review of attributional LCAs.

However, one subcategory of attributional LCA is also not generally amenable to comparison with others using alternative methods: economic input-output-based (EIO) LCAs. EIO-LCAs define system boundaries within the domestic economy by the monetary linkages among industry categories. Databases reporting environmental burdens per monetary unit are matrixed to these monetary flows to estimate life cycle environmental burdens. This approach differs substantially from the more typical attributional LCA method, called process-based LCA. Process-based LCA uses an engineering, bottom-up approach to define mass and energy flows in each phase of a technology's life cycle. The two approaches are not amenable to harmonization since their structure is so different. Because process-based LCAs are much more common in the literature, in this study, EIO-LCAs will be excluded from the pool eligible for harmonization. Studies that combine process and EIO-based approaches (so-called hybrid LCAs) need to be evaluated on a case-by-case basis to decide whether the differences in methodological structure preclude harmonization.

Within the attributional class of literature, LCA results often vary substantially within a given technology category. In some cases, this variation can be attributed to human error through flawed calculations, sub-optimal methodological choices, poor data selection, or misinterpretation of input data; however, much of the variation is due to "legitimate" differences. For instance, the research question that frames the study can drastically alter the approach and thus the result. As an example, one researcher might be concerned with the impacts of utilizing local feedstocks, whereas another researcher conducting a similar study could investigate the most economical feedstocks. Legitimate alternative results would follow from these two research questions; the latter study could assess imported feedstocks, which are likely to utilize fundamentally different transportation and production pathways from that of local feedstocks. Similarly, legitimate differences of opinion regarding methodology occur, such as the method utilized to allocate impacts across multiple co-products or decisions setting system boundaries. While this report focuses on describing how to harmonize inconsistencies that are amenable to harmonization, it is left to the analyst to decide whether some potentially harmonizable factors are actually better left unharmonized.

These variances in approach hinder comparison across studies for a particular technology as well as the larger body of LCA literature. A holistic and consistent treatment of LCA literature through harmonization can filter out inferior data and methods, screen out analysis that is inapplicable to the research questions or use of the harmonized results, categorize work based on the technology/process chain scope, reconcile system boundaries and other methodological differences, and transform reported metrics into common units/categories. By overcoming these barriers through harmonization, LCAs of energy systems can more readily be used in other research contexts and better meet the needs of researchers and decision makers. For instance, harmonized estimates of life cycle GHG emissions will presumably (for instance, as shown by Farrell et al., 2006) display less variability than the as-published estimates from the same set of literature. Simple statistical estimates of central tendency and variability will be more robust when based on the harmonized estimates and could help inform environmental decision making. Also, the set of harmonized estimates could form the basis for building a meta-model that could provide a “best” estimate (composed of the best attributes of the constituent studies) of environmental burdens. The meta-model could be exercised across legitimate ranges of input parameters to assess variability and uncertainty more formally.

## 2 “Dimensions of Incommensurability”

A 2009 report by Plevin laid out several key “dimensions of incommensurability” among LCA studies. In addition, NREL’s ongoing effort to harmonize estimated GHG emissions from electricity generation technologies has identified several other important considerations.

These dimensions are organized into four general types, for a total of ten dimensions:

- LCA Type/Perspective: Generally not harmonizable
- Temporal and Spatial Dimensions: Some of these dimensions are harmonizable
- Technology System Dimensions: Some of these dimensions are harmonizable
- Data/Parameter Dimensions: Most often, these are harmonizable.

Table 1 outlines the ten dimensions. The first column lists the title of each of the ten dimensions grouped into their respective types. The second column describes both the dimension and its cause. For aid in identification, the third column provides common examples encountered in the LCA energy literature. The “harmonization barriers” column conveys the relative ability to harmonize the dimension. Green cells indicate readily harmonizable dimensions, red cells are unharmonizable, and yellow cells are potentially harmonizable, depending on the circumstance. Within the cells, the text describes the reason for this characterization; the yellow cells also include a description of the circumstances in which they can be harmonized. This table does not address all possible situations in the literature; it is offered as a general guide to aid in the development of a plan to address each dimension, as needed, for harmonization.

**Table 1: Description, Examples, Barriers, and Actions (in NREL’s LCA Harmonization Project) Taken on “Dimensions of Incommensurability”**

"Dimensions of Incommensurability"	Description/Cause	Example of the Problem	Harmonization Barriers	Harmonized for Electricity?
<b>Dimension of Analysis Type/Perspective</b>				
<i>Consequential and Attributional LCAs (process-based and EIO-based)</i>	Different perspectives. Consequential LCAs assess larger system changes over longer periods of time. Process-based attributional LCAs assess smaller system changes over shorter periods of time. Economic Input-Output (EIO)-based attributional LCAs link monetary flows among industrial sectors with environmental burdens per dollar spent in those sectors. Consequential LCAs will include system feedback impacts.	Ex. 1: Consequential - Quantification of greenhouse gas (GHG) impacts of indirect land use changes that occur through price changes. Ex. 2: Attributional - Emissions from a coal plant smoke stack. Ex. 3: EIO-LCA - environmental burdens associated with spending money in a certain economic sector including effects resulting from other sectors that are economically tied to the one in question.	Generally not harmonizable. Attributional and consequential analyses ask fundamentally different research questions, whose answers are not comparable. EIO-LCAs methods and boundaries differ so significantly from process-based that the results are also not generally harmonizable. Studies that combine process and EIO-based approaches could be considered for harmonization after consideration of the extent of their methodological differences.	No, papers screened out.
<i>Market Mediated Impacts</i>	Primarily an issue of distributing impacts among multiple products. Attributional approach: “Allocate” the impact on the basis of some metric inherent to the products themselves (Ekvall 2001). Consequential approach: Expansion of the system boundaries to use products replaced by co-product to determine the distribution (Ekvall 2001).	Ex. 1: The use of different co-product methods produces greenhouse gas emission estimates in the range of approximately 6 kg/mmBTU to 33 kg/mmBTU and 45 g/mmBTU to 65 g/mmBTU for soybean biodiesel and corn grain ethanol, respectively. There is also no consistency between the magnitude of the impact of a particular methodology across fuel pathways (Wang 2009). Ex. 2: Distribution of the impacts of uranium ore mining among multiple mine products (Lenzen 2006).	Some barriers to harmonization. Assuming product parameters are available, harmonization of "allocation" methods is possible. Switching from "allocation" to "system expansion" is difficult if not impossible because of the need for data on other product markets that may or may not exist. The reverse is less problematic if product parameters are available.	No, but categorized

"Dimensions of Incommensurability"	Description/Cause	Example of the Problem	Harmonization Barriers	Harmonized for Electricity?
<b>Temporal and Spatial Dimensions</b>				
<i>Context of the Study</i>	The context in which the technology is located, which includes existing economic, environmental, and social surrounding systems it will interact with.	Ex. 1: The type and quantity of organic material that creates methane emissions associated with hydropower dams is dependent on the geographic location of the dam (Rashad 2000). Ex. 2: Power output of a solar cell can be changed from one location to another by modifying assumed solar radiation.	Some barriers to harmonization. The context that a technology is placed in some cases is inseparable from the LCA without fundamentally altering the original study. In these cases, it is more useful to categorize these dimensions and determine when the context has an impact on the LCA results. In other cases, such as background energy mix or solar radiation levels, harmonization is possible.	Partially, some categorized
<i>Temporally Dependant Impacts</i>	Alternative accounting methods of day-to-day impacts that vary over time, one-time impacts, and application (or lack thereof) of discount rates to quantify future impacts in a single number.	Ex. 1: Technology degradation over time. Ex. 2: A nuclear plant built now could have a much different day-to-day life cycle GHG emissions profile 40 years out due to changes in ore quality used (Storm van Leeuwen 2005).	Few if any barriers to harmonization. Because this is an LCA output reporting issue, normalization is possible with complete study reporting. Proxy information may be necessary otherwise to perform back calculations.	Yes
<i>Scope of Impacts</i>	Range in impacts assessed spatially (local, regional, international), temporally (immediate or long-term impacts), and/or how far along chemical reaction chains the effects are followed.	Ex. 1: The global warming potential standard in 2001 for methane over 100 years compared to the 2007 standard for methane over 20 years. Ex. 2: NO <sub>x</sub> 's multiple air and water chemical pathways.	Some barriers to harmonization. Harmonizable in many cases such as GHGs where boundaries of impact assessment are consistent across studies. Not possible when geographic and temporal boundaries/contexts substantially differ.	Only for GHGs

"Dimensions of Incommensurability"	Description/Cause	Example of the Problem	Harmonization Barriers	Harmonized for Electricity?
<b>Technology System Dimensions</b>				
<i>Life Cycle Technology System Boundaries</i>	Changes in the scope of the system boundary of the technology process chain.	For nuclear, boundaries would start with direct impacts from a nuclear plant, then could included less direct impacts of mining of uranium; construction of the plant; and waste handling, and then more distant activities such as mine environmental cleanup.	Some barriers to harmonization. Harmonizable when the boundaries are clearly established and life cycle stages do not overlap. Not possible when LCA and/or sub-stage system boundaries are fundamentally different at the dataset level.	Partially
<i>Life Cycle Variation within System Boundaries</i>	Changes in methodological accounting or the technology process chain (not affecting the technology being studied).	Ex. 1: Corn grain ethanol produced in the U.S. Midwest using corn grown in the Midwest compared to corn grown in Georgia (Groode and Heywood 2007). Ex. 2: Use of waste feedstocks that would have been land-filled necessitating the calculation of an avoided emissions credit.	Some barriers to harmonization. Harmonizable when the source of the variation is not linked to other factors and the variation can be added or removed (Ex. 2). Not possible when variation is implicitly linked to other factors such as geography (e.g., municipal solid waste composition).	Partially
<b>Data Input and Output Dimensions</b>				
<i>Functional Units</i>	Includes explicit fundamental unit differences (e.g., g/kWh), implicit differences in how it is calculated (e.g., HHV: higher heating value vs. LHV: lower heating value), and implicit differences in time horizons (e.g., average over a lifetime).	Multiple uses of biomass for energy lead to a functional unit comparable across scenarios of heat, electricity, and fuel, such as grams/hectare. A grams/hectare functional unit is not comparable to other electricity technologies.	Few if any barriers to harmonization. Because this is an issue of LCA output reporting, most changes in functional units can be completed using information provided within the LCA or common unit conversion standards.	Yes

<b>"Dimensions of Incommensurability"</b>	<b>Description/Cause</b>	<b>Example of the Problem</b>	<b>Harmonization Barriers</b>	<b>Harmonized for Electricity?</b>
<i>Case Studies, Theoretical Estimates, and Projections</i>	Different study perspectives that use empirical datasets for case studies, empirical datasets to make theoretical inferences about non-existent technologies, and empirical datasets in modeling to make predictions.	A projection of the impacts of a wind turbine for 2005 in a 1995 study compared to an experimentally based case study in 2005.	Some barriers to harmonization. At the dataset level, datasets can be removed, replaced, or projections undone. However, at some point, this fundamentally changes the study to a completely different LCA.	Partially
<i>Dataset/Parameter Inputs</i>	Human error in data/parameter application in an LCA or in its original generation leading to problems with its application.	Continued use of outdated databases to carry out current photovoltaic (PV) LCAs such as Ecoinvent (Fthenakis 2010).	Few if any barriers to harmonization. Assuming the LCA is not fundamentally flawed and reporting is complete, the dataset can be removed or replaced.	Yes

Each individual harmonization project will address these dimensions in varying degrees. Ideally, harmonizing consequential LCAs would take precedence; however, for the aforementioned reasons (part 1) this is not possible. It is also not possible to establish general prioritization rules for the remaining dimensions. The same issues that create legitimate variation in the LCA literature (alternative research questions and methodology) also make the prioritization of dimensions dependent on the context of the harmonization project; different research goals, prioritization of these goals, and differences in the literature collected will affect the relative importance of the individual dimensions. Each harmonization project needs to establish its own protocol to fit the individualized research needs and best allocate resources to produce useful results.

Despite context-specific considerations, the primary goal of all harmonization projects should be to establish what “legitimate” variation exists in the selected literature; it is not possible, nor is it desirable, to eliminate all of the uniqueness within the studies and coalesce the results into one value. Secondary goals include determining the uncertainty of the estimates and identifying the source of the variation that remains. As an example, consider a harmonization project concerning photovoltaic (PV) LCAs specific to the United States. It may sometimes be useful to generate a single average GHG emission estimate for photovoltaic panel construction and installation within the United States. However, homogenizing the studies to produce a national average may neglect important and legitimate regional variability associated with solar panel construction. Eliminating such resolution limits the applicability of the harmonization results to other research projects and policy analysis, all of which will have different regional contexts. It is counterproductive to generalize the results of LCAs; harmonization intends to align methodology and assumptions while maintaining fidelity to the studies’ unique perspectives, detail, and insight.

The last column in Table 1 shows how NREL’s harmonization of LCAs on electricity generation technologies approached each of the 10 “dimensions of incommensurability.” Due to its comprehensive scope, the NREL harmonization project addressed all of the dimensions. The extent of harmonization of any particular dimension was determined by considering the amount of work necessary to harmonize compared to the expected gains in insight from reducing variability.

### **3 Phase-by-Phase Approach to Carrying out a Harmonization Project**

Conducting an LCA harmonization project requires a phase-by-phase approach rather than a linear step-by-step process; characterizing it as “phase-by-phase” references the need for a recursive process, whereas “linear step-by-step” refers to a direct, chronological approach. The time and resources necessary to process the large body of literature necessitates an iterative process to deal with unexpected issues as they arise, the revising of project plans, and the general need to rework some phases over the course of the project as new information becomes available. The harmonization project proceeds from phase to phase as the bulk of the work for a particular phase is accomplished; however, portions of several phases will be occurring simultaneously sometimes across several technologies. In many ways, this phased approach is similar to the process established by the International Standards Organization (ISO) for

conducting an LCA. In this process, one starts with a goal/scoping stage, moving to data collection/organization, and finishing with the assessment. The ISO similarly suggests that reinterpretation occur throughout the process (ISO 2006).

Five phases of a harmonization project:

- Phase 1: Identify the goal of the harmonization
- Phase 2: Establish harmonization scope, standards, and screening criteria
- Phase 3: Gather, categorize, filter, and extract the to-be-harmonized results
- Phase 4: Carry out harmonization
- Phase 5: Where applicable, construct a meta-model

### **Phase 1: Identify the Goal of the Harmonization**

In the first phase, the problem or research question guiding the harmonization is outlined along with the general goals of the project. This process provides the framework in which methods and processes will be developed and used in the following phases. For some harmonization projects, the problem and the end goal of the research will be complex and specific; in the case of NREL's harmonization of electricity generation LCAs, the problem and goals of the project were more general, with a focus on comprehensive analysis of all technologies of modern relevance.

### **Phase 2: Establish Appropriate Scope of Dimensions, Standards, and Screening Criteria**

To formulate a plan of action for the project, it is necessary to establish the appropriate scope and context of the dimensions to be harmonized, as well as basic standards for the harmonized dimensions. This process should be done iteratively with an initial review of relevant literature as the content of the studies to be harmonized will greatly determine the scope of the analysis and appropriate screening criteria. This scope-setting process includes selecting dimensions to harmonize and deciding the extent of harmonization, followed by the selection of boundary conditions for the project as a whole. Such conditions include the geographical and temporal boundaries. The standards include dimensional units of the results and conversion factors. For example, NREL's electricity harmonization project set the global warming potentials used to calculate the impact of the various GHG species relative to that of CO<sub>2</sub> to the IPCC 2007 values with a 100-year time horizon.

After selecting the boundary conditions and standards, the second step is to establish screening criteria to filter the acquired studies. This requires determining the elements necessary to qualify a paper for inclusion in the project, determining the characteristics that will be scrutinized to identify the quality of the study, and establishing a minimum research quality standard. Utilizing screens will ensure that only relevant and high-quality information is gathered and retained, thereby reducing project work and strengthening the harmonized results. Because many studies will report results under multiple scenarios, the quality and relevance screens should be applied at the level of the paper; and once it passes this level, at the level of the scenario as well.

NREL's electricity generation-focused LCA Harmonization project, consistent with its comprehensive scope, set broad eligibility criteria regarding system boundaries. There were no

geographical boundaries, though technologies were limited to those of importance in the United States. Temporally, technologies needed to be of modern or future relevance. The functional unit established was a unit of generation (kWh) or capacity (kW); for GHG emissions, this meant a functional unit of g CO<sub>2</sub>e / kWh or g CO<sub>2</sub>e / kW. When applicable, the impacts are amortized over the lifetime of the technology.

As for screening, technologies not deemed relevant to electricity generation (e.g., biomass for fuels) were first screened out. The next screen eliminated articles based on the following criteria:

- Electricity is not produced by the technology analyzed
- Not a full life cycle assessment (i.e., if less than two phases of the life cycle are evaluated)
- Conference papers less than or equal to five double-spaced pages in length
- Trade journal articles less than or equal to three pages in length
- PowerPoint presentations, posters, or abstracts
- Published prior to 1980 (because LCA as a field didn't mature until after this approximate date).

A second, more rigorous quality screen evaluated articles based on additional criteria:

- Quality of LCA and GHG accounting methods
- Completeness of reporting regarding the technology investigated, the inputs, and the results of the analysis
- Modern or future relevance of the technology and its defining input data (life cycle inventory).

### **Phase 3: Gather, Categorize, Filter, and Extract the To-Be-Harmonized Results**

In the third phase, the screens are implemented, categorizing and filtering out papers. It is useful to keep a record of the studies considered, due to potential changes in project goals or future work of a similar nature. The screening process may be carried out in different ways for different technologies and metrics due to technology-specific issues. For instance, the magnitude of a particular impact (e.g., SF<sub>6</sub> emitted from PV) can vary between technologies, implying that a screening criterion based on a study including known important factors might be relevant for one technology and not for others. Similarly, the relevance of study age will depend on how technology has changed over time. A plethora of factors will influence how categorization and filtering is applied to each technology.

Information reported in scenarios from studies passing all screens can be extracted during the screening process. The boundaries established in phase 2 control what needs to be gathered from each study, although several items should always be collected. These include important details or descriptions of the technology or product process chain, such as capacity and other important parameters of operation. Temporal and spatial dimensions of the technology should also be

documented in case it is necessary to control for technological change over time. Another important aspect is to ensure that results are not duplicative across multiple references, e.g., the same author group reporting the same results in a conference proceeding and then a journal article or a review article simply reprising results reported in the original source.

As a general rule, if the project is starting phase 3 while phase 2 is only roughly defined or incomplete, it is most efficient to extract more information than is needed to prevent rework, provide the foundation for unforeseen future analysis, and lead to greater familiarization with the literature.

#### **Phase 4: Carry Out Preliminary Harmonization**

After categorizing the gathered literature based on non-harmonizable factors such as sub-technology, feedstock, location, etc., several relatively simple preliminary harmonization steps can be implemented to reduce (sometimes significantly) the variability in life cycle impact estimates with minimal effort. The first step is to convert metrics of interest to the desired functional units. This may require several different conversions, such as to correct the heating value (HHV vs. LHV), or extraction of alternative data to derive the necessary results in the correct functional units (e.g., converting per kWh to per kW). The next step is to align the calculations of the various metrics; for instance, correcting the GWPs to the 100-year, IPCC 2007 values in the calculations of GHG species impact. Similar conversions may be necessary for other metrics.

The remaining preliminary harmonization step is to consistently apply the implicit time dependent component of the functional unit, either through its removal or its normalization across estimates. For example, for electricity technologies, the lifetime, efficiency, and capacity (or instead of efficiency and capacity, then the annual energy generation) of the technology are needed to return construction and decommissioning impacts, reported per kWh over the plant life, to their one-time cost. If applicable, discount rates can be applied or removed at this time. After the implicit time components are removed, normalized results can be generated by amortizing the impacts over the lifetime of the plant using a set of proxy plant operation parameters applied to each LCA estimate. If no discount rates are being used, no changes are needed in the quantification of the fixed impacts, even if those impacts are expected to vary over time. If these impacts are going to change over time and a discount rate needs to be added or removed, such normalization is not possible unless the plant operation impacts are reported in the form of a function or a time series.

For the harmonization of electricity generation technologies, no discounting was used, and impacts were spread equally over the lifetime of the technology with reporting of one-time upstream and downstream emissions in both a per kWh and per KW capacity (functional unit selected). LCA results were converted and reported in terms of LHV, and IPCC 2007, 100-year time horizon GWPs were used for GHGs when possible. The presence of other impacts were noted or recorded as reported

At this point, a decision is necessary on which technologies and/or sub-technologies need to undergo a more extensive harmonization. This distinction requires assessing whether the pool of qualifying references that report life cycle results for the metric of interest is large enough and displays enough as-published variability to justify the effort of continued harmonization. If there

is a reasonable number of references (e.g., 10), but the variability in as-published results is low (a subjective assessment), then additional harmonization is not necessarily warranted. If the pool of references reporting results is small, then it is likely that additional LCA research is needed before a harmonization or meta-analysis can be useful. For technologies that do not require additional harmonization, basic statistical metrics (e.g., arithmetic mean and standard deviation) can be reported at the technology level, sub-technology level, and/or any other established categories.

### **Phase 5: Where applicable, construct a meta-model**

Analytically, phase 5 is a fairly involved process, because construction of a meta-model requires extensive review and research into papers for technologies selected to move on to this phase. Guidelines for constructing meta-models have been developed based on work produced in previous studies and recommendations provided by Plevin (Farrell 2006, Plevin 2009a, Plevin 2009b). Constructing a meta-model on *all* previously published literature passing quality and relevance screens is unlikely to be a realistic prospect given the time required to research each paper for this phase. A selection or sampling of the quality studies collected that best represents the range of estimates for a selected metric should be used to construct the meta-model. Five to ten papers is recommended, but this number may depend on other factors such as the level of variation that may need to be explained.

To construct the meta-model, first, one must create a modeling framework in which data from the studies can be inserted for the particular technology or sub-technology. Once the framework is established, settle on a normalized and standardized set of parameters to which the input data will be converted. For the purposes of transparency and review of work, pre- and post-conversion values should be reported. The model framework can be validated by comparing its results to the original reference's results and to other published research to detect and debug problems.

One important step in further harmonization of the selected studies is to align system boundaries. The boundaries of each LCA study for the selected metric should be normalized by first creating separate, revised instances of the model for each study. Data from each study that falls outside the established life cycle boundaries can be deleted from use in the meta-model. When an original study does not estimate the impact of a certain process that's within the standard system boundary, proxy data based on other studies judged to be of high quality should be used to fill in missing parameters. The decision of whether a best estimate from a single study, averages of multiple high quality studies or another method is used to quantitatively determine the value of the missing parameter is to be made by the analyst. Throughout the meta-model development process, the data sources and assumptions of the original studies should be reviewed to determine age, content, quality, relevance, proper interpretation of the underlying source data, quantitative calculation errors, etc. which can inform whether other harmonization steps leading to further congruity among the selected studies are warranted. The result of the meta-model development process, to this point, is the adjustment of the impact estimates of the original studies to ones more methodologically consistent.

A final, optional step is to create a "best" composite impact estimate based on elements selected across multiple studies. Whether the best estimate for a given element is an average across multiple studies or is an estimate from a single study is a decision for the analyst after carefully

considering the options. Instead of, or in addition to, the creation of a best, composite impact estimate another option is to statistically analyze the adjusted study estimates (e.g., arithmetic mean and standard deviation).

## 4 Concluding Thoughts

The results of harmonization should return more robust understanding of variability, uncertainty and central tendency in estimates of life cycle environmental burdens. Already, this process as applied to several electricity generation technologies has suggested that our knowledge of the life cycle GHG emissions from certain technologies is well researched and robust, where for others, there are significant gaps in our understanding, resulting from a lack of study or large variability in as-published estimates. In this way, the literature review and harmonization process can aid in R&D prioritization. Harmonization can also develop the knowledge necessary to build meta-models which, when fully exercised, can quantify the sensitivity of modeled impacts to changes in input parameters. Harmonization also compliments life cycle assessment as normally practiced, where a single technology and scenario is investigated thoroughly, by providing a broader review across variations in technology, location, operation, etc.

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