Life-Cycle Assessments: Linking Energy, Economics, and the Environment

Steve A. Shankle, Pacific Northwest Laboratory

Life-cycle assessments offer one-stop shopping answers to the total energy and environmental implications of alternative technologies, as well as providing employment and income consequences. In the past, life-cycle assessments were generally used to compare product packaging methods. For a comprehensive guide to life-cycle assessments, see EPA (1993a, 1993b, 1993c, 1993d), and SETAC (1991, 1992, and 1993). For a comprehensive list of LCA projects, see DOE (1993). Recently, the lifetime impacts of the production and use of biomass ethanol transportation fuels have been assessed. In an ongoing study, the lifetime impacts of electric-powered vehicles versus conventional fuels are being assessed. In a proposed study, the impacts of recycled office paper versus office paper from virgin sources would be assessed.

A LCA proceeds by developing mass and energy inventories during all phases of the life-cycle. Special attention is given to energy consumption and environmental releases. Economics are incorporated by evaluating the macroeconomic impacts of the alternative policies, such as employment, wages, and output. Economics can also be incorporated by attempting to place values on the damages imposed by the environmental releases associated with alternative scenarios.

This paper discusses life-cycle assessment techniques and their application to building energy issues. Life-cycle assessments show great promise for analysis of buildings energy policy questions.

Introduction

LCAs examine the environmental impacts of a product from a “cradle-to-grave” perspective, considering all stages in the product life cycle: resource extraction, resource transportation, resource conversion to a manufactured product, product distribution, end-use, and all associated secondary processes (waste management, recycling, manufacturing of secondary material and energy inputs, etc.). LCAs allow the environmental and energy consequences of alternative technologies to be compared, accounting for all stages of the technology.

In the federal sector, LCAs are being used to better understand the energy and environmental impacts of technologies that are being developed as part of major R&D programs. As one example, in fiscal year 1994, the U.S. Department of Energy (DOE) will spend over $40 million dollars on R&D associated with biomass-derived fuels (e.g., ethanol). From a life-cycle perspective, biomass-derived fuels require dedication of large quantities of land to biomass agricultural plantations, plantation operation (including fertilizer application), operation of ethanol production facilities, and increased transportation requirements relative to gasoline. The energy and environmental impacts associated with biomass-derived fuel are complex. Consequently, DOE is seeking to understand the full life-cycle implications of biomass-derived fuels so that intelligent decisions can be made within existing R&D programs to minimize the environmental impacts associated with the technologies that will be commercialized as part of DOE’s large R&D programs. In addition, DOE must understand the highly complex gasoline life-cycle so that there is a clear understanding of net reduction in national environmental impact when a gallon of gasoline is displaced by a gallon of biomass-derived fuel. Due to the complexities of the gasoline and biomass-derived fuel life-cycles, it is clear that the traditional perspective of only considering the difference in vehicle tailpipe emissions when alternative fuels are used is not a fair comparison.

This paper describes the basic components of a LCA, and discusses the methodologies required to complete each of the components. The paper concludes with an example of the application of LCA to building sector energy issues.

Principles of Life-Cycle Assessment

LCA tools and techniques have been developed over the last several years by the Environmental Protection Agency (EPA), the Society of Environmental Toxicology and Chemistry (SETAC) and the Department of Energy. An LCA is defined to consist of three major elements: (1) inventory assessment; (2) impact assessment; and (3) economic valuation. [1]

Inventory assessments compile mass and energy balances [i.e., quantification of material inputs, material outputs (including products, co-products, and environmental releases), energy inputs, and energy outputs], and define labor requirements associated with the life cycle of a technology. Most LCAs conducted to date have consisted solely of inventory assessments. An inventory assessment provides a great deal of information useful in the evaluation of technologies: an inventory assessment can quantify the releases of criteria air pollutants; can quantify greenhouse gas emissions; and can quantify the life-cycle energy consumption associated with alternative technologies. Frequently these quantities are sufficient to allow comparison of technologies. In some cases, however, it is desirable to translate the inventory into impacts, and to attempt to value those impacts. In this case, it is necessary to continue with the impact assessment and the economic valuation elements.

Impact assessments estimate human health, ecological impact, and economic impacts based on data compiled during the inventory assessment. Impact assessments can be extremely difficult, complex, and expensive to perform. In some cases, it may be impossible to defensibly translate inventories into impacts.

Economic valuation tools are used to calculate the social costs and benefits of human health, ecological, economic, and employment impacts. The aggregate net social benefits (or costs) derived from a technology can be used to compare alternative technologies or policies. Like impact assessments, economic valuations can be difficult, complex, expensive, and sometimes impossible to defend.

The results of a LCA include not only a quantitative assessment of the social costs and benefits of a technology, but also identify key activities/processes in the life cycle warranting further environmental R&D or policy consideration. A completed LCA allows the identification of critical processes upon which waste reduction or emission control activities can be focused.

Each major element in a LCA is discussed in more detail in the following sections.

Inventory Analysis

Inventory analysis consists of compiling a material and energy balance: a complete list of energy inputs, material inputs, energy outputs, and material outputs (including products, co-products, and residuals). Ideally, a 100% complete material and energy balance would be compiled for every unit process in each life-cycle scenario evaluated. However, due the complex nature of the data collection task, it is always necessary to prioritize which items will be inventoried. This always creates the potential for omitting an important inventory item from consideration; however, through careful scoping this risk can be minimized.

An inventory analysis begins with a life-cycle map, which shows the processes being considered, and their interrelationships. Theoretically, a detailed analysis of the materials and energy flows of every process is then compiled. In reality, only those processes deemed important enough to justify the extensive data collection process are considered in detail. An inventory analysis begins with initial material extraction (such as coal mining for electricity generation), and proceeds through manufacture, use, and disposal of a product. Important secondary sets of processes are considered as well. For example, when comparing fluorescent and incandescent lamps, not only is the life-cycle of the lamp considered, but so is the life-cycle of the electricity generated to power the lamps.

Impact Analysis

As a starting point, it is important to note that while inventory assessment and impact assessment are often described as discrete steps of a linear process, in practice they need to be conducted in an iterative and interactive way. Only by considering impact issues of concern can the inventory assessment be designed and conducted in such a way as to provide adequate data to the impact assessment stage. Likewise, only by considering the various production processes in the inventory map can the impact assessment be focused on the key, relevant impact issues of concern.

The impact assessment phase of an LCA is concerned with identifying and evaluating the major social and environmental impacts of the production processes being analyzed, based on the data derived from the inventory analysis. The impact assessment allows for a comparative analysis of impacts between various scenarios, rather than an actual determination of impacts from any one scenario.

Major impact categories used in impact assessment include:

- human health, including worker exposure and general population exposure;
- ecological health, including both species-level impacts (loss of salmon runs) and ecosystem-wide impacts (loss of biological productivity and biodiversity);
- resource sustainability, including impacts to both renewable and non-renewable resources; and
- non-environmental social welfare, including such impacts as economic impacts, cultural heritage impacts, impacts to community infrastructure, and so forth.

A key concept in impact assessment is the idea of "stressors." Stressors are the physical, chemical, or biological factors resulting from a production process (i.e., both inventory inputs and outputs) that specifically lead to impacts on the various end points identified-human health, ecological health, etc. Most obviously, stressors include the chemicals emitted into the environment from a production process that are directly harmful (i.e., toxic) to humans or ecosystems. In addition, however, stressors include non-toxic chemicals that also have impacts on humans or the environment, such as greenhouse gases (which generally do not pose toxic hazards, but can lead to global warming). Stressors also include non-chemical factors such as noise, resource consumption, and land use changes.

While the above picture of impact assessment has described a relatively straightforward procedure, in practice there are many issues that must be addressed for the impact assessment to be successful. For example, in theory the impact assessment should include a comprehensive accounting of impacts to the environment arising from production processes. However, in practice such a comprehensive analysis can quickly become infeasible for a variety of reasons, including: adequate data to describe the relationship between stressors and endpoints does not exist; there is not an adequate theoretical understanding of the relationship in the first place; or simply, the modeling effort is too resource-intensive. A key issue when performing an impact assessment—and when iterating between inventory assessment and impact assessment—is to insure that the objectives of the assessment (level of detail, certainty of impact, etc.) are matched to the available analytic resources. For example, a more superficial screening effort to identify generic categories of impact can be based on less rigorous analysis than a detailed risk assessment. Likewise, it may not be possible to include all impacts into the analysis, but rely on a prioritization scheme that focuses only on those impacts of greatest concern.

Impact Valuation

Few life-cycle assessments have attempted to translate inventory analysis into impacts, and to then attempt to value those impacts. Valuation of impacts, while difficult and subject to criticism, can be a vitally important stage of the analysis. Valuation allows a ranking to be developed among competing scenarios on the basis of their environmental damages, while a strict inventory analysis is unable to rank alternatives when they are characterized by a number of parameters. Valuation of environmental impacts is an extremely difficult and complex task, and the results are frequently controversial.

Valuation of the impacts associated with technologies is usually based on determining the amount that individuals would be willing to pay to avoid the impacts, called the Willingness To Pay (WTP). This can be accomplished by directly asking individuals their WTP, or by attempting to determine how much individuals value the services they receive from the resource, and inferring their WTP from that value. Direct elicitation of an individual's WTP is obtained through the Contingent Valuation Method (CVM), where value is based upon how respondents react to hypothetical markets. This approach provides what economists call a "stated preference. " The second type of approach embraces a number of indirect methods that yield what economists call a "revealed preference, " and these approaches are based upon behavior observed in real markets.

The CVM requires an extremely carefully designed survey, where individuals state their WTP to avoid a well-defined impact. The advantage of the CVM is that the results it obtains are easy to interpret: individuals directly state the value of the resource. The CVM is also less data intensive than many of the revealed preference techniques. Most importantly, the CVM can be used in cases where revealed preference techniques are impossible, such as in determining passive use values. The CVM also has its disadvantages, of course. The most important is the fact that the CVM frequently requires respondents to attempt to value something that they have no real world experience in valuing. While this problem can be minimized through careful survey design, there is no way to eliminate doubt as to the validity of responses given to CVM surveys. The use of the CVM was recently examined by a blue-ribbon panel of economists set-up by NOAA. The panel consisted of Kenneth Arrow (co-chair), Robert Solow (co-chair), Edward Learner, Paul Portney, Roy Randner and Howard Schuman, and reported its results in the Federal Register (58 FR 4601, Friday, January 15, 1993). The panel concluded that the CVM could be used to determine lost values from natural resource damages, given that a fairly strict set of conditions on the construction and fielding of the survey instruments. The CVM is particularly useful in determining passive use values, where revealed preference techniques cannot be used.

Revealed preference methods rely on the fact that while individual's values for non-market goods cannot be directly observed, it is sometimes possible to observe the values that individual's place on closely related market goods, called complementary goods. The most commonly used revealed preference method for valuing recreational use values is the travel cost methodology. This is actually a number of methods, all of which have in common the fact that recreationists frequently must incur some cost to obtain the recreation services they desire. The value that an individual places on a recreational experience is presumably equal to or greater than the costs that the individual must incur to obtain the experience. In the case of an individual driving into the forest on a camping trip, the value of the experience is assumed to be at least equal to the cost of gasoline, automobile depreciation, supplies, and the value of the time spent obtaining the experience. A travel cost study would proceed by estimating the amount people spend on obtaining the non-market good, and statistically linking that to the characteristics of the good. The resulting statistical demand curve can be used to estimate the losses incurred due to a change in the characteristics of the good.

Application of LCA to Building Sector Energy Issues

The major benefit of applying LCA to buildings energy issues it the ability to sort out the relative environmental impacts of alternative building energy technologies. This paper will discuss applying LCA to a common building energy technology choice: compact fluorescent lighting versus incandescent lighting.

Compact fluorescent lighting systems can provide significant energy savings over incandescent lighting. Replacement of incandescent lamps with compact fluorescent lamps can easily achieve energy savings in excess of 50 %. The U.S. Environmental Protection Agency (EPA) has a "green-lights program" that promotes the use of fluorescent lights rather than incandescent lights. One concern that has been raised is that EPA is promoting the use of fluorescent lamps which are ending up in the solid waste stream, going to landfills and causing mercury releases to the groundwater and surrounding soils. That concern has caused some organizations to react by trying to prevent the disposal of fluorescent tubes in landfills. If a decision is made to restrict the disposal of fluorescent tubes, consumers, both industrial and private, will have an incentive to resume using incandescent lamps, which don't release heavy metals when landfilled.

Life-cycle assessment provides an important tool to evaluate the relative environmental impacts of incandescent and compact fluorescent lamps. While compact fluorescent may release mercury into the solid waste stream upon disposal, their greater energy efficiency and their longer lives result in environmental benefits that probably outweigh the solid waste consideration.

The fluorescent lamp uses about half as much electricity as the incandescent lamp: as a result, there are reductions in heavy metal emissions from power plants and mining and extraction sites. From a life-cycle perspective, when the impacts of electricity generation are accounted for, an incandescent lamp releases about four to ten times as much mercury into the environment. One needs also consider the fact that compact fluorescent lamps can be expected, on average, to last up to ten times longer than incandescent lamps, thereby reducing the total volume being sent to landfills. The bottom line is that our conclusions may be quite different from a life-cycle perspective than from a narrow, single unit process perspective.

Figure 1 is a highly simplified map of the life-cycle of a lamp: either incandescent or fluorescent. The lamp is manufactured, transported to point of use, used, and disposed of. In the use phase, electricity is required, necessitating an electricity generation process. Raw materials and energy are used throughout the life-cycle, and air emissions and solid waste impacts result from the lamp life-cycle.

As a first cut at quantifying some of the life-cycle impacts, the air emissions from the electricity generation phase were calculated. Emissions were calculated for the operation of a single 75 watt incandescent lamp, operated for 1,460 hours (4 hours per day) over one year. The lamp is contrasted to a 20 watt compact fluorescent replacement. The compact fluorescent puts out slightly less light (about 90% of the incandescent), and so the energy consumption numbers were adjusted for light levels. This is equivalent to assuming that, in a large installation, roughly 10% more compact fluorescent would be installed than incandescent. Over the year, the incandescent draws 110 kWh, while the compact fluorescent draws 45 kWh. Table 1 shows the emissions impacts of the years operation. Given the U.S. electricity generation mix of fuels and technologies that existed in 1991, the incandescent is responsible for roughly double the emissions of the compact fluorescent. When looking at the disposal process, the relative lives of the lamps come into play. A years operation "consumes" about 15% of the compact fluorescent lamp, and about 4% of the compact fluorescent ballast. The same years operation "consumes" almost two incandescent lamps. While the mercury

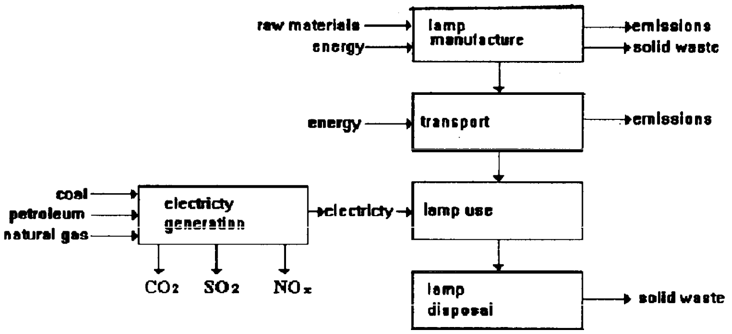

Figure 1. Simplified Life-Cycle Map

Table 1. Emissions Impacts of Alternative Lighting Technologies

Electricity Generation Process

System	Energy Use (kWh)	CO2 Emissions (Pounds)	SO2 Emissions (Pounds)	NOx Emissions (Pounds)
20 watt compact fluorescent	45	0.0558	0.0005	0.0002
75 watt incandescent	110	0.1352	0.0011	0.0006

components of the fluorescent tubes may well be a concern, the sheer volume of solid waste generated is much less for the fluorescent.

Limitations of LCA

LCAs are not suitable for all technology policy questions. At their current stage of development, the inventory assessment stage of a LCA is expensive and time consuming, with tremendous data requirements. The impact assessment and economic valuation elements are still extremely difficult, despite many years of effort on the part of economists, biologists, ecologists, and a host of other disciplines.

The inventory assessment element of a LCA should be getting more manageable in the future. As data are collected for LCAs, they should become available to researchers for use in studies with overlapping unit processes. One promising area for this type of piggybacking is in the characterization of electricity generation processes. Electricity generation enters as a process in any LCA where electricity is used. As the electricity generation processes is described in LCAs to a greater and greater extent, persons conducting LCAs will be able to virtually use electricity unit processes "off the shelf." It is toward this end that PNL is working with EPA, EPRI, and the World Bank as part of a consortium to develop data for use in LCAs concerned with electricity generation and use.

Conclusion

LCAs to date have not focused on the issues facing buildings energy researchers. Potential applications include quantifying the energy and environmental impacts of alternative lighting technologies. Other issues that need this type of analysis include the impacts of new working fluids used in air conditioners and heat pumps, intended to reduce greenhouse gas emissions. Any degradation in the energy efficiency performance of the equipment could well result in impacts on the electricity generation process that swamp the benefits of non-CFC fluids.

LCAs are difficult, complex analyses. They require extensive data collection, and the tools to simplify their use are still under development. Careful planning and scoping is essential to the success of these analysis. However, LCAs provide a type of holistic, system-wide analysis that is not available from other approaches.

Endnotes

1. SETAC 1993 includes “economic valuation” as a component of “impact assessment.” For the purpose of this paper, the two are treated as distinct elements because each element has a distinct technical approach, and each requires a distinct set of analytical skills (e.g., risk analysis and toxicology for the impact element, and economics for the valuation element).

2. A useful reference that summarizes many issues related to impact assessment is A Conceptual Framework for Life-Cycle Impact Assessment: published by the Society of Environmental Toxicology and Chemistry (SETAC 1993). This document is the result of a consensus-based workshop designed to develop a clear and consistent conceptual framework for impact assessment. As such, the document provides a useful organizing structure for impact assessments, but does not necessarily include detailed methodologies to support directly implementable approaches.

References

SETAC Foundation for Environmental Education, Inc. 1991. *A Technical Framework for Life-Cycle Assessments.* Pensacola, FL. Society of Environmental Toxicology and Chemistry.

SETAC Foundation for Environmental Education, Inc. 1992. *Conceptual Framework for Life-Cycle Impact Analysis.* Draft. Pensacola, FL. Society of Environmental Toxicology and Chemistry.

SETAC Foundation for Environmental Education, Inc. 1993. *A Conceptual Framework for Life-Cycle Impact Analysis.* Pensacola, FL. Society of Environmental Toxicology and Chemistry.

U.S. Department of Energy. 1993. *Life-Cycle Cost Assessment (LCCA) Preliminary Scoping Report.* RTI Project Number 5699. Prepared by Research Triangle Institute, Research Triangle Park, NC.

U.S. Environmental Protection Agency. 1992. *Total Cost Assessment: Accelerating Industrial Pollution Prevention Through Innovative Project Financial Analysis.* EPA1741/ R-92/002. Prepared by Tellus Institute, Boston, MA.

U.S. Environmental Protection Agency. 1993a. *Life-Cycle Assessment: Inventory Guidelines and Principles.* EPAI 600/R-92/245. Prepared by Battelle Institute, Columbus, OH, and Franklin Associates Ltd., Prairie Village, KS.

U.S. Environmental Protection Agency. 1993b. *Life-Cycle Design Manual: Environmental Requirements and the Product System.* EPA/600/R-92/226. Washington, D.C.

U.S. Environmental Protection Agency. 1993c. *A Framework and Methods for Conducting a Life-Cycle Impact Assessment.* Draft Report. Prepared by Research Triangle Institute, Research Triangle Park, NC.

U.S. Environmental Protection Agency. 1993d. *Life-cycle Assessment: Guidelines for Assessing Data Quality.* Draft Report. Prepared by Research Triangle Institute, Research Triangle Park, NC.