Sustainability Science and Engineering
Defining principles

Edited by

M.A. Abraham
Department of Chemical and Environmental Engineering, The University of Toledo, Toledo, OH, USA

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Chapter 7

Life Cycle Based Sustainability Metrics

Gregory A. Keoleian, David V. Spitzley

Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, 440 Church St., Ann Arbor, MI 48109-1041, USA

1. Introduction

Sustainability challenges confronting society in the 21st century include global climate change [1], declining fossil resources [2], persistent organic pollutants [3], freshwater scarcity [4], ecosystem degradation [5], biodiversity loss [6], overpopulation [7], and limited access to basic human necessities particularly in developing countries [8]. Ultimately, natural resource depletion and pollution are driven by material and energy flows associated with goods and services. The life cycle of a product system, which includes the material and energy flows across materials production, manufacturing, use and service, and end-of-life management stages, is a logical framework for understanding and improving the link between production and consumption activities and natural systems. It has become clear that significant changes in the production and consumption of goods and services are essential for maintaining the planet's life support system, which is increasingly threatened. Life cycle-based sustainability models and metrics play a key role in guiding the transformation of technology, consumption patterns, and corporate and governmental policies for achieving a more sustainable society.

Life cycle modeling represents a unique sustainability assessment framework for at least four reasons:

(1) The Life cycle of a product system encompasses all processes for addressing societal needs including materials production through end-of-life management.

(2) The Life cycle links production and consumption activities.
(3) The Life cycle boundary enables a comprehensive accounting of sustainability performance including environmental, social, and economic metrics.
(4) Metrics can be used by key stakeholders that manage and control the life cycle supply chains to guide their improvement.

A wide set of analytical methods and tools have been developed around a life cycle system boundary. Table 1 provides a list of life cycle based techniques and examples of metrics that have emerged over the last three decades.

These tools yield a wide array of metrics that can contribute to the understanding and assessment of environmental, social, and economic sustainability of goods and services. Life cycle methods serve to help operationalize the broader concepts of sustainable development as articulated in the Brundtland Commission definition: development which "...meets the needs of the present without compromising the ability of future generations to meet their own needs" [9].

The objective of this chapter is to review the range of life cycle methods and metrics for evaluating the sustainability of products and technology. This review will highlight the relevant aspects of sustainability that each method addresses. In addition to analyzing these tools, this chapter will demonstrate the application of life cycle models and metrics for diverse sectors including transportation, buildings, renewable energy, and consumer products. Strengths and limitations of these methods and metrics for assessing sustainability will also be discussed. The authors envision that life cycle metrics and indicators will continue to evolve in the decades ahead and in the process provide more explicit meaning to the term sustainability.

2. Life cycle assessment

Life cycle assessment (LCA) is an analytical technique for assessing the potential environmental burdens and impacts associated with a product system from the generation of the raw materials to the ultimate management of material

Table 1
Life cycle-based methods for sustainability metrics development

Method	Example metrics
Life cycle assessment	Ore consumption (kg), global warming potential (kg CO_2 equivalent)
Life cycle energy analysis	Energy consumption (MJ), net energy ratio
Life cycle cost analysis	Private costs ($), social costs ($), total costs ($)
Life cycle optimization	Optimal service life (years)
Life cycle sustainability matrix	Population obesity (%), rate of land conversion (ha/year)

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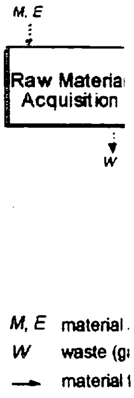

remaining at the end-of-life [10]. LCA provides metrics that can be used to measure progress toward environmental sustainability. The stages in a product life cycle are shown in Fig. 1.

This method results in an environmental profile that measures environmental performance at each life cycle stage. LCA, which has undergone significant development over the last three decades [10–14], can be considered the most advanced method for assessing sustainability. The four components of LCA including goal and scope definition, inventory analysis, impact assessment, and interpretation, also serve as an important foundation of other life cycle-based methods as well as other sustainability assessment methods. These four steps and their relationships to each other are shown in Fig. 2.

Goal and scope definition establishes the objectives of the analysis, intended audience for study results, system boundaries, allocation rules, nature of the data to be collected, specific metrics to be evaluated, and peer review requirements. A critical activity within goal and scope definition is the determination and specification of a functional unit for the system under study. The functional unit describes the fundamental objective of the system and provides the basis for

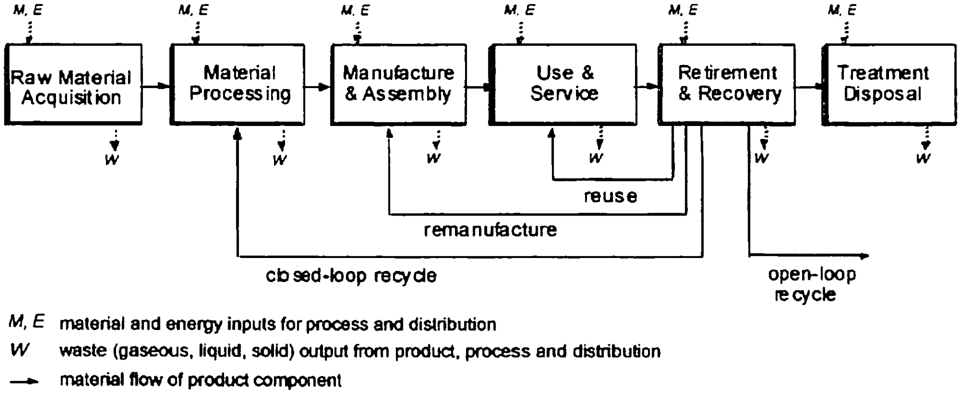

Fig. 1. Product life cycle stages.

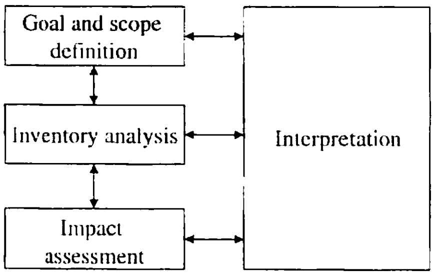

Fig. 2. Life cycle assessment activities [10].

the scope of the study. The functional unit should be measurable, meaningful to the intended audience, and relevant to data collection. Examples of functional units include 120,000 miles of operation for a five-passenger mid-sized automobile, 1 kWh of delivered electricity from a 1 GW baseload power plant, and 100,000 L of delivered carbonated beverages. LCA done for the purpose of evaluating alternative systems must compare systems on the basis of equivalent function as captured in the functional unit.

The life cycle inventory (LCI) analysis step is focused on the collection and analysis of data on the input and output flows associated with the system under study. In this step, system boundaries and allocation rules identified in goal and scope definition are applied. The inventory step and the specific challenges associated with data collection, allocation, and system boundary definition are discussed in detail in Section 2.1.

Life cycle impact assessment (LCIA) serves to translate the myriad input and output flow data compiled during inventory analysis into meaningful information regarding the environmental effects of the system. Impact assessment involves categorization of flows, characterization of impacts, and may also include normalization and weighting of results. Current practice in LCIA, standard methodologies, challenges, and limitations are discussed in detail in Section 2.2.

Interpretation considers the full study results in the context of the stated objectives, potential limitations, uncertainties in data, and the intended audience. In this step, opportunities for system improvement are discussed and results are placed in the appropriate context for the intended application. LCA results have been used to support policy deliberations [15], as an input to design improvement [16], and in support of product labeling [17].

2.1. *Inventory analysis*

LCI analysis is an accounting of the material and energy inputs and outputs between a system under study and the environment (termed elementary flows). Accounting in LCI considers flows across a series of individual life cycle stages. Activities conducted in LCI form the core of LCA. Typical metrics tracked in LCI include biotic and abiotic resource inputs, air pollutant emissions, water pollutant emissions, solid waste (hazardous and non-hazardous), recycled materials, products, and co-products. The challenges in conducting an LCI study relating to system boundaries and data collection are not unique to LCA. Successfully overcoming these challenges can provide the foundation for other sustainability assessment frameworks.

Several organizations have provided useful guidance for conducting a LCI analysis. The International Organization for Standardization (ISO) 14041 standard and the technical report ISO TR 14049 provide the internationally

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accepted code of practice for LCA [18,19]. In addition, the US Environmental Protection Agency (US EPA) [12], and the Society of Environmental Toxicology and Chemistry (SETAC) [14] provide additional clarification and guidance.

Although system boundaries and allocation procedures must be specified as part of the goal and scope definition, they directly impact the data collection procedure and are discussed here for clarity. In reality, the process of defining system boundaries and necessary allocations is an iterative process involving balancing study goals with data collection and analysis feasibility. System boundaries should be defined to combine a series of interrelated activities and operations into a comprehensive network supporting a specific function. Ideally, all system inputs and outputs should be captured as elementary flows to or from the environment. Elementary flows are described in a state of natural occurrence, i.e. no additional processing or transformation is performed outside of the system boundaries. In practice, system boundaries are defined using cutoff rule based criteria such as environmental relevance, mass contribution, and energy contribution.

Defining system boundaries can be especially problematic when some of the operations involved in the system produce multiple products [20]. In this situation, general guidance, including that codified in ISO 14041, on defining system boundaries recommends allocation according to one of four approaches — avoiding allocation, system expansion, causal allocation, or technical allocation.

Allocation of operational burdens should be avoided by attempting to subdivide the operation into smaller unit processes. When this is not possible, the system boundaries should be expanded to include additional system functions and related processes and/or co-products. In comparative studies, alternative systems should also be expanded to include these additional functions. For example, the waste management practices for some products may result in the generation of electricity in waste to energy plants.

Under a system expansion approach this electricity should be included in the system boundary and any alternative systems would need to include operations required for equivalent electricity production. When system expansion is not possible, operational burdens should be allocated between product outputs according to defined causal relationships between the products. If a painting operation produced multiple painted products, allocation could be based on the relative surface area of each product produced.

Allocation of environmental burdens between products can also be done on the basis of physical or technical information not directly attributed to operating burdens. The most common example of this is allocation based on product economic data.

As decisions regarding data allocation and system boundaries are reached, a record of these system definitions should be made. This record generally takes the form of a process flow diagram. LCI flow diagrams should provide details sufficient to effectively communicate unit processes studied and relationships in system modeling. These diagrams serve to guide the data collection process and verify data completeness.

One of the greatest challenges in conducting a LCI is the data collection process. Data limitations exist for several reasons including proprietary concerns, aggregation across more than one product system, and lack of a consistent tracking system. Analysts are more successful in gathering data when organizations holding the data are collaborating with the study. When this is the case, specific primary data should be collected following a well-documented procedure (see, for example LCI data collection forms provided in Annex A of ISO 14041) [18].

Frequently, LCI data collection will require information on operations and activities for which primary data are unavailable. In this case, analysts rely on existing LCI databases and other literature sources to compile data. Published databases designed for use in LCI are available for sale from several distributors. In addition, several organizations have conducted LCI studies which are publicly available at no cost. Both types of data sources contain information on common unit processes and systems associated with the production of frequently referenced materials. Publicly available LCI data sets are listed in Table 2.

Within these data sets as well as other published LCI studies, the accuracy of energy data tends to be greater than for air pollutant emissions and water pollutant emissions. Air pollutant emissions and water pollutant emissions can vary widely between databases due to differences in regulatory limits, technology, and measurement practices.

Case study: Life cycle inventory for acomplex system — A typical North American Car. A majority of life cycle inventory studies in the 1970s through 1990s investigated relatively simple product systems, such as packaging, with a limited number of parts and materials involved. When the full system life cycle of materials extraction, processing, transport, forming, handling, use, and end-of-life is considered, even a relatively simple system becomes complex. Starting with a complicated system only serves to magnify data collection and modeling challenges.

Nevertheless, a team from the University of Michigan, in partnership with Ecobalance, Inc., and cooperating with Chrysler (now DaimlerChrysler), Ford, General Motors, the Aluminum Association, the American Iron and Steel Institute, and the American Plastics Council, conducted a LCI study on a complete North American automobile [21]. The material variety, product and process complexity, and scope of supply chain posed significant challenges for LCI. Automobiles typically contain over 20,000 individual parts. Collection of specific inventory data for each part was time and resource prohibitive.

In order to reduce the system complexity while maintaining an accurate LCI model of the system, the vehicle was subdivided into six systems, 19 subsystems, and 644 discrete parts and components composed of 73 materials. An example

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Table 2
Selected examples of available life cycle inventory data sets

Source	URL	Data age	Geographic focus	Description
US LCI database project	http://www.nrel.gov/lci/	2004	United States	58 process modules describing the production and use of common materials and fuels
The eco-inventory of Packaging (BUWAL 250)	http://www.umwelt-schweiz.ch/buwal/	1998	Switzerland	Commodity packaging materials from production through conversion, distribution and disposal
Database for environmental assessment of materials	http://www.nims.go.jp/ecomaterial/ecosheet/ecosheet.htm	2000	Japan	Data on alloys, alloying elements, steelmaking processes, and social stocks
Association of Plastic Manufacturers in Europe	http://www.apme.org	1989–2004	Europe	Material production and forming data for commodity and engineering plastics
International Iron and Steel Institute	http://www.worldsteel.org/lci.php	1999–2000	Global	Material production and forming for 14 steel grades/types
LCI report for the North American aluminum industry	http://www.aluminum.org	1995	North America	Various processes within the aluminum product life cycle including information on primary and secondary aluminum
LC Acess	http://www.epa.gov/ORD/NRMRL/lcaccess/	n/a	Global	Searchable listing of available data sources

n/a = not applicable.

of this hierarchy is shown in Fig. 3. Small parts with similar materials and processing (e.g. screws, bolts, and other fasteners) were aggregated into single components in order to simplify the modeling. Data collection focused on 13 specific manufacturing facilities with representative processes, homogenous output, and strong relevance to the study.

The results of this modeling provide the LCI profile of a generic North American family sedan. The life cycle energy profile of this system is shown in Fig. 4, while LCI results for selected metrics are shown in Table 3. The results of this analysis reaffirmed the importance of the use phase as the major determinant of life cycle energy performance. The importance of the use phase is also

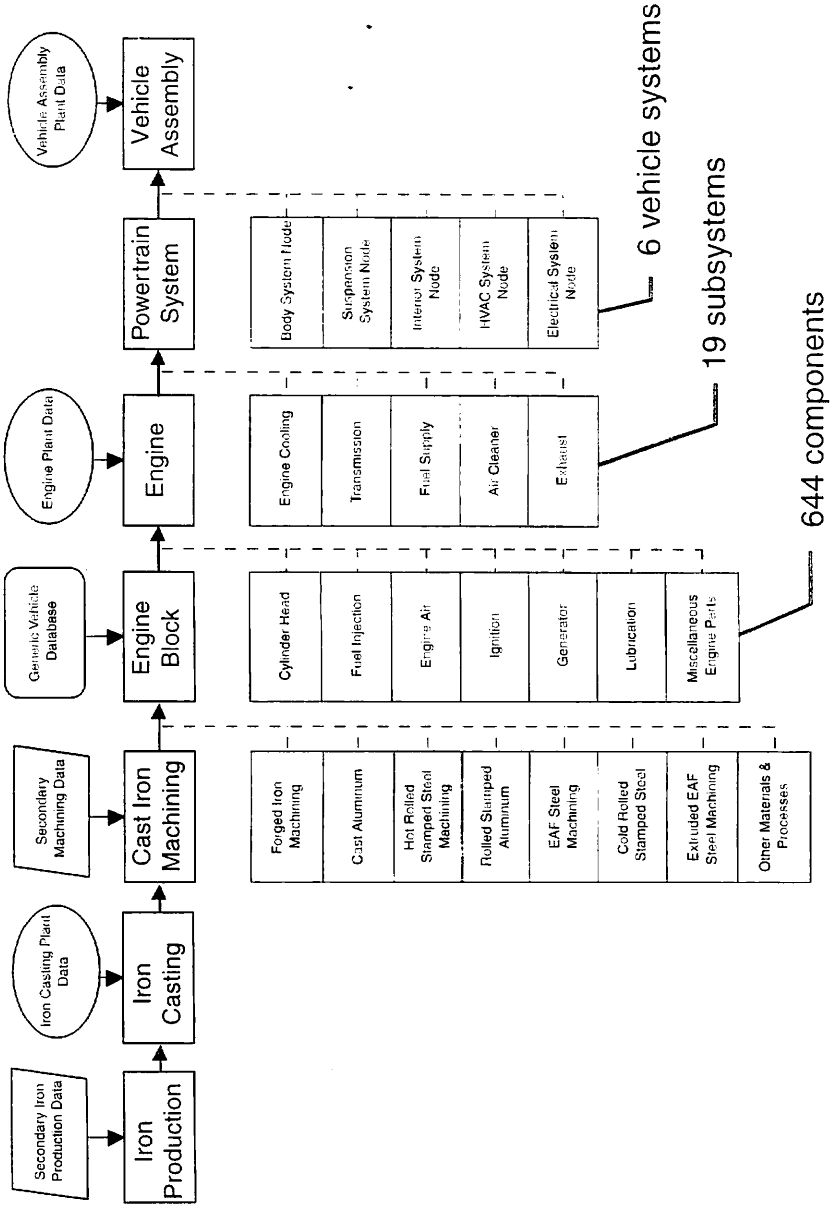

Fig. 3. Hierarchical structure example — manufacturing stage, engine block and related systems, and subsystems [21].

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Fig. 3. Hierarchical structure example – manufacturing stage, engine block and related systems, and subsystems [21].

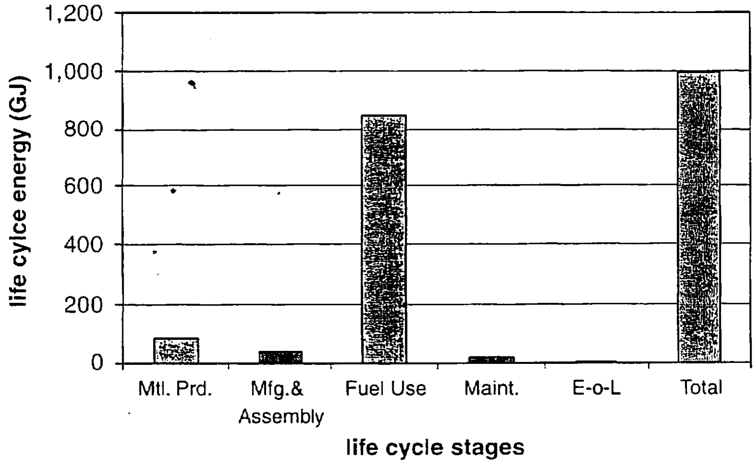

Fig. 4. Life cycle energy profile for a generic North American vehicle.

Table 3
LCI results for a generic North American vehicle

Inventory item	Life cycle performance	Use phase (%)
Energy (MJ)	995,000	87
Carbon dioxide (g)	61,300,000	88
Carbon monoxide (g)	1,940,000	97
Non-methane hydrocarbon (g)	259,000	92
Nitrogen oxides (g)	256,000	91
Solid waste (kg)	4380	25

Source: Sullivan et al., data corrected to final results.

apparent in airborne emission metrics. Other metrics, such as waterborne effluents (not shown in Table 3) and solid waste, exhibited much less dependence on the use phase.

2.2. *Impact assessment*

LCI analysis provides a useful framework for tracking and quantifying the material and energy inflows and outflows related to a product or process system. However, in order to characterize the environmental and societal effects of the system, LCIA is required. The purpose of LCIA is to assess a system's LCI analysis results to better understand their significance with respect to selected impact categories, such as resource depletion, human health, and ecological health. The procedures of LCIA are less standardized and more complex than those of LCI, and require more value judgments [23].

Several organizations have contributed to the standardization of LCIA. Noteworthy examples include the ISO 14042 standard and Technical Report 14047 [24,25], the SETAC Working Group on LCIA. More recent examples include the United Nations Environment Program (UNEP) — SETAC Life Cycle Initiative [26], and the US EPA through efforts to develop and disseminate the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) [27,28].

According to ISO 14042, LCIA consists of two required steps — classification and characterization — and three optional activities — normalization, grouping, and weighting. Classification consists of assigning LCI results (e.g. kg NO_x emissions) to specific impact categories of interest (e.g. photo-oxidant formation and acidification).

Common examples of LCIA categories include depletion of abiotic resources, depletion of biotic resources, impacts of land use, land competition, loss of biodiversity and life support function, greenhouse effect, stratospheric ozone depletion, human toxicity, eco-toxicity, smog formation, acidification, and eutrophication. Less common categories include odor, noise, radiation, waste heat, and casualties. The second required operation in LCIA, characterization, consists of calculating overall impact results by category. This operation typically requires the use of characterization factors that convert a specific inventory result to overall impact category totals (e.g. kg SO_2 equivalent acidification per kg NO_x emitted). Selected impact assessment categories and units of characterization are shown in Table 4.

Normalization is an optional element of LCIA in which category results are evaluated relative to a common standard in an attempt to enable comparison against a common baseline (e.g. impacts attributable to the system relative to total regional impacts).

Grouping, also an optional activity, involves sorting impact categories into groups sharing a common theme. A typical example of grouping involves ranking categories by priority — low, medium, or high.

The final optional activity in LCIA is weighting. Weighting consists of converting category results to a common scale using factors designed to reflect the relative importance of each category. Weighting factors are frequently used to calculate a single numerical score based on LCIA results to facilitate comparisons between systems.

Generally, LCIA is accomplished through the application of established characterization factors to LCI results. For example, automobiles have been shown to emit 850 and 164 kg of CO and NO_x, respectively, over a 10-year life cycle [35]. Characterization factors for impacts categories, including photochemical smog formation and acidification, relevant to North America are available in the TRACI software package from US EPA and are shown in Table 5 [28]. In this example, multiplying the reported emissions by the appropriate

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Table 4
Selected impact categories and units of characterization

Impact category	Example characterization units	Sources of methodology discussion
Land use	ha-year	[29,30]
Loss of biodiversity	metric tons of net primary production/ha, metric tons of gross primary production/ha	[31]
Global warming	kg CO_2 equivalent	[1,32]
Ozone depletion	kg CFC-11 equivalents	[27,32]
Human toxicity	kg benzene equivalent,[a] kg toluene equivalent,[b] DALY[c]	[27,33]
Eco-toxicity	Ecological toxicity potential relative to 2,4-D	[27,34]
Smog formation	kg O_3 equivalent, g-NO_x equivalents/m	[28,32]
Acidification	kg SO_2 equivalents, mol H^+ equivalents	[28,32]
Eutrophication	kg NO_x equivalents, kg N equivalent	[28,32]

[a] For carcinogen impacts.
[b] For non-carcinogen impacts.
[c] For particulate (criteria) air pollutants, DALY = disability adjusted life years.

Table 5
Example LCIA calculations based on automobile emissions

Substance (i)	Inventory result (e_i) [35]	Photochemical smog characterization factor (cf_i) [36][a]	Acidification characterization factor (cf_i) [36][a]	Photochemical smog (I_i)	Acidification (I_i)
CO	850 kg	0.017 g NO_x eqv./m/kg	n/a	11 g NO_x eqv./m	n/a
NO_x	260 kg	1.2 g NO_x eqv./m/kg	40 H^+ mol eqv./kg	310 g NO_x eqv./m	10,000 H^+ mol eqv.
Category Total (I)	—	—	—	320 g NO_x eqv./m	10,000 H^+ mol eqv.

n/a = not applicable.
[a] US national characterization factors.

characterization factors and summing the results within each impact category accomplishes the fundamental components of LCIA. The relationship between impact category total (I), substance characterization factor (cf_i), and emissions of substance i (e_i) is as follows:

$$I = \sum cf_i \, e_i \tag{1}$$

Table 6
Global warming potential characterization factors [1]

Substance	Global warming potential (kg CO_2 eqv./kg)
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296
Hydrofluorocarbons (e.g. HFC 134a)	1300
Perfluorocarbons (e.g. CF_4)	5700
Sulfur hexafluoride (SF_6)	22,200

Table 5 presents the impact results for life cycle emissions of two air pollutants for a mid-sized automobile.

The use of characterization factors, such as those shown above, results in an assessment of impact indicators or "mid-points." The term mid-point indicates that these factors characterize impacts at an intermediate point between the source and a final observable effect. For example, greenhouse gases are emitted into the atmosphere and trap heat re-radiated from the Earth's surface leading to what is known as the greenhouse effect and ultimately, to global climate change. Observable effects include significant changes in temperature, precipitation, and sea level. The global warming potentials given in Table 6 are the characterization factors used for calculating the global warming impact. Global warming potentials are based on the radiative forcing (heat-absorbing ability) of each greenhouse gas as well as the decay rate of each gas relative to carbon dioxide over a 100-year time horizon. These factors do not provide any specific indication of the ultimate effects on sea levels or other end points as a result of emissions. Thus, the term mid-point is used to describe these impacts.

Some researchers have proposed alternative methods for impact assessment that begin with the end-points of interest and work backward in what is known as a top-down approach [37]. The top-down approach begins with the identification of end-points and the associated societal values, and then works toward emissions to derive characterization factors. The top-down approach is fundamentally consistent with ISO 14042 goals, but poses challenges for many impact categories due to the complexity of relationships and difficulty in forecasting end-point effects.

One example of the use of an end-point characterization factor is the evaluation of human health effects from criteria air pollutant emissions in TRACI [27]. Characterization factors for these effects were calculated in three stages. First, emissions for specific regions (US states) were modeled to determine expected changes in particulate matter concentrations resulting from each emission and the associated population exposures. The second stage translated concentration exposures into specific morbidity and mortality effects according to published concentration–response functions.

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Finally, these morbidity and mortality effects are expressed in DALYs as a measure of expected combined years of life lost and years lived with disability. This procedure takes advantage of a series of well-documented relationships to relate the end-point of interest (DALYs) to emissions of a limited number of substances (NO_x, PM_{10}, $PM_{2.5}$, total suspended particulates, and SO_x). The top-down approach may ultimately result in more robust impact assessment, however, limitations in currently available data restrict the application of end-point factors. The bottom-up approach is the focus of this discussion as it is the more common approach, provides impact results sufficient for decision makers in most situations, and minimizes uncertainty relative to a top-down approach [38].

Uncertainties in impact assessment continue to pose a challenge to the effective use of LCIA in sustainability metrics and decision making. Sources of uncertainty in LCIA are inherent in the methodologies used to derive impact assessment characterization factors. Characterization factors provide a linear relationship between inventory results and quantified impacts. In reality, many impacts exhibit significant non-linearities with increasing environmental loadings. For example, soils may be buffered against acidification, economic factors will influence rates of consumption of abiotic resources and their reserve base, and plants and animals may exhibit the ability to absorb substances below a threshold with no observable effect.

Uncertainties in LCIA characterization factors and their application generally result from temporal and regional scaling. Uncertainty introduced through temporal scaling relates to the timing of the loading and the time horizon for impact evaluation. A common example of an environmental impact sensitive to temporal scaling is smog. Rush hour emissions are more likely to cause smog than emissions that occur overnight. However, existing characterization factors rarely distinguish between emissions at different points in time.

In addition to occurrences at various points in time, environmental impacts also occur at various spatial scales. Global impacts include climate change, ozone depletion, and resource depletion; regional or local impacts include acidification, photochemical smog, eco-toxicity, and human health. Regional differences have little or no effect on global characterization factors, but factors for regional impacts are heavily influenced by spatial differences. For example, unique geographic features in the Los Angeles basin led to specific transport phenomena that influence photochemical smog formation. Clearly, characterization based on phenomena observed in other regions would introduce uncertainties if applied to emissions in the Los Angeles basin.

Recent efforts, such as those by US EPA in the development of TRACI, have focused on the development of regionally appropriate characterization factors. Bare et al. reported that the use of regionally appropriate characterization factors can reduce uncertainty in impact assessment results for impacts such as acidification, eutrophication, and smog formation by orders of magnitude [27].

Nevertheless, broad regional factors, such as those developed at a state level, may not accurately reflect specific local conditions, leaving some inherent uncertainty in the application of impact characterization factors.

2.3. Economic input–output LCA and hybrid methods

The economic input–output (EIO) LCA method uses a commodity input–output (IO) matrix to trace economic transactions throughout the supply chain for a particular product system. Resource inputs and environmental outputs are then coupled to the economic transactions to construct a LCI. The concept to link environmental burdens to an economic input output matrix was originally proposed by Leontief over 50 years ago [39]. The EIO LCA method was refined and applied relatively recently by Horvath and Hendrickson [40]. Their model utilizes a 1992 commodity IO matrix of the US economy as developed by the US Department of Commerce, which includes 485 industrial sectors. Vectors of resource input coefficients and environmental output coefficients are created for each sector and these coefficients represent resource consumption, emissions, and waste per dollar of industrial output. Specific examples of data sources for computing these coefficients include RCRA (Resource Conservation and Recovery Act) Subtitle C hazardous waste generation, management and shipment biannual report, Toxic Release Inventory Data, and US EPA AP-42 emissions factors.

The attractive feature of EIO LCA is that it has the potential to be more comprehensive than process level LCA. The method accounts for upstream processes and indirect inputs that might not be included in a process level LCA. For example, the steel used to make the stamping press used to stamp the steel for an automotive panel is generally neglected in a process level LCA whereas an EIO LCA would capture this input.

The EIO LCA method suffers from several problems that generally differ from those encountered in the process analysis LCA method [41]. The major limitations of the EIO LCA method relate to the high level of aggregation of industry or commodity classifications both for economic transactions and for resource and environmental coefficients. For example, material production of specific polymers such as PET and ABS are grouped together under plastic materials and resins sector. Coefficients are averaged for the whole sector and will not represent differences between products within a sector. Another limitation results from the fact that monetary value can distort physical flow relations between industries due to price inhomogeneity [41]. For example, the resource and environmental intensity for production of a $50.000 vehicle is not expected to be 2.5 times that of a $20,000 vehicle.

The limited availability of sectoral environmental statistics is a concern particularly for small to medium-size businesses, mobile sources, and non-point sources. Despite these challenges EIO LCA is increasingly being used [40,42,43].

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The hybrid EIO process analysis LCA method provides a way to exploit the strengths and overcome deficiencies in each method. One hybrid application utilizes a detailed process level analysis of the manufacturing stage in a process-based LCA and uses the EIO LCA method to evaluate all material and energy inputs into this stage. Although other approaches to simplification of rigorous process level LCA have been proposed [44], hybrid systems utilizing some EIO LCA elements appear most promising.

3. Life cycle energy analysis

Life cycle energy analysis is a subset of LCI that tracks energy flows. LCI of energy use is a valuable tool for identifying the life cycle stages and processes of a product system that consume the greatest energy resources. This metric might be considered the single most significant metric for assessing sustainability for several reasons:

(1) greenhouse gas emissions often correlate strongly with energy use (especially when fossil fuels are used as energy sources);
(2) a wide range of other air pollutant emissions originate from energy production and conversion; and
(3) energy data are relatively more available and with greater accuracy than data for other impact categories.

The life cycle energy profiles of products vary dramatically in magnitude and composition/distribution. Table 7 presents life cycle energy metrics for a variety of product systems.

For many products that require energy to operate, the use phase of the life cycle dominates the energy consumption. This pattern is observed for automobiles, buildings, and appliances. One noteworthy exception is desktop computers where the energy requirements for semiconductor manufacturing are substantially greater than the use phase energy. The relatively short expected service life of computers compared to automobiles and buildings also influences the ratio of use phase energy to total life cycle energy. Although not indicated in Table 7, the end-of-life management stage, in general, is the least energy intensive.

Life cycle energy modeling is useful in exploring strategies to reduce operating energy for products. Tradeoffs can exist if a strategy increases material production energy but reduces the use phase energy requirements. For example, an aluminum body automobile will increase fuel economy through lightweighting but material production energy will increase relative to a steel body vehicle. Adding insulation to a house increases material production energy but the use phase benefits will generally outweigh the difference. Life cycle energy models serve to resolve these tradeoffs.

Table 7
Life cycle energy analysis results for various product systems

Product system (functional unit)	Life cycle energy (GJ)	Life cycle energy/ functional unit	Use phase (%)	Source
Passenger car (120,000 miles, 10 years)	998	8.3 MJ/mi or 100 GJ/year	85	[35]
Residential home (50 years, 228 m^2)	16.000	70 GJ/m^2 or 320 GJ/year	91	[45]
Energy efficient residential home (50 years, 228 m^2)	6400	28 GJ/m^2 or 128 GJ/year	74	[45]
Desktop computer (3 years, 3300 h)[a]	16.8	5.1 MJ/h or 5.6 GJ/year	34	[43]
Mixed use commercial building (75 years, 7300 m^2)	2.300.000	316 GJ/m^2 or 3100 GJ/year	98	[46]
6 oz yogurt packaging (1000 lb yogurt delivered)	0.002	5.23 GJ/1000 lb	38	[47]
32 oz yogurt packaging (1000 lb yogurt delivered)	0.007	3.62 GJ/1000 lb	48	[47]
Household refrigerator (20 ft^3, 10 years)	108	10.8 GJ/year	94	[48]
Office file cabinet (one cabinet, 20 years)	2.4	120 MJ/year	n/a[b]	[49]

[a] Values shown have been recalculated from source to account for electrical grid primary energy efficiency of 0.26.
[b] Energy use during the use phase of the file cabinet life cycle is negligible.

Life cycle energy modeling can also distinguish energy resources used for a product system. In addition to the total energy consumption per functional unit, the renewable energy fraction of total consumption is also an important indicator of sustainability.

3.1. Life cycle energy analysis of energy technologies: net energy ratio

Energy ratios have been used since the 1970s to describe the relative effectiveness of energy technologies in converting input energy into useful output. The

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initial development of energy metrics was driven by concerns over the viability of fossil fuel substitutes as long-term energy sources. These concerns gave rise to the concept of net energy initially defined as the value of energy to society after energy required for obtaining and concentrating the energy carrier are subtracted [50]. Using this definition, at least eight unique expressions of energy ratio equations have been developed in the literature [51]. These ratios combine one or more energy parameters into a single metric. Key energy parameters include total system energy output, losses of energy within the system, input from supporting energy systems, and energy contained in feedstock resources.

While no one form of this metric may be appropriate in all situations, the original intent of "net energy" as defined by Odum and others should be maintained. This definition calls for an understanding of the relationship between output energy and input energy as it relates to the effectiveness of a given system in providing for energy growth. Therefore, the net energy ratio of an energy system can be defined as the ratio of total energy production (E_{out}) to the sum of total primary non-renewable energy requirements associated with feedstock (E_{F}) and process operations (E_{P}). For example, in a biomass electricity generating system this ratio is equal to the electricity generated over the non-renewable primary energy for agricultural production, processing, transport, and construction of the generating facility. In the case of photovoltaics, the denominator would include the primary energy required to manufacture, install and maintain the photovoltaic panels and balance of system components. This is shown mathematically in below.

$$NER = \frac{E_{\mathrm{out}}}{E_{\mathrm{F}} + E_{\mathrm{P}}} \tag{2}$$

This definition specifies primary energy as the flow of interest to insure that the full infrastructure system of energy production and delivery, and the associated losses in efficiency, are taken into account.

The resulting metric provides a meaningful assessment of the ability of the system to leverage limited energy resources — an important indicator of sustainability. The net energy ratio for various electricity generating options is indicated in Table 8.

4. Life cycle cost analysis

Economic metrics play a key role in the assessment of sustainability performance. However, traditional accounting systems, those designed to meet fiduciary responsibilities of firms, often fail to provide meaningful metrics for evaluating economic sustainability. An alternative cost analysis approach is required, one that considers the full life cycle of goods and services and accounts for externalities typically ignored in traditional cost accounting systems. Life cycle cost

Table 8
Representative net energy ratio values for electricity generation technologies

Technology/Study	Net energy ratio
Solar – photovoltaic	
BIPV [52]	3.6–5.9
BIPV [53]	5.7
CdS/CdTe [54]	9.5
Hydroelectric	
1296 MW [51]	31
114 MW [55]	24
Wind	
Plains site–Ridge site [51]	47–65
Offshore–On-land [56]	31–46
Inland–Coastal [57]	10–30
Biomass	
Willow [58]	10–13
Hybrid poplar [59]	16
Various crops [60]	15–21
General [55]	7.0
Coal	
Technology range [61]	0.29–0.38
Co-fire biomass [58]	0.34
Natural gas	
Combined cycle [62]	0.40
Combined cycle [53]	0.43
Nuclear	
Pressurized water reactor [51]	0.31

(LCC) analysis is a tool that can be used to study the monetary values for processes and flows associated with a product system. When properly applied, LCC assessment provides economic values for flows identified in a LCI and reports them using a common unit of measure ($), which is often easier for decision makers to consider in contrast to the incommensurable values from an LCA.

There are several approaches to LCC analysis. The most commonly applied method records the purchase (C_p), operating (C_{op}), service and maintenance (C_{sm}), and end-of-life management costs (C_{eol}) for a product system. In this approach the life cycle cost of a product or system is recorded as the sum of the costs in each stage. This relationship is shown as.

$$LCC = C_p + C_{op} + C_{sm} + C_{eol} \tag{3}$$

The simple LCC relationship shown in Equation (3) applies to systems with little temporal difference between or within life cycle stages. For most systems, LCCs occur at different points in time and therefore the time value of money must be considered. Discounting is an economic tool used to compare costs or benefits occurring at different points in time. The goal of discounting is to convert future economic values into present-day monetary terms. The calculation of discounted costs utilizes a discount rate (r) and a period of time (n). The discounted life cycle cost (LCC_{pv}) of a system with a lifetime of n years can be calculated as shown.

$$LCC_{pv} = \sum_{t=0}^{n} \frac{LCC_t}{(1+r)^t}. \tag{4}$$

For example, Table 9 provides the LCCs associated with automobile ownership over a 10-year life time. A discount rate of 0% provides the constant dollar LCC of the automobile.

The example shown in Table 9 considers only the transactional costs (also known as private costs) associated with the automobile system. The transactional costs of the product life cycle do not include the external costs (also known as social costs) that are needed for a more comprehensive accounting of costs in the development of sustainability metrics. Examples of social costs associated with automobile ownership include military, air pollution, global warming, safety, congestion, land and roads, parking spaces (unpaid), water pollution, noise, highway litter, police costs, court costs, and disposal [64]. Several researchers and organizations have developed tools and data to support external cost accounting. For example, Ogden has published external costs for a mid-sized automobile as shown in Table 10. The data shown in Tables 9 and 10 suggest that consideration of even a limited set of external costs can increase estimated LCCs for an automobile by 15–19%.

The assessment of external costs of products and services is complicated by the limited data available and a lack of consensus on appropriate valuation of environmental and societal functions that may not be assigned market values. External costs are born by society and are not reflected in transaction cost. Determination of appropriate external cost values generally involves evaluating

Table 9
Life cycle ownership costs for a 2001 family sedan with a 10-year lifetime [63]

Discount rate (real) (%)	Purchase price ($)	Fixed operating cost ($)	Variable operating cost ($)	End-of-life value ($)	Discounted ownership cost ($)
0	20,200	7320	18,800	(1510)	44,800
2	20,200	6660	16,600	(1240)	42,100
4	20,200	6090	14,600	(1020)	39,900
6	20,200	5600	13,000	(843)	38,000
8	20,200	5160	11,700	(700)	36,300

Table 10
External costs for a conventional mid-sized automobile with a 10-year lifetime [65]

Category	Present value of cost[a] ($)
Oil supply insecurity (military costs)	2650
Air pollution costs	2640
Greenhouse gas emissions cost	1430
Total external cost	6720

[a] External costs shown here are discounted using a rate of 3%.

Table 11
Example values for external costs of CO_2 emissions related to global warming

Study	Value (1990$/metric ton CO_2)	Discount rate (%)	Source
ExternE: externalities of energy	3.8–126	1–3	[67]
Fankhauser	6.2	0.5[a]	[66]
Ogden	33	3	[65]
Chicago climate exchange	1.7	n/a	[68]

n/a = not applicable.
[a] Range of values studied with upper and lower bounds of 3% and 0%, respectively, and a "best guess" of 0.5%.

the expected environmental and societal damages caused by system outputs. For example, damages attributed to emissions of greenhouse gases include loss of crop yield, damage to property, ecosystem loss, mass migration, and increases in cataclysmic weather events. The cost associated with these damages and/or an individual's willingness to pay to avoid damages depends on the location and population under consideration. Economic estimates of willingness to pay for societal goods (external costs) are typically evaluated using contingent valuation methods (see for example [66]). Results from such studies may provide external cost values that vary by an order of magnitude or more.

A representative range of values for global warming costs associated with CO_2 emissions are shown in Table 11. While most of the data in Table 11 result from the application of the contingent valuation approach or an approach combining contingent valuation with market values, the Chicago Climate Exchange provides an exclusively market-based cost of CO_2. This value represents the current cost to corporations interested in purchasing credits to offset CO_2 emissions. Limited incentives to reduce greenhouse gas emissions lead to a lower than expected market cost for CO_2. Specific study methodology and assumptions may vary, however, one significant source of differences in values is the discount rate applied.

As discussed earlier, the value of money is not constant over time. This holds true for both societal and private costs. While discount rates for private costs are well established and reasonably standard (typically ranging between 3% and 5%), discounting of societal costs is less standardized. Some authors have suggested that future generations will value environmental goods, such as the presence of old growth forests, equivalently to current populations. This would require that societal costs for environmental goods are assigned a discount rate of zero [69]. Values in the range of 1– 3% appear to be most common for societal costs, however, some sources site values of 5% or more [65,67]. One potential solution to this dilemma is the use of sliding scale discount rates that vary over time (also called gamma-discounting), such as those proposed by Weitzman [70]. In the Weitzman sliding scale, the short-term (1–5 years) discount rate (4%) is higher than the intermediate rate (6–25 years, 3%), which is higher than the long-term rate (26 –75 years, 2%).

Case study: Life cycle costs of electricity. The sustainability challenges of the existing fossil-fuel-based electricity generation infrastructure are well documented and include high costs, limited access in developing countries, local air pollution, greenhouse gases, unreliability, and resource depletion. Many renewable alternatives have been proposed as possible solutions to these challenges and the environmental benefits of these alternatives have been documented using LCA. In order to understand the economic implications of this suite of alternatives a LCC assessment is required.

This case study considers LCCs of generated electricity at a utility scale. For this system the traditional stages of purchase, operation, service and maintenance, and end-of-life, become initial capital and construction, fuel, non-fuel operations, and decommissioning. Additionally, the external costs of pollution damage will be considered. All costs are discussed in terms of levelized cost per kWh of electricity generated. The levelized cost represents the net present value of all payments required to cover the cost of the system divided by the total lifetime generation. Values discussed here reflect 20 years of operation assuming operation begins in 1999. Previous research has suggested that substantial increases in evaluation period (from 20 to 30 years) results in only a minimal change in levelized costs (decrease of between 0.2 and 0.3 ¢/kWh) [71].

The cost of electricity generation is typically tracked as the sum of capital costs, fuel costs, and non-fuel operating costs. Capital costs include equipment, materials, labor, land, direct and indirect construction costs, design and engineering, initial loading of consumables (e.g. catalyst) and contingency costs. Fuel costs reflect the price the producer pays for primary fuels used in the production of electricity. Non-fuel facility operating costs include labor, maintenance, administration, and non-fuel operating inputs.

In addition to the private costs of electricity generation, the external costs must be included in a total LCC assessment. The costs of damage caused by pollution is an example of the external costs to society of electricity generation. Costs of damage caused by life cycle pollutant emissions (C_p) from electricity generation systems are calculated as the sum of unit damage costs (u_i) multiplied by emissions mass (e_i) as follows.

$$C_p = \sum u_i e_i \tag{5}$$

As discussed earlier in the chapter, a wide range of values are available for unit damage costs of pollution. Representative values for emissions from utility generation in the mid-western US are shown in Table 12. These values are based on research originally published by Fankhauser [72] and Banzhaf [73], and modified by Lewis et al. [74].

The total LCC is calculated as the linear sum of the four factors discussed above. Values for three renewable and three non-renewable utility scale-generating technologies are shown in Table 13. While the renewable technologies studied generally show lower pollution costs, the nuclear power pollution costs are also relatively low. This can be attributed to the selected methodology, which accounts only for the damage costs of air pollutants and not the potential damages associated with spent nuclear fuels. A more complete accounting of external social costs would incorporate these and other factors, such as the loss of ecosystem function associated with hydropower and the impacts of potential acid mine drainage associated with coal acquisition.

Additionally, wind, biomass, and nuclear technologies generally exhibit higher capital costs than the other systems. In the case of the renewable technologies this is attributed to investor uncertainty regarding long-term technology viability and lower production volumes for core equipment. An exception to this is the direct-fire biomass technology (capital cost of 2.3 ¢/kWh) that utilizes boiler systems similar to those used for over 50 years in coal plants. In the case of nuclear power, the higher capital costs are associated with greater upfront investment in facility, design, verification, equipment, and construction.

Table 12
Unit damage costs for common electric utility emissions [74]

Pollutant	Unit damage cost
Carbon dioxide ($/ton carbon)	30
Carbon monoxide ($/ton)	1
Lead ($/ton)	1965
Methane ($/ton)	172
Nitrogen oxides ($/ton)	218
Nitrogen oxide ($/ton nitrogen)	4498
Particulates ($/ton)	2624
Sulfur oxides ($/ton)	84

Table 13
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Table 13
Life cycle costs of electricity generating technologies (¢/kWh) [51]

Technology	Capital cost	Fuel cost	Non-fuel operating cost	Pollution cost	Total life cycle cost
Hydroelectric, one large-scale installation	1.7	—	0.15	0.1	2.0
Wind, two wind farms	4.7–6.4	—	0.8–1.1	0.01	5.5–7.5
Biomass, three willow conversion technologies	2.3–4.1	1.4–2.2	1.6–2.1	0.10–0.11	5.5–8.4
Coal, average plant	2.1	1.3	0.3	6.0	9.7
Natural gas, combined cycle	1.1	2.0	0.4	1.0	4.5
Nuclear, PWR	3.9	2.6	1.9	0.04	8.4

PWR = Pressurized water reactor.

Ultimately, LCC metrics can assist in evaluating the tradeoffs inherent in technology selection. Some systems, such as coal, exhibit low life cycle transactional costs but place a large external cost burden on society. While others, such as wind, require greater investment in capital, but limit the damage to society caused by air pollution.

5. Life cycle optimization

A critical question regarding the life cycle management of any product system is, "What is its optimal service life?" [75,76] The answer may vary depending on the optimization criteria used, which may include environmental, economic, functional performance, and aesthetic objectives. From an environmental perspective, this is a particularly complex question to resolve for products that consume energy in their use phase. On the other hand, indefinite useful life is generally desired when considering energy and environmental criteria for products that do not require energy inputs in the use phase. In the case of automobiles, household appliances, and computers, there exist multiple tradeoffs between maintaining an existing model and replacing it with one that is more efficient. The efficiency gain from model replacement should exceed the additional resource investments required to produce the new model.

A life cycle optimization (LCO) model was developed recently to evaluate optimal service life from energy, emissions, and cost perspectives [35]. This LCO model is based on a dynamic programming method with inputs derived from LCA. Dynamic programming is a collection of mathematical tools used to analyze sequential decision processes. The planning horizon is divided into multiple stages at which different decisions may be made depending on the state of the system at that time. A given decision will transform the system to a new state with a new corresponding outcome. Dynamic programming seeks the particular sequence of decisions that best satisfies a decision maker's criteria over the complete planning horizon. In a dynamic programming model, the time horizon of the problem is the period of time over which the decisions are made.

Figure 5 provides a schematic example of the LCO model applied to vehicle replacement. The y-axis is the cumulative environmental burden such as NO_x emissions or energy consumption, while the x-axis represents time. The initial vehicle is assumed to be produced at time 0, and a new model vehicle with a different environmental profile is introduced at time T_a and T_b. Decisions to keep or replace vehicles are made at the points marked by black dots. Environmental burdens from materials production and manufacturing are shown as a step function at the time a vehicle is produced. The slope of each line segment represents an energy efficiency or emission factor of a vehicle model. The slopes tend to increase with time, indicating deteriorations of emission controls or energy efficiencies.

Assume that, at time 0, a decision maker tries to minimize the environmental burden of a criterion within the time horizon N based on information the decision maker has regarding the environmental performance of future vehicles. The decision maker seeks a solution of the form "Buy a new vehicle at the start

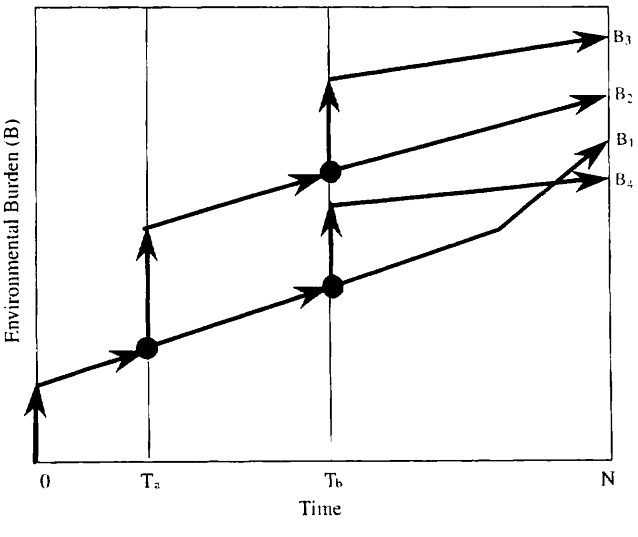

Fig. 5. Schematic example of the life cycle optimization (LCO) model based on four policies. B_1–B_4 represent the final environmental burdens for the four policies [35].

of year 0 and keep it for α years and retire it: then buy a new vehicle at the start of year α and keep it for β years and retire it, etc." As an example, consider four policies depending on the decisions at T_a and T_b.

(1) If the vehicle owner keeps the initial vehicle throughout the time horizon N, the cumulative environmental burden (B) will result in B_1. The slope change between T_b and N represents vehicle deterioration expected for older cars.
(2) If the vehicle owner replaces the initial vehicle with a new vehicle at time T_a and keeps the new vehicle until N, the cumulative environmental burden (B) will result in B_2.
(3) If the vehicle owner replaces the initial vehicle with a new vehicle at time T_a and replaces this second vehicle again at time T_b, the cumulative environmental burden (B) will result in B_3.
(4) If the vehicle owner replaces the initial vehicle at time T_b with a new vehicle and keeps the new vehicle until N, the cumulative environmental burden (B) will result in B_4, which is the minimum possible outcome.

This LCO model was developed and applied to study optimal lifetimes of mid-sized generic cars over a 36-year time horizon (between calendar year 1985 and 2020). Optimal replacement policy was investigated that minimized life cycle energy, emissions, and cost as individual objective functions.

Table 14 gives the optimization results of generic mid-sized model scenarios. The optimal set of lifetimes for the energy/CO_2 objectives in Table 14 can read, for example, "Keep the model year 1985 car for 18 years and retire it at the end of 2002, then buy a model year 2003 car and keep it for another 18 years until 2020 in order to minimize energy/CO_2 emissions when driving a mid-sized passenger car 12,000 mi/yr." For CO, NMHC, and NO_x pollutants with 12,000 miles of annual mileage, automobile lifetimes ranging from 3 to 6 years are

Table 14
Optimal vehicle lifetimes and cumulative burdens for a 36-year time horizon between 1985 and 2020 (12,000 miles of annual driving) [35,63]

Objective minimized	Optimal vehicle lifetimes (years)[a]	Private cost (constant 1985$)	Cumulative environmental burdens				
			Energy (10^3 GJ)	CO_2 (10^5 kg)	CO (10^6 g)	NMHC (10^5 g)	NO_x (10^5 g)
Energy/CO_2	18, 18	77,300	3.34	2.18	4.95	6.18	6.52
CO	3, 3, 4, 6, 6, 7, 7	117,000	3.84	2.46	2.76	4.29	4.54
NMHC	6, 6, 10, 14	94,800	3.53	2.29	2.96	4.07	4.47
NO_x	5, 5, 6, 6, 14	101,000	3.65	2.36	2.86	4.14	4.32
Private explicit ownership cost	17, 19	76,200	6.97	4.54	5.64	9.50	11.0

[a] Replacement intervals for a 36 year time horizon.

optimal for 1980s and early 1990s model years, while optimal lifetimes are expected to be 7–14 years for model year 2000 and beyond. On the other hand, a lifetime of 18 years minimizes cumulative life cycle energy and CO_2 based on driving 12,000 miles annually.

The expected median lifetime of an average car has increased from 12.5 years for model year 1980 to 16.9 years for model year 1990 [77]. Thus, generally, cars are driven for a longer time than is optimal from a regulated emissions perspective, while median automotive lifetimes have been almost ideal from a CO_2 and energy perspective.

The LCO model was also modified to investigate optimal household refrigerator service life. Model runs with a time horizon between 2004 and 2020 show that current owners (2004) should replace typical mid-sized 1994 models and older, which would be an efficient strategy from both cost and energy perspectives [78].

6. Life cycle sustainability indicators

The life cycle framework can also be used to construct a matrix of environmental, social, and economic sustainability indicators for a system. These indicators can be organized by life cycle stage and then categorized into the "triad" of sustainability: economic, social, and environmental. This approach was used to assess the sustainability of the US food system [79]. Table 15 presents the full matrix of sustainability indicators developed by Heller and Keoleian. In many instances, the division of economic, social, and environmental sustainability is somewhat arbitrary since particular indicators often address more than one aspect of sustainability. Also identified in Table 15 are the primary stakeholders involved or influential in each stage of the food system. The indicators evaluated in Table 15 can be both qualitative and quantitative.

This matrix approach can be used to evaluate the sustainability of other product systems. Indicators based on the three dimensions of sustainability developed elsewhere (e.g. Global Reporting Initiative [80]) do not necessarily follow a life cycle framework but can provide useful examples of social indicators.

7. Conclusions

This chapter demonstrated the capabilities of life cycle-based models and metrics for assessing and guiding the sustainability of products and technology. LCA has been applied for over three decades. Increasingly, firms are recognizing the value of life cycle thinking in sustainability metrics and will begin to implement life cycle methods as tools become more accessible. A few final observations regarding these tools and their future development are offered to conclude this chapter.

Table 15
Life cycle sustainability indicators for the food system [79]

Life cycle stage	Stakeholders	Indicators		
		Economic	Social	Environmental

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Table 15
Life cycle sustainability indicators for the food system [79]

Life cycle stage	Stakeholders	Indicators		
		Economic	Social	Environmental
Origin of (genetic) resource — seed production, animal breeding	Farmers Breeders Seed companies	Degree of farmer/operator control of seed production/breeding	Diversity in seed purchasing and seed collecting options Degree of cross-species manipulation	Ratio of naturally pollinated plants to genetically modified/hybrid plants per acre Reproductive ability of plant or animal percent of disease-resistant organisms
Agricultural growing and production	Farm operators Farm workers Agricultural industry Agricultural schools Government Animals	Rates of agricultural land conversion Output/input productivity percent return on investment Cost of entry to business Farmer savings and insurance plans Flexibility in bank loan requirements to foster environmentally sustainable practices Level of government support	Average age of farmers Diversity and structure of industry, size of farms, number of farms per capita Hours of labor/yield and/income Average farm wages vs. other professions Number of legal laborers on farms, ratio of migrant workers to local laborers percent workers with health benefits Number of active agrarian community organizations percent of agricultural schools that offer sustainable agricultural programs, encourage sustainable practices Number of animals/unit, time animals spend outdoors (animal welfare)	Rate of soil loss vs. regeneration Soil microbial activity, balance of nutrients/acre Quantity of chemical inputs/unit of production Air pollutants/unit of production Number of species/acre Water withdrawal vs. recharge rates Number of contaminated or eutrophic bodies of surface water or groundwater percent waste utilized as a resource Veterinary costs Energy input/unit of production Ratio of renewable to non-renewable energy Portion of harvest lost due to pests, diseases

Table 15 (*continued*)

Life cycle stage	Stakeholders	Indicators		
		Economic	Social	Environmental
Food processing, packaging and distribution	Food processors Packaging providers Wholesalers Retailers	Relative profits received by farmer vs. processor vs. retailer Geographic proximity of grower, processor, packager, retailer	Quality of life and worker satisfaction in food processing industry Nutritional value of food product Food safety	Energy requirement for processing, packaging and transportation Waste produced/unit of food percent of waste and byproducts utilized in food processing industry percent of food lost due to spoilage/mishandling
Preparation and consumption	Consumers Food service Nutritionists/ Health pro-fessionals	Portion of consumer disposable income spent on food percent of food dollar spent outside the home	Rates of malnutrition Rates of obesity Health costs from diet related disease/conditions Balance of average diet percent of products with consumer labels Degree of consumer literacy regarding food system consequences, product quality vs. appearance, etc. Time for food preparation	Energy use in preparation, storage, refrigeration Packaging waste/ calories consumed Ratio of local vs. non-local and seasonal vs. non-seasonal consumption
End-of-life	Consumers Waste managers Food recovery & gleaning organizations	Ratio of food wasted to food consumed in the US Dollar spent on food disposal	Ratio of (edible) food wasted vs. donated to food gatherers	Amount of food waste composted vs. sent to landfill/incinerator/ wastewater treatment

1. The life cycle framework is a logical system boundary for defining sustainability metrics to evaluate performance and guide system improvement. Many useful analytical tools including LCA, life cycle energy analysis, LCC analysis, LCO, and life cycle sustainability indicators, have been developed and applied to a variety of systems for measuring aspects of environmental, economic, and social sustainability. LCA provides many important measures for assessing environmental sustainability while LCC analysis can provide a microscale perspective on economic sustainability. Using a life cycle framework to investigate the social dimensions to sustainability can also provide a powerful tool, but this area is much less developed.
2. Data availability and quality remains a major challenge in conducting a LCA. National database initiatives (e.g. US, Japan, Switzerland) and life cycle projects undertaken by industry associations (e.g. APME, IISI, AA) are essential for the development of the life cycle field. In addition to data limitations and time requirements, system boundary issues and truncation are factors that impact the ease and accuracy of conducting a process level LCA. EIO LCA is emerging as an alternative approach that can address some of these challenges. The high level of aggregation of Input/Output tables with respect to products, processes, and technologies limits the accuracy of this approach. Hybrid EIO and process level LCA represents one way to combine the positive attributes of each method.
3. What single metric would best represent environmental sustainability if only one impact category (e.g. greenhouse gas emissions, resource depletion) could be used to assess the environmental sustainability performance of a product system? Life cycle energy consumption might be recommended as a key indicator for serving this general purpose. Declining energy non-renewable energy sources such as petroleum and natural gas is a major sustainability challenge facing society in the 21st century. In addition, greenhouse gas emissions, acidification, and smog formation are important impact categories that often correlate with energy use, particularly fossil fuels. Consequently, life cycle energy analysis might be emphasized if resources are severely limited for environmental sustainability assessment.
4. The net energy ratio is an important sustainability metric derived from life cycle energy analysis of energy carriers including electricity and transportation fuels. This metric indicates the capability of the energy system to leverage non-renewable energy inputs. The net energy ratio is particularly useful in evaluating the sustainability of alternative renewable energy technologies such as photovoltaics, wind, biomass electricity, and biomass transport fuels.
5. LCC assessment indicates how costs are distributed across the supply chain and which stakeholders incur costs and benefits. This can provide valuable insights into the microscale dimensions of economic sustainability. The LCC analysis can be very useful in evaluating the public works projects such as

road infrastructure. For example, design alternatives can be explored that minimize LCCs that include agency costs (construction and maintenance) and social costs (user costs and external costs). Social costs include congestion, lost productivity, vehicle damage, accidents related to poor roads, and traffic during rehabilitation activities [81]. External costs include pollution, which can also be monetized and compared with other LCCs.

6. Life cycle-based social sustainability metrics represent an area in need of development. In addition, methods for evaluating incommensurable environmental, social, and economic sustainability measures and resolving trade-offs when considering alternatives is also an area for investigation. Alignment between social, economic, and environmental sustainability indicators would be the desired outcome in the life cycle design and management of product systems.
7. Developing absolute measures of sustainability may be the most challenging area for research. Most of the metrics for assessing sustainability performance are relative metrics rather than absolute measures. In other words, we can say that less of an impact is better but it is difficult to say what is "sustainable" in the absolute sense. How much carbon dioxide emitted from a product system would be considered sustainable? Even if a sustainable global greenhouse gas emissions target could be established there is no clear method for allocating a global emission threshold to a specific product system. Ecosystems are the foundations of our life support system. Consequently, more research is needed to define life cycle metrics for assessing ecosystem structure, function, and health.
8. Advancements in the field of LCA have been made through professional societies including ISO, SETAC, the Society of Automotive Engineers (SAE), Institute of Electronics and Electrical Engineers (IEEE), International Society for Industrial Ecology (ISIE); academia; and several governmental organizations including the US EPA and UNEP. In academia these tools are being developed in a variety of disciplines including public health, natural resources, environmental science, chemical engineering, mechanical engineering, industrial engineering, and materials science. The field is very interdisciplinary which makes it a rich area for research scholarship.

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