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# Treatise on Sustainability Science and Engineering

Springer

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I.S. Jawahir · S.K. Sikdar · Y. Huang
Editors

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# Preface

"Treatise on Sustainability Science and Engineering" is aimed at bringing out the state-of-the-art developments in sustainability applications, including principles and practices developed and implemented across a wide spectrum of industry. This book presents a total of 18 chapters, authored by prominent researchers and application specialists in sustainability science and engineering, and these chapters are thematically assembled in the following four major parts:

Part I: Design for Sustainability (6 Chapters)
Part II: Sustainability Metrics and Analysis (4 Chapters)
Part III: Sustainable Energy (5 Chapters)
Part IV: Sustainable Supply/Value Chains (3 Chapters)

Part I introduces design for sustainability concepts, methodologies, principles, and practices through systematic studies in a total of six closely related chapters covering a range of models and design and application methodologies for sustainability, beginning with a "Life-Cycle Optimization Methods for Enhancing the Sustainability of Design and Policy Decisions" outlining and presenting life cycle optimization methods.

LCO developed for evaluating the optimal service life and asset management decisions from energy, emissions, costs, and policy issues. This LCO model is based on dynamic programming methods. Applications are drawn from automobiles and the household refrigerators and air conditioners, with trade-offs between utilizing the existing product models and replacing it with the more efficient newer one. This is followed by "Second Thoughts on Preferred End-of-Life Treatment Strategies for Consumer Products" providing further thoughts on new, preferred end-of-life strategies for consumer products which have, typically, lifetime extensions as preferred options to disassembly options for reuse and recycling. This priority hierarchy method was shown as too simplistic in the light of new technological advances involving the use of self-disassembly methods and business propositions, with research-driven case studies demonstrating the reversal of such traditional priority end-of-life options by emphasizing the viability of systematic product reuse, refurbishment or disassembly for reuse where material recycling was shown as the only realistic scenario. “A New Methodology for Integration of End-of-Life Option Determination and Disassemblability Analysis” in this part presents a new methodology for integrating the process of end-of-life determination with product disassembly decision methods by introducing a five-stage strategy: (1) product definition, (2) determination of end-of-life option with residual value calculation, (3) evaluation of disassembly methods with relevant cost analysis, (4) calculation of recycling costs, and (5) documentation of a disassembly report. A case study is presented to demonstrate the feasibility of this new methodology. “Sustainability Under Severe Uncertainty: A Probability-Bounds-Analysis-Based Approach” deals with an introduction of a probability bound analysis (PBA) method for handling uncertainties due to lack of and/or imprecise information on sustainability. The use of this method was shown as feasible for modeling the propagation of uncertainty through complex mathematical models in simulation and decision making. This is shown through a study of two different computational algorithms: Dependency Bound Convolution (DBC) for simple algebraic formulations, and the Black-Box Compatible (BBC) methods for complex models. “Life Cycle Assessment (LCA): A Means to Optimise the Structure of Sustainable Industry” in this part shows the Life Cycle Assessment (LCA) method as a means to optimize the structure of the sustainable industry by showing that sustainability will influence all aspects of industrial processes including the raw material base, size, and location of their interactions within and with the environment, and with the economic and social implications. A case study of first generation bioethanol processes is demonstrated to highlight such interactions. The last chapter in this part “Practical Approaches to Sustainability: iSUSTAIN® Tool for Green Chemistry Case Study” introduces a Green Chemistry Scoring Tool iSUSTAIN™. This tool is based on the 12 principles of green chemistry where metrics were developed for each tool to measure the sustainability contents of products and processes in terms of their inherent “greenness”.

Part II presents a detailed sustainability metrics and analysis in four chapters. “Measuring Sustainability: Deriving Metrics from a Secure Human–Environment Relationship” presents a practical means for measuring sustainability in terms of developed metrics with minimum human adverse effects. It is promoted that the newly defined metrics must define the boundaries of human activities relative to environmental capabilities to offer some early warning signs of such conditions that would normally be unfavorable to human life, thus leading to an imposed change. “Science-Based Metrics for Product Sustainability Assessment” makes an attempt to present a framework for developing science-based metrics for evaluating product sustainability.

This chapter shows the recent NIST efforts in addressing the need for developing such metrics and tools for scientific evaluation of life cycle economic and environmental performance of products. The latter is shown to be measured using LCA methods that assess the “carbon footprint” of products, as well as 11 other sustainability metrics including fossil fuel depletion, smog, water use, habitat alteration, indoor air quality, and human health. These performance metrics are applied in the assessment of 230 building products within the NIST's Building Environmental and Economic and Sustainability (BEES) tool involving a BEES case study of five floor covering products. "Key Business Metrics that Drive Sustainability into the Organization" presents key business metrics that drive sustainability into the organizations based on the stakeholder context from the sustainability-related aspirations, goals, and challenges that are both internal and external to an organization. This chapter also introduces the GEMI *Metrics Navigator*$^{\text{TM}}$ process, a roadmap for identifying key sustainability issues, and business metrics, which are aimed at achieving the sustainability goals of an organization. The next chapter in this part "Environmental Assessment and Strategic Environmental Map Based on Footprints Assessment" presents a novel graphical representation using an environmental evaluation and strategic environmental map based on the various footprints such as carbon footprint, water footprint, energy footprint, emission footprint, work environment footprint, etc. This graphical method allows the use of these footprints with an additional dimension of cost.

Part III integrates five interrelated chapters in the major area of sustainable energy. This part begins with a "Exploring How Technology Growth Limits Impact Optimal Carbon Dioxide Mitigation Pathways" showing how technology growth can limit impact optimal carbon dioxide ($CO_2$) mitigation pathways. In this chapter, alternative growth bounds on wind and solar power, nuclear power, and $CO_2$ sequestration are examined for a hypothetical greenhouse gas (GHG) mitigation scenario. A nested parametric sensitivity analysis is used to examine the response to individual and combinations of bounds. Both, modeling and planning perspectives are shown. "Nanoscale Engineering Approach for Enhancing the Performance of Photovoltaic Cell Technologies for Non-Fossil Energy Sources" presents a specific nanoscale engineering approach for enhancing the performance of photovoltaic (PV) cell technologies for the use of non-fossil energy sources. Two emerging technologies, PV cells and concentrated solar power (CSP) are shown as capable of delivering the large portion of United States' energy needs in the next 40 years if they are properly developed. In this chapter, first, fundamental mechanisms of how electricity is generated by these two technologies are described. Next, recent developments in the application of nanotechnology for enhancing PV cell performance are presented. This chapter shows a nanoscale engineering approach for developing device designs that would counter the two limiting factors. "Sustainable Mobility: Insights from a Global Energy Model" presents sustainable mobility insights from a global energy model that includes a detailed description of light-duty vehicle and fuel technologies, used to investigate cost-effective light-duty vehicle/fuel technologies in a carbon-constrained world. Three conclusions emerged from this chapter. First, there is no "silver bullet" vehicle or fuel technology. Second, a multisector perspective is needed when addressing greenhouse gas emissions. Third, alternative fuels are needed in response to the expected dwindling oil and natural gas supply potential by the end of the century. "Life-Cycle Analysis of Biofuels and Electricity for Transportation Use" presents a LCA of biofuels and electricity for transportation use. This chapter shows that the transportation sector has been relying solely on petroleum, consuming more than 50 % of the global world oil production, with the United States being the top oil-importer country. Two major issues facing the transportation sector in the U.S. and other major countries are shown: energy security and environmental sustainability. It was shown that improvements in the energy efficiency of vehicles and the substitution of petroleum fuels with alternative fuels can help to slow the growth in the demand for petroleum oil and mitigate the increase in greenhouse gas emissions. Biofuels and electricity are known for their potential reduction of petroleum use and greenhouse gas emissions. This chapter examines the potential reduction of life cycle energy use and greenhouse gas emissions associated with the use of biofuels in internal combustion engine vehicles and electricity in plug-in hybrid electric vehicles and battery-powered electric vehicles. The last chapter in this part "Liquid Biofuels: We Lose More Than We Win" shows a critical scenario where biomass, according to the world trends, is shown as a priority resource for fossil fuel substitution, and that biomass is increasingly used for both the transport and the heat and power sectors, with increasing interest in using it for chemical production as well. The chapter shows that as the magnitude of biomass, that is or can be made available for energy purposes, is small compared to the magnitude of the new potential customers for it, any long-term and large-scale prioritization of biomass for one purpose will imply a loss of alternative uses of the same biomass. If the lost alternatives are, then, significantly more efficient as well as economically more attractive in fossil fuels substitution and $CO_2$ reduction, we lose more than we win. The authors claim that this is the case for most liquid biofuels, including first generation biodiesels (plant biodiesels) as well as first and second generation bioethanols produced in Europe and the USA.

Part IV presents three interesting chapters on sustainable supply chains, with the opening chapter "Meeting the Challenge of Sustainable Supply Chain Management" showing that assessing and improving the sustainability of products and services requires a life cycle approach, consideration of the complete supply chain, and examination of the role of consumption as the driver for production. It is shown that the economic and environmental dimensions can be explored by integrating value chain analysis (VCA) and LCA to show the distribution of economic benefits and environmental impacts along the supply chain. Environmental intensities (i.e., impact per unit of added value) are shown as frequently high for material extraction and refining, and reduce progressively along the supply chain through manufacturing and distribution. Incorporating consideration of social equity in analysis of supply chains was shown to require further methodological development involving a "soft system" analysis to complement the "hard system" approaches of VCA and LCA. From the consumption perspective, it is shown that sustainable development requires not only reduction in the environmental intensity of products and services, but also more equitable distribution of economic and social benefits along the supply chain. "Sustainable Consumption and Production: Quality, Luxury and Supply Chain Equity" shows that the pressures of social and environmental responsibility require companies to consider sustainability issues across the full product life cycle, from the conduct of upstream suppliers to the disposition of obsolete products. In this regard, leading companies are shown to be adopting a variety of sustainable business practices that reduce their supply chain footprint while generating increased value for stakeholders. Systems thinking and life cycle management are shown as key elements in achieving measurable improvements in sustainability and profitability. The author shows that the incremental supply chain efficiency improvements are insufficient to slow the increases in carbon emissions and other adverse ecological impacts and collaboration is urged among progressive multinational companies with governments and nongovernmental organizations to enable decoupling of material flows from the economic value creation. "Transforming Supply Chains to Create Sustainable Value for All Stakeholders" presents the need for sustainable value creation by showing that promoting sustainability in business operations requires that products, processes as well as the entire supply chain (the system), is designed and operated by taking account of not only economic benefits, but also environmental and societal implications. The chapter presents that from a supply chain perspective, economic value added (EVA) has long been used as a measure to evaluate supply chain performance. This chapter presents the concept of sustainable value creation and why the scope of conventional supply chain management processes must be broadened to generate sustainable value. This chapter offers a discussion of successful and disastrous case examples.

Overall, the four parts of this proposed book-volume are filled with closely knitted, carefully chosen, and interacting 18 chapters of significant state-of-the-art work. All chapters have been peer-reviewed and revised accordingly. We sincerely thank all reviewers who carefully reviewed the chapters and provided valuable comments for revision. This edited book would add significant values to the readers in the domain of sustainability science and engineering. Researchers in academic and industrial organizations, technical and managerial staff from companies, and staff from governmental organization would benefit from the collection this work, which is aimed at advancing the current state-of-the-art into next level for greater societal benefits.

The authors and co-authors of all chapters deserve credit for their excellent contributions and timely actions on various aspects of the production of this book. We also sincerely thank the two graduate students at the University of Kentucky, Tao Lu and Chris Stovall for their hard work in carefully proofreading all finally updated chapters, and for working with all authors of chapters in completing documentation needed for the publication of this book. We also thank the publishers for their support and help in publishing this book.

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# Contents

Part I Design for Sustainability

## Part II Sustainability Metrics and Analysis

## Part III Sustainable Energy

## Part IV Sustainable Supply/Value Chains

# Part I
# Design for Sustainability

# Life-Cycle Optimization Methods for Enhancing the Sustainability of Design and Policy Decisions

**Gregory A. Keoleian**

**Abstract** A critical question regarding the life-cycle design and management of any product system is, "What is its optimal service life?" The Center for Sustainable Systems at the University of Michigan has developed life-cycle optimization (LCO) methods and models to evaluate optimal service life and asset management decisions from energy, emissions, cost, and policy perspectives. This LCO model is based on a dynamic programming method with inputs derived from life-cycle assessment and life-cycle cost analysis. From an environmental perspective, this is a particularly complex question to resolve for product systems with nonlinear use phase burdens and uncertain technology improvement trajectories. This chapter presents the basic LCO methodology and demonstrates its application to automobiles and household refrigerators. In both cases, there exist multiple tradeoffs between utilizing an existing product model and replacing it with one that is more efficient. The operational efficiency gain from model replacement should exceed the additional resource investments required to produce the new model. LCO simulations indicate that optimal replacement schedules are strongly influenced by technology improvement rates, product deterioration rates, production versus use phase impact ratios, and consumer use patterns. Results from replacement case studies of automobiles, refrigerators, air conditioners, and highway infrastructure will be highlighted and general principles for enhancing sustainability will be presented. Life-cycle optimization is expected to become another important technique to add to the life-cycle modeling toolkit for informing design and policy decisions.

**Keywords** LCA · Service life · Life-cycle cost · Life-cycle optimization

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# 1 Introduction

We retire and replace products for multiple reasons including technical obsolescence, fashion obsolescence, degraded performance or structural fatigue caused by normal wear over repeated use, environmental or chemical degradation, and damage caused by accidents or inappropriate use. A commonly held belief is that extending the service life of a product will always improve overall sustainability performance. By extending the life of the product, the manufacturing environmental burdens and costs of a new product are avoided or delayed and the impacts associated with product retirement can also be displaced. In simple terms, longer-lived products save resources and generate less waste, because fewer units are needed to provide that same length of service. This product life extension principle or strategy has been advocated by many environmentalists and is also reported in the academic literature. For example, several designs for environment or design for sustainability frameworks have included product life extension as a key strategy for reducing impacts (Stahel 1986; Keoleian and Menerey 1993, 1994; Anastas and Zimmerman 2003). Product life extension can be achieved through a variety of product design approaches such as enhanced durability, adaptability, reliability, remanufacturing, and reuse.

This principle is generally accurate for products that do not create impacts during the use phase. For example, manually operated garden tools such as a spade or rake should be designed for maximum service life and repair mechanisms such as replacing a handle will generally lead to lower impacts than complete product replacement. Optimal replacement policies for more complex energy-consuming products such as automobiles, appliances, electronics, buildings and infrastructure, and other systems that may also undergo rapid technological innovation require much more sophisticated analysis.

The need to rapidly transform our product systems for achieving sustainable development is well understood. The transition from old less sustainable to new more sustainable systems is critical for reducing material and energy consumption, greenhouse gas emissions, water consumption, and ecological and human health impacts. Dramatic improvements in use phase performance can outweigh impacts associated with manufacturing new products for replacement. The key parameter is the rate of improvement; otherwise without improvement life extension is a more effective strategy.

The life-cycle optimization (LCO) method was developed at the Center for Sustainable Systems through an NSF Technology for Sustainable Environment grant. This interdisciplinary research project combined expertise in industrial ecology with industrial and operations engineering. The idea for the research was initiated when I and a colleague (Jonathan Bulkley) asked the simple question to a new doctoral student (Hyung Chul Kim), “When should we retire our older automobiles?” The simple question, however, required an in-depth and complex treatment of the problem. The LCO method, which will be summarized in this chapter, was initially published (Kim et al. 2003). In addition to automobile replacement policy, this method has been applied to refrigerators (Horie 2004; Kim et al. 2006), clothes washers (Bole 2006), and most recently household air conditioners (De Kleine et al. 2010a, b).

The purpose of this chapter is to present the LCO methodology for guiding product design and replacement policy; demonstrate the LCO method with applications to automobiles and refrigerators; and conclude with some observations and recommendations about replacement policy. A brief overview of the relevant literature will be presented in the Background (Sect. 2) and the Objectives will be outlined in Sect. 3. A description of the LCO method and basic model equations is provided in the Methods and Applications (Sect. 4). The results from the application of the LCO method to automobiles and refrigerators are presented in Sect. 5. Based on these two case studies and LCO research of other systems, this chapter concludes with key findings and principles for guiding design and policy in Sect. 6.

## 2 Background

Life-cycle assessment (LCA) is the analytical tool for evaluating environmental sustainability performance of a product system (ISO 1998; Keoleian and Spitzley 2006). This assessment provides a comprehensive profile of the environmental burdens and impacts across materials production, manufacture, use, and retirement stages of a product system. Life-cycle cost analysis is a similar tool for measuring purchase, use and service, and disposition costs. These tools, however, are insufficient by themselves in examining issues of optimal service life or the timing for product repair, retirement, and replacement.

The literature for optimal product management decisions from an economic perspective is very well established in the industrial engineering and operations research literature. The treatment of optimal replacement policy and decisions from an environmental sustainability perspective has only been considered more recently. While retirement decisions are most often guided by economic considerations, the optimal product service life also poses a complex resource and environmental management problem. The basic tradeoff between keeping an existing product and replacing it with a new one to improve environmental performance is illustrated in Fig. 1 for an automobile. The older vehicle is shown on the left and is referred to as the *defender* in industrial engineering vernacular, and the *challenger* represents newer model vehicles. The initial capital and resource investment has been made for the existing vehicle but it is inefficient and more polluting than a newer model. Although the newer model is more efficient, the production of the new vehicle creates burdens and impacts.

In addition to the research of the Center for Sustainable Systems at the University of Michigan that will be highlighted in this chapter, a few other relevant research studies will be described briefly. The integration of optimization techniques in LCA was first applied by Azapagic and Clift (1999). They developed a life-cycle-based multi-objective optimization method for environmental management of a product system.

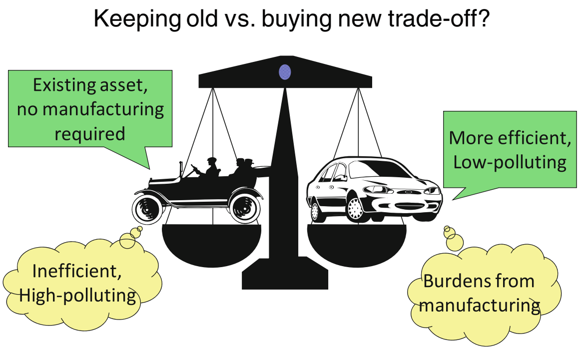

**Fig. 1** Environmental tradeoff between an existing vehicle and a newer model

This technique was used to select an optimal set combination of chemical manufacturing processes with respect to multiple environmental and cost objectives. In this case study, the use and disposal phases of the products were not considered and therefore it can be classified as a “cradle-to-gate” study. While it did not address product replacement decisions, it likely represents the first application of optimization methods with LCA.

There are also several studies that have explored remanufacturing strategies using LCA. For example, Kerr and Ryan (2001) have studied remanufacturing of copier machines and Smith and Keoleian (2003) investigated remanufactured automobile engines. They compared remanufacturing strategies with new product replacement alternatives. These studies, however, did not utilize optimization methods.

Finally, Kagawa et al. (2006) investigated the environmental and economic consequences of product lifetime extension. They conducted an empirical analysis of automobile life extension. Although this was not an optimal replacement study, this macroeconomic analysis provided interesting findings regarding the impact of car lifetime extension on the environment and the domestic economy.

## 3 Objectives

The objectives of this chapter are to present the LCO method and demonstrate its application for guiding product replacement policy of two product systems, automobiles and household refrigerators.

These two different systems are analyzed and the results are contrasted. Both examine the optimal replacement policy over the 1985–2020 time horizon; one for an average mid-sized car and the other for a typical household refrigerator in the US. It is important to note that these studies were originally published in 2003 and 2004, respectively.

The replacement policies were developed based on different objectives (i.e., objective functions). The replacement schedules for the automobiles minimized

$CO_2$, $NO_x$, NMHC (non-methane hydrocarbons), CO, energy, and cost. For refrigerators, the replacement policies for optimizing energy, greenhouse gas emissions, and cost were investigated.

# 4 Life-Cycle Optimization Method and Applications

## *4.1 LCO Method*

The LCO model is constructed using a dynamic programming method. Dynamic programming is a mathematical tool used to find an optimal sequential decision (or optimal path) that best satisfies a decision maker's objective such as economic cost. The optimal path of decisions minimizes the cumulative life-cycle inventories (LCIs) (or costs) incurred from producing (or purchasing), using, and disposing of a series of product model years.

Figure 2 is a schematic example of the LCO model applied to product replacement. The *y*-axis depicts the cumulative environmental burden of a criterion (e.g., CO, NMHC, $NO_x$, $CO_2$, or energy consumption), while the *x*-axis represents time. The initial product is assumed to be produced at time 0, and a new model product with a different environmental profile is introduced at time $T_a$ and $T_b$. Decisions to keep or replace products are made at the points marked by black dots. Materials production and manufacturing environmental burdens are shown as a step function at the time a product is produced. The slope of each line segment represents an energy efficiency or emission factor of a product depending on the criterion to be minimized. The slopes tend to increase with time, indicating possible deterioration in energy efficiency or other burdens. 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

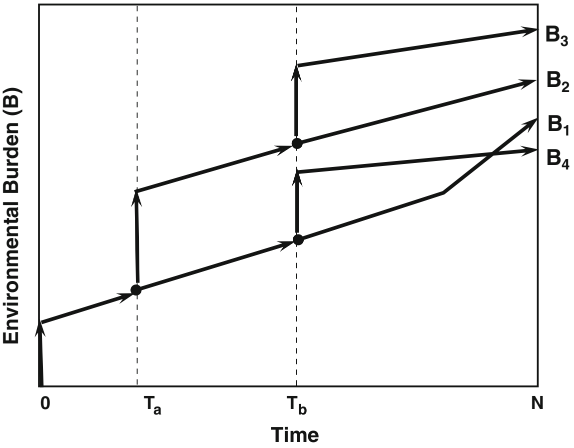

**Fig. 2** Schematic example of the life-cycle optimization (LCO) model based on four policies. $B_1$–$B_4$ represent the final environmental burdens for the four policies

environmental performance of future product models. The decision maker seeks a solution of the form "Buy a new product at the start of year 0 and keep it for $R$ years and retire it; then buy a new product at the start of year $R$ and keep it for $\hat{a}$ years and retire it, etc." As an example, consider four policies depending on the decisions at $T_a$ and $T_b$. It is assumed that retiring a product and buying a new product occurs simultaneously.

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

With this hypothetical example, policy (4) is the optimal policy, and the optimal product lifetimes are $T_b$ and $N - T_b$. However, in a real-world problem with a longer time horizon, the number of possible policy choices is often enormous. If a decision maker seeks an optimal replacement policy during a time horizon $N$ with a new product at the beginning of year 0, and the product replacement decisions are made at the beginning of every year from year 1, the number of possible outcomes is $2^{N-1}$. In addition, the environmental profiles of $N$ different model years need to be considered based on product age. The LCO model provides an efficient algorithm to find an optimal policy, and the dynamic LCIs determine the environmental profiles of each product's model year and age.

In a typical dynamic programming model, a set of system characteristics is defined in the state of the system for each time epoch. Decisions are made at each time epoch throughout the time horizon of optimization. A state is defined by a vector $(i, j)$ that represents model year $i$ and age $j$ of a product. The dynamic LCIs and costs are characterized for each state of the system. The LCO model to find optimal refrigerator lifetimes for environmental criteria is constructed using the following notations and equations:

| | |
|---|---|
| $n$ | First year |
| $N$ | Last year |
| $M$ | Maximum physical life |
| $B_M(i)$ | Environmental burden (hereafter called burden) from the materials production of model year $i$ |
| $B_A(i)$ | Burden of the manufacturing of model year $i$ |
| $B_U(i, j)$ | Burden of the use phase during year $j$ of model year $i$ |

| | |
|---|---|
| $B_E(i, j)$ | Burden of the end-of-life stage of model year $i$ retired at the end of year $j$ |
| $u(i, j)$ | Cumulative burden of purchasing (producing) a new product at the start of year $i$ and keeping it for $j$ years. For any model year $i$, $u(i, 0) = 0$ |
| $f(i)$ | Minimum possible burden accumulated from the start of year $i$ through the end of year $N$ given that a purchase is made at the start of year $i$ |
| $x_i$ | Number of years owning product of model year $i$ |

$$u(i,j) = \begin{cases} B_M(i) + B_A(i) + B_E(i, i+j-1) + \sum_{k=1}^{j} B_U(i,j) & \text{if } j > 0 \\ 0 & \text{if } j = 0 \end{cases} \tag{1}$$

$$f(i) = \begin{cases} \min\limits_{x_i \in \{1,2,\ldots,M\}} \{u(i,x_i) + f(i+x_i)\} & \forall\, i = n, \ldots, N \\ 0 & \forall\, i > N \end{cases} \tag{2}$$

For each criterion, this model seeks to minimize the environmental burdens from the life-cycle of model years $n$ to $N$ by deciding $x_i$, the number of years before purchasing a new product. A computer program to find the optimal path of sequential replacement decisions was coded using C language. A similar LCO model was also constructed for the cost criterion considering the life-cycle costs from purchasing, using, and disposing of a product.

## 4.2 LCO Application to Automobiles and Refrigerators

The application of the LCO method requires the construction of an LCO model based on life-cycle profiles for environmental burdens (e.g., energy), impacts (e.g., global warming impacts), and costs as shown in Fig. 3. The life-cycle profiles for each model year option are inputs into the LCO model and the simulation results generate the optimal replacement schedules. The life-cycle energy profiles for the

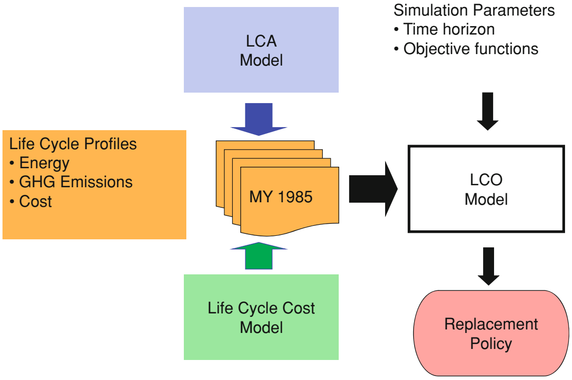

**Fig. 3** Life-cycle optimization model structure and input

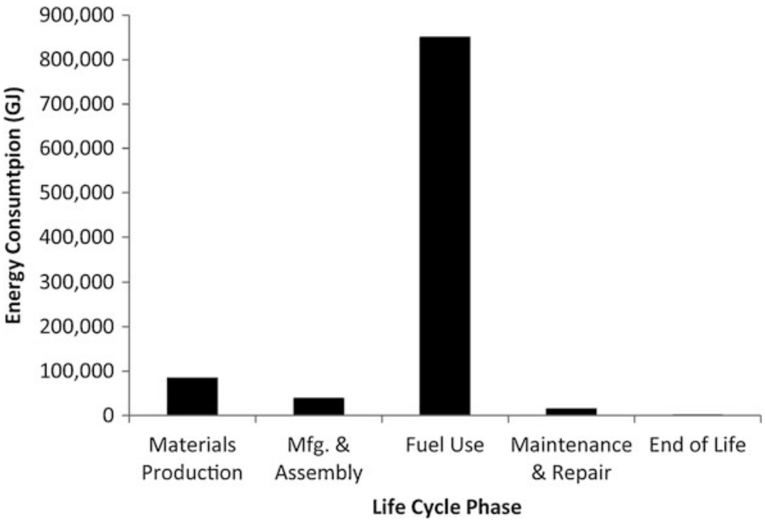

**Fig. 4** Life-cycle energy consumption for a 1995 generic vehicle based on 120,000 miles of driving

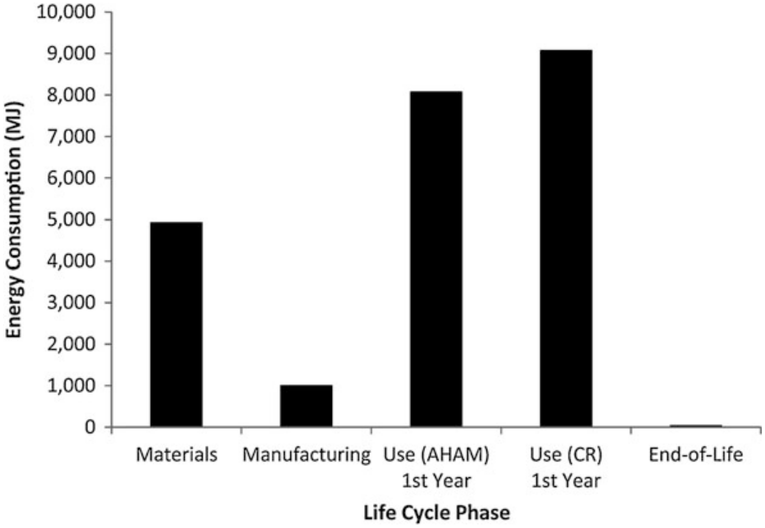

**Fig. 5** Life-cycle energy consumption based on 1-year usage of mid-sized 1997 refrigerator model (*CR* Consumer Reports, *AHAM* Association of Home Appliance Manufacturers survey)

mid-sized automobile and household refrigerator are shown in Figs. 4 and 5, respectively.

The production and use phase burdens for each model year are determined from historical records and projections are made for future improvements. For example, the use phase energy consumption trends and simulation forecasts used for the

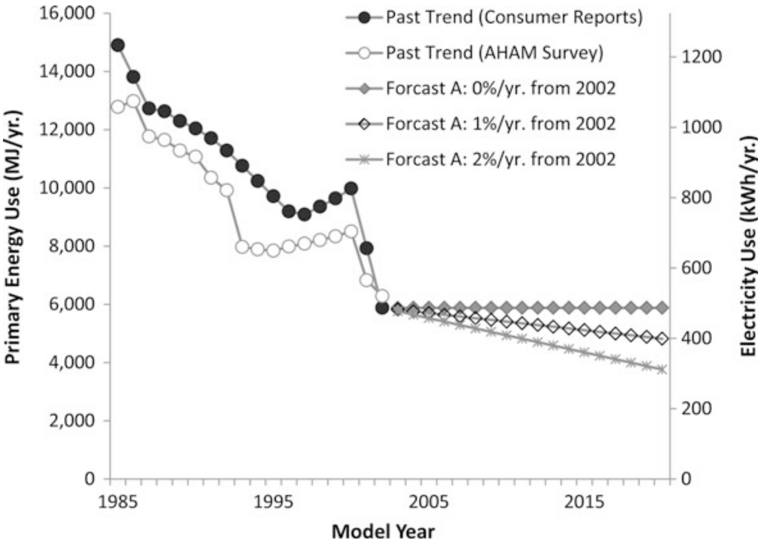

**Fig. 6** Past trends and future forecast scenarios of energy use during the first year of a new refrigerator model. *Forecasts A*, *B*, and *C* assume that the energy consumption for a new model refrigerator would decrease 0 %/year, 1 %/year, and 2 %/year of 2002 model, respectively (AHAM 2003; Consumers Union 2002)

refrigerator LCO study are shown in Fig. 6. A maximum lifetime of 20 years for all refrigerator models was used as a modeling constraint.

For the fuel economies of average new cars between 2000 and 2020, the reference case scenario of US DOE Energy Information Administration Annual Energy Outlook 2001 was selected. According to this source, fuel economies will increase from 27.0 to 32.5 miles per gallon between 1985 and 2020 for an average new car. A maximum physical lifetime of 20 years for all mid-sized passenger car models was assumed as a modeling constraint. A detailed description of model parameters is provided in Kim et al. (2003) for the LCO automobile study and Kim et al. (2006) for the LCO refrigerator study.

## 5 Results and Analysis

### *5.1 Automobiles*

The LCO model was applied to US mid-sized cars to evaluate the optimal lifetime and recommend future policies. The simulations were conducted to minimize energy consumption, $CO_2$, CO, $NO_x$, NMHC, and cost. The model years for the simulations are set between 1985 and 2020 and the maximum physical life of a vehicle (*M*) is assumed 20 years.

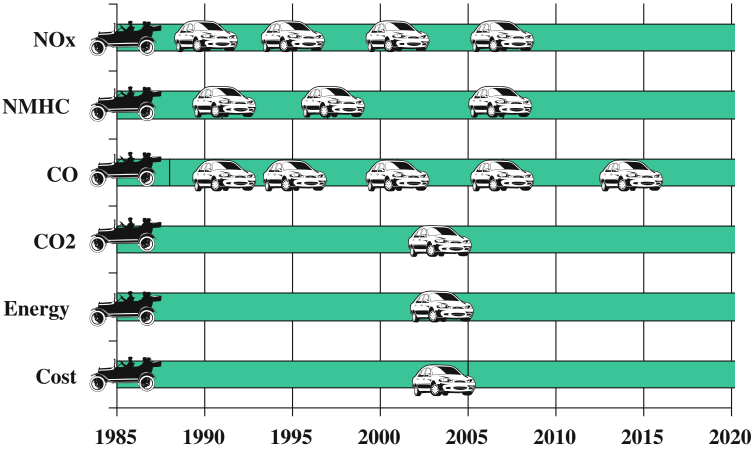

**Fig. 7** Optimal vehicle replacement lifetimes for minimizing life-cycle NOx, NMHC, CO, $CO_2$ and cost objectives over the 1985–2020 time horizon

Figure 7 presents the simulation results for each objective. The timing of each vehicle replacement is indicated by a vehicle icon. The optimal set of lifetimes for the $CO_2$ objective, for example, can be interpreted as "keep the model year 1985 car for 18 years and retire it at the end of 2002, then buy a model year 2003 and keep it for another 18 years until 2020 in order to minimize $CO_2$ emission when driving a vehicle 12,000 miles per year." The energy and cost optimum policy are also similar (18, 18 replacements), The reason for the long optimal service life is that the savings from improvements in new model fuel economy are very small compared to energy, cost, and $CO_2$ emissions from production of the new model vehicles. The identical results for the energy and $CO_2$ objectives can be attributed to the fossil fuel combustion, which accounts for the majority of both energy consumption and $CO_2$ emission during a vehicle life.

In contrast to the energy, $CO_2$, and cost objectives, the replacement policy for the regulated pollutants occurs at much more frequent intervals due to dramatic reductions in vehicle tailpipe emissions over time. These rates of improvement are the dominant factor in influencing replacement policies: the $NO_x$ optimum policy (5, 5, 6, 6, 14), the CO optimum policy (3, 3, 4, 6, 6, 7, 7), and the NMHC optimum policy (6, 6, 10, 14).

The optimal vehicle life generally decreases with increasing annual VMT. This result can be explained by the growing dominance of vehicle use phase emissions and energy consumption as well as a higher deterioration rate from increasing annual VMT. In other words, as the VMT increases, driving a new, lower-emitting, and efficient vehicle becomes more important while the additional emissions from retiring an old vehicle and producing the new vehicle become relatively insignificant.

## 5.2 Refrigerators

The optimal lifetime of refrigerator model years between 1985 and 2020 is determined for the objectives of energy, cost, and global warming impact (GWI) on the basis of the dynamic LCI datasets assuming a 20-year maximum physical lifetime. Figure 8 shows the optimal lifetimes as well as the cumulative LCIs and costs from the model runs assuming that a consumer purchases a new refrigerator at the beginning of 1985. The optimal set of lifetimes for the energy optimization policy based on the data from Consumer Reports can read, for example, "keep the model year 1985 refrigerator for 2 years and replace it with a model year 1987, keep the model year 1987 for 5 years and replace it with a model year 1992,…, and keep the model year 2014 refrigerator for 6 years, in order to minimize the cumulative energy usage over the time horizon between 1985 and 2020." As can be seen, optimal refrigerator lifetimes for energy and GWI objectives are significantly shorter than those for cost objective and the real-world average. The similar results for the energy and GWI objectives may be associated with the fact that the $CO_2$ emissions associated with electricity generation and refrigerator production are the most dominant global warming gases. However, from a consumer's perspective, such frequent replacements would be impractical considering the 36–50 % additional cost to the cost optimal policy (lifetime of 18 years). On the other hand, the cost optimal policies incur 22–24 % additional energy consumption compared to the energy optimal policies.

The efficiency improvement forecasts for future model years can affect the optimal lifetimes of future models for the energy objective. The benefits of replacing old models with new models grew in parallel with improving efficiencies

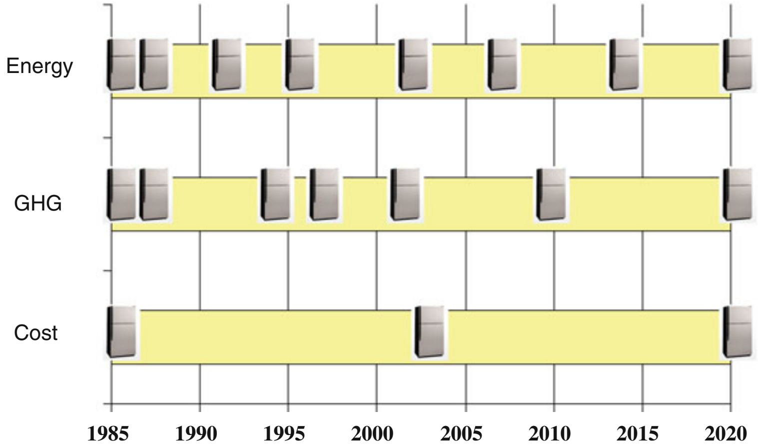

**Fig. 8** Optimal refrigerator replacement lifetimes for minimizing life-cycle energy, global warming impact (GSI) based on greenhouse gas emissions (GHG), and cost objectives over the 1985–2020 time horizon

over model years. However, optimal lifetimes for the cost objective were unresponsive to the efficiency improvement scenarios probably because the efficiency changes have a relatively small impact on the life-cycle costs. Deterioration was also an important factor that influenced optimal lifetimes. The benefits of frequent replacement of refrigerators also grew with rapid deterioration of efficiencies as refrigerators aged.

Optimal lifetimes are affected by efficiency scenarios and assumptions, along with life-cycle environmental and cost profiles. Nonetheless, the overall trends—short optimal lifetimes for energy and GWI objectives and long optimal lifetimes for the cost objective.

The LCO simulation was also run from the perspective of a current owner in 2004. The results indicated that replacing an existing mid-1990s or previous model (with over 1,000 kWh annual energy use) at the beginning of 2004 is beneficial from both cost and energy perspectives. Strictly from an energy perspective, the customer would replace any refrigerators older than 2001 but this is clearly not cost effective.

## 6 Conclusions

The LCO model can provide useful information to consumers, designers, manufactures, and policy makers for improving the sustainability performance of product systems for meeting societal needs. This model indicates the optimal replacement schedules for products with respect to specific environmental objectives. The LCO model described in this chapter was applied to two different product systems yielding very different optimal replacement schedules.

The optimal replacement schedule results for both product systems indicate that the replacement frequency depends on several key factors including: the specific objectives, the rate of future technology improvements, the impact distribution between production (fixed) and use (marginal) activities, consumer use patterns, and deterioration in product performance over time (e.g., vehicle emissions).

Although the use phase is the most dominant source of environmental burdens for both automobiles and refrigerators, the characteristics of energy efficiency improvement and deterioration are quite different. Until recently, the fuel economy standards for automobiles had remained nearly unchanged since the mid-1980s and fuel economy deterioration with vehicle age is known to be negligible. In the case of refrigerators, on the other hand, major efficiency improvements were achieved in the last decade, primarily due to the series of federal energy efficiency standards for appliances enacted in 1990, 1993, and 2001. Also, deterioration is likely to be a significant factor for increasing electricity consumption. Therefore, the optimal lifetimes for the energy objective were considerably shorter in the case of refrigerators (2–7 years for the baseline scenario) than in the case of automobiles (18 years) if optimized over model years between 1985 and 2020.

The design life and durability of a product would ideally be related to the rate of efficiency improvement. Products based on rapidly changing technology may not be proper candidates for enhanced design durability. If a simple product will soon be obsolete, making it more durable could be counterproductive. In complicated products subject to rapid change, adaptability is usually a better strategy. For example, modular construction allows easy upgrading of fast changing components without replacing the entire product. In such cases, useful life is expected to be short for certain components, so they should also not be designed for extreme durability.

In addition to temporal considerations, product replacement policy can also be influenced by geographical location. A recent study of household central air conditioners indicates how optimal replacement schedules are influenced spatially by climate zones and how regional standards can be effective in achieving greater environmental and economic benefits than national standards (De Kleine et al. 2010a, b).

Life-cycle optimization provides a decision-making tool for managing not only consumer products, but large-scale systems such as buildings and infrastructure. For example, the LCO model has also been applied to infrastructure systems that require large capital investments with maintenance costs and have long service lives. Road pavement poses significant modeling challenges given the interactions between pavement and vehicle systems. Models are required to simulate congestion related to road construction events, road deterioration behavior, road roughness effects on fuel economy, and vehicle technology improvements. Here optimization is used to determine asset management decisions including budget allocation decisions, pavement material selection, and the timing and frequency of rehabilitation events. The LCO method was recently applied to alternative road pavement overlay systems (Zhang 2009; Zhang et al. 2010a, b).

Developing LCO models can be valuable in informing the key decision makers responsible for these transformations including consumers, manufacturers, the service industry, and government agencies that set standards and create incentives. There is tremendous opportunity to accelerate the replacement or renovation of the existing stock of products such as automobiles and consumer appliances to enhance environmental sustainability performance. The case studies conducted by the Center for Sustainable Systems have shown how LCO can become an important sustainability tool for guiding product design and policy decisions in the future.

This author wishes to finally conclude by acknowledging funding from the National Science Foundation under the 1999 Technology for Sustainable Environment (TSE) Program Grant BES-9985625 and the many contributions of students and colleagues including Hyung Chul Kim, Darby Grande, Han Zhang, Robb De Kleine, Yuhta Horie, Richard Bole, James Bean, Jonathan Bulkley, Michael Lepech, Marc Ross, and Helaine Hunscher.

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# Second Thoughts on Preferred End-of-Life Treatment Strategies for Consumer Products

**Joost R. Duflou, Joris Van Ostaeyen and Wim Dewulf**

**Abstract** Traditionally, eco-design has been steered by an implicit hierarchy of preferences with respect to the end-of-life options for products of which the total life cycle impact is to be minimised. In this context, life time extension is typically preferred over disassembly for reuse of components, which in its turn is preferred over material recycling. However, this priority hierarchy is often too simplistic to accept it as a general applicable guideline: both ecological and economic considerations can make life time extension and/or the reuse of components non-favourable strategies in cases where product performance and resource efficiency may evolve rapidly as a result of continuous innovation. Furthermore, where ecological indicators might confirm the suitability of a life time extension strategy at component level, economic constraints often make such scenarios infeasible. De facto today few disassembly activities prove to be economically viable. However, the emergence of new technologies and business models could indicate a reversal of the trend to abandon the higher priority end-of-life treatment methods for manufactured goods. Based on extensive, case study driven research, successful business models were revealed that improve the economic viability of systematic product reuse, refurbishment or disassembly in function of component reuse. Where material recycling proves to be the only realistic scenario, newly emerging self-disassembly techniques could help to improve the feasibility of pure material fraction separation before shredding is applied.

**Keywords** End-of-life treatment · Eco-design · Life time extension · Reuse · Self-disassembly · Product-service systems

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## 1 Introduction: Traditional End-of-Life Priority Hierarchy

Reaching a convenient level of comfort [higher levels of the Maslow pyramid (Maslow 1943)] unavoidably requires adjustments to our natural environment. These changes are typically implemented through the application of a range of products and systems, the manufacture and use of which results in environmental impact. Impact avoidance by eliminating the need for such products is in many cases technically not feasible without reducing the comfort levels offered. Traditionally the approach advocated for impact minimisation has therefore been to aim at the conservation of the integrity of products in their end-of-life (EOL) stages, thus spreading the impact of production and EOL treatment over a maximised functional life span. In times when landfill problems were becoming more and more visible, the target of waste avoidance indeed seemed an obvious priority. To maximise the functional life time of products and systems seems a logical solution to support or further this approach. When wear and tear or functional requirement shifts finally result in the decision to discard products, the same logic can be repeated at component level. In a dogmatic vision reuse of subsystems is typically only considered a suitable EOL destination for product components when the product integrity cannot be preserved. Where final discarding of products and components seems unavoidable, closed loop recycling comes into the picture. Here the major concern is to assure sufficient material purity in order to allow reuse of materials without significant quality deterioration. The recent Cradle to Cradle hype (McDonough and Braungart 2002) is merely an extension of this strategy to biosphere recycling of renewable material categories. The preference list can be extended up to the ultimate lowest priority level of discarding in landfills. Such priority ranking approaches have been formalised in a series of publications and have also affected governmental policies in a number of countries. In the Netherlands, for example, the so-called Ladder of Lansink (Fig. 1) was introduced as a policy instrument in a parliamentary debate in 1980 (Lansink 1980 and OECD 1982).

The maturity that life cycle assessment quantification techniques have reached today allows verification of the correctness of the assumed impact minimisation strategies underlying such EOL treatment priority hierarchies. In Sect. 2 the analysis results for a number of specific doubt cases are reported. Besides

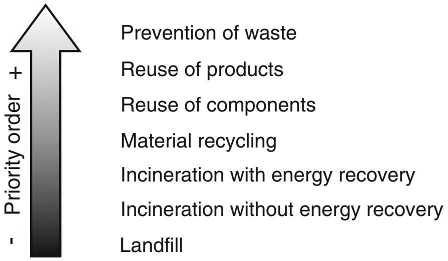


**Fig. 1** Lansink's ladder: ecological hierarchy of end-of-life options (Lansink 1980)

ecological considerations, also economic constraints can form counter indications for respecting the hierarchy ranking in EOL treatment methods. Section 3 illustrates how the economic feasibility of systematic disassembly is affected by the business model context. The productivity improvements required to achieve a breakeven level in comparison with low level recycling are discussed. Where the efficiency of disassembly proves to form a major obstacle for reuse and/or high level recycling strategies, innovative joining techniques may provide a way out. Section 4 summarises recent developments in this respect.

## 2 Extended Use: Not a Good Idea After All?

Two important reasons can be quoted casting doubt on the general applicability of an extended use period as an impact reducing measure. On the one hand, many products are characterised by a gradually declining technical performance: besides increasing spare part or consumable consumption, raising energy fluxes often give away such deterioration patterns. On the other hand, product innovation often leads to improved performance and/or an increase in efficiency in new product generations. In consequence the same functionality can often be provided at lower energy costs and reduced emissions. Extending the life time of older products implies a choice to accept a higher impact per functional unit than strictly required according to the state-of-the-art. Of course the manufacturing and EOL treatment impact need to be taken into account when determining an optimal life time for product replacement. Such exercises were conducted for a number of common household appliances and have been reported in earlier publications by the authors (Dewulf and Duflou 2004; Duflou et al. 2006; Devoldere et al. 2009; Dewulf et al. 2005). For the case of washing machines, for example, the deterioration of motor energy consumption, of transmission belt and pulley efficiency reduction and increasing energy consumption due to lime deposition on heating elements have to be taken into account (Devoldere et al. 2009).

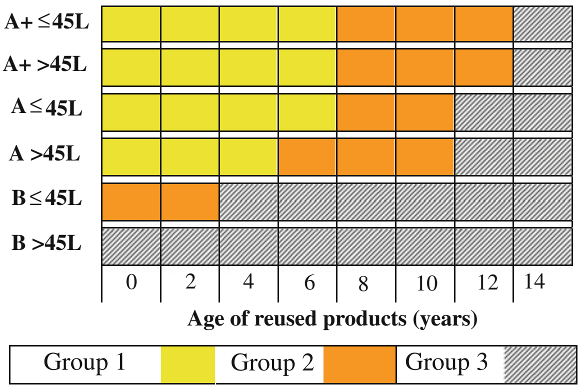
For a functional design life time of 15 years and for an average intensity of use, depending on age, energy class and water consumption, second hand washing machines can be classified into three groups, as summarised in Fig. 2:

- Group 1: Reuse is both environmentally and economically beneficial compared to the purchase of a new washing machine.
- Group 2: Reuse is either environmentally or economically beneficial compared to the purchase of a new washing machine.
- Group 3: Reuse is neither environmentally nor economically beneficial.

The economic evaluation was based on a total cost of ownership comparison with the purchase of an average state-of-the-art new type of device.

It is obvious that but for the most recent models, characterised by a high energy efficiency (A+ and A labels), both economic and environmental concerns should lead to a decision not to extend the life time of the washing machine. Even for A+

**Fig. 2** Graphical representation of critical reuse boundaries in function of energy label classification and water consumption level per use cycle for washing machines (Devoldere et al. 2009)



and A type devices, the maximum life time for products to be considered for reuse is limited to 6 years before either economic or environmental considerations start to provide counter indications.

Similar analysis results can be obtained for other product types characterised by active energy consumption, such as e.g. refrigerators (Fig 3).

It is obvious that the outcome of an optimal life time analysis depends on the deterioration rates for existing products and the efficiency improvements to be expected for new generations. Although such values can be obtained as extrapolations from historical observations, a significant degree of uncertainty remains that can substantially affect the optimal life time predictions. Figure 4 illustrates this sensitivity for the example or the automotive sector (Dewulf and Duflou 2004).

In conclusion it can be stated that, for products characterised by an active consumption pattern (energy and/or consumables), life time extension is often not recommendable from an ecological and/or economic perspective.

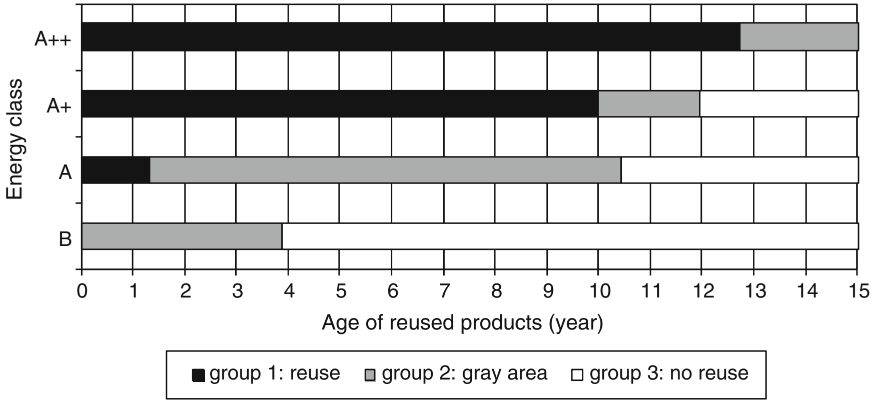


**Fig. 3** Analysis outcome for different categories of refrigerators based on combined environmental impact and life cycle costing criteria (Dewulf et al. 2005)

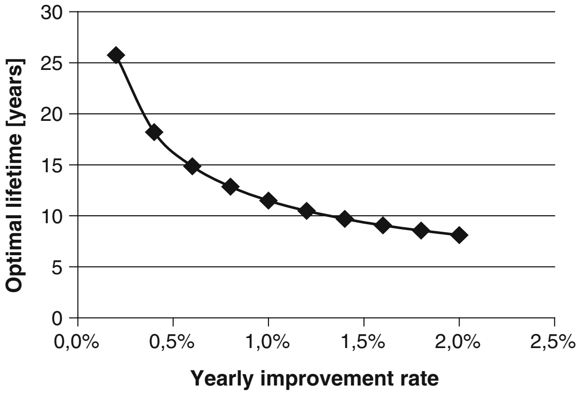


**Fig. 4** Sensitivity of the optimal lifetime to the yearly fuel efficiency improvement rate of new cars (Dewulf and Duflou 2004)

## 3 Component Reuse: Design for Disassembly or for Recycling

By reusing components, much of the efforts (energy, material and labour) that were initially invested in shaping a product can be salvaged. Unless a more efficient product of a newer generation exists, the ecological rationale of remanufacturing—the process of restoring discarded products to useful life (Lund 1996)—seems clear. And even if newer, more efficient versions exist, a modular product design could accomplish that parts or components of a product can be reused over different product generations, without compromising the efficiency. The same argument developed in the previous paragraph can be valid on the component level though: reuse of components that have a profound impact on the materials and energy consumption of a product is often not an environmentally sound EOL strategy. For other components, a higher ecological priority of part or component reuse through remanufacturing in comparison with recycling, incineration or dumping in landfills seems justified.

Less obvious is the economic feasibility of remanufacturing. Historically, most manufacturers have ignored the EOL management of their products altogether (Thierry et al. 1995). The remanufacturing industry in the US alone is referred to as a 'hidden giant' (Lund 1996) with an annual turnover of over $53 billion (Hauser and Lund 2003). But only a small portion of products brought on the market today will be remanufactured in the future (Giutini and Gaudette 2003).

Design for Remanufacturing has not received as much attention in the literature as Design for Recycling (Ishii 1998). Only for a limited amount of products particular consideration is given to remanufacturability during product design. In a traditional business model, where ownership is transferred to the customer at the moment of sale and society bears the costs and environmental impact of product disposal, there are no economic incentives for manufacturers to Design for Remanufacturing. On the contrary, if the key profit driver of a manufacturer is the sales of new products, there is even a disincentive to develop products that are intrinsically easy to be remanufactured, as these could jeopardise future income.

But two recent trends could trigger a higher proliferation of Design for Remanufacturing: legislation on Extended Producer Responsibility (EPR) on the one hand and the adoption of new business models by the industry on the other hand.

Over the last years, new legislation has enforced the responsibility for taking back and recycling certain products on the producer. For example, the European WEEE directive (2002/96/EC)—implemented in 2004—imposes responsibility of waste management of electronic and electrical components on the manufacturer[1] of such equipment (European Parliament and Council 2003). One of the intentions of the directive was to promote the reuse of components, but in reality the implementation has only been partially successful and the intended incentive mechanisms to consider EOL during product design are—at least at the moment—not effective (Sander et al. 2004). The EPR legislation has led to the establishment of consortia, the producer responsibility organisations (PROs), who manage the collection and processing of discarded products and charge their member companies certain fees for the EOL management of their products. Designing products with reman. in mind is mostly not rewarded by lower fees, as there are no mechanisms to charge the real cost of EOL management to the suppliers (Lifset and Lindhqvist 2008). A recast of the EU directive has been published in 2012 (European Parliament and Council 2012). It remains unclear whether the altered legislation will put into place an effective incentive mechanism that enables producers to design for reman. But evidently altered legislation could force manufacturers to be more concerned of reman during product design.

Another trend that might enhance the reman of products is the shift that many manufacturers are experiencing towards alternative business models, so-called ‘Product-Service Systems’ (PSS), in which companies are selling the use or functionality of their products instead of selling the products themselves. Under a PSS business model, ownership of the product and EOL responsibility often stay with the producer or a closely related business entity. Instead of focusing on the production cost, under these circumstances the supplier is inclined to minimise the Total Cost of Ownership of his products, including the costs of EOL treatment (Mont 2002). Suppliers are more likely to consider the remaining value in products at the end of their life time and the ever-increasing cost for waste disposal resulting from stricter environmental legislation. Therefore, the economic viability of remanufacturing will be positively influenced in a PSS scenario.

This observation was confirmed in a recent analysis of factors influencing the economic feasibility of disassembly activities (Duflou et al. 2008). Based on 17 case studies collected worldwide, a set of case features were subjected to a data mining analysis.

Outcome of a principal component analysis (PCA) exercise was, among others, the observation of a significant correlation between extended product ownership and systematic EOL disassembly, as well as a clear link between extended product

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[1] Or importer/retailer.

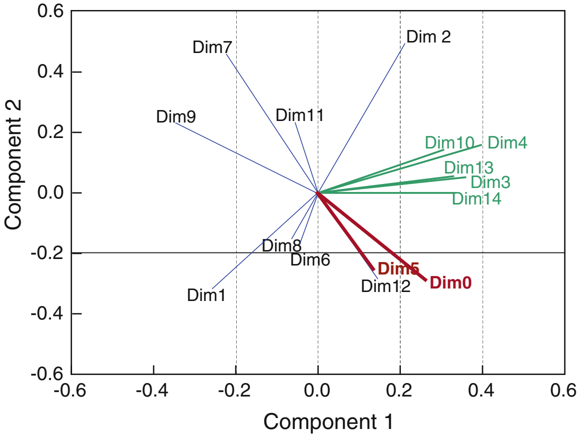

**Fig. 5** Principal Component Analysis representation identifying correlations between characteristics of EOL disassembly activities for a series of worldwide case studies (Duflou et al. 2008)

responsibility and profitability of disassembly activities. Figure 5 illustrates the correlation between ‘Profitability of EOL disassembly activities’ (Dim0) and ‘Product ownership by the EOL treatment company’ (Dim5, defined as the degree to which the disassembly operator is linked to the product[2]) in a PCA reduced vector space representation (Duflou et al. 2008). Furthermore, the PCA study reveals a clear link between ‘Involvement of the original manufacturer in the EOL treatment activity’ (Dim4), the ‘Degree of automation’ (Dim10) and the ‘Long-term planning of the involved companies’ (Dim14).

There are some industrial examples where the adoption of a PSS business model goes hand in hand with (design for) remanufacturing. The photocopier, large-scale plotter and printer industry is characterised by a shift from traditional product sales towards leasing oriented business models. For example, Xerox Corporation has extensive remanufacturing programmes for photocopiers and print and toner cartridges since the end of the 1980s and reported in 2001 savings of about $250 million per year from remanufacturing operations (Kerr and Ryan 2001; Azar 2001). Sundin presents some Swedish examples such as Toyota Material Handling Group (TMHG), a manufacturer of forklifts, and Swepac, a manufacturer of soil compactors (Sundin 2007, 2009). These companies have both implemented a combination of a PSS business model (rental contracts) and the establishment of remanufacturing operations.

Thus, although remanufacturing is most often environmentally preferable over discarding of products or components, there are at the moment few economic incentives for a manufacturer to invest in ‘design for remanufacturing’. But two factors could lead to a proliferation of remanufacturing: stricter legislation on Extended Producer Responsibility and the adoption of PSS business models by the industry.

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[2] A minimal score corresponds to responsibility for EOL processing only, while the maximum score is allocated for operators owning the product during the use phase.

## 4 Material Recycling

In contrast with component reuse, where the residual value of the disassembly output may still be substantial, recycling oriented EOL scenarios provide a limited economic return. Product categories containing large fractions of precious materials, such as copper windings in heavy duty electro-motors or transformers, form exceptions. Material recycling is therefore conducted under severe economic constraints which typically do not allow to include pure material fraction separation through selective disassembly as a process step. An EOL product and materials flow analysis was conducted for the Belgian context with economic benefits as the only decision criterion to determine the preferred EOL scenarios for the market players represented in this model (Willems et al. 2004). For WEEE products the results are summarised in Fig. 6, clearly illustrating that, compared to semi-manual disassembly procedures as used today, a cost reduction of at least 65 % is required to make full disassembly the preferred scenario for the most promising product categories.

Such an efficiency gain can typically not be achieved through automation or investments in flexible disassembly toolkits (Duflou et al. 2008). The ecologically preferred scenario of pure material recycling (cradle to cradle) therefore seems not compatible with economic drivers.

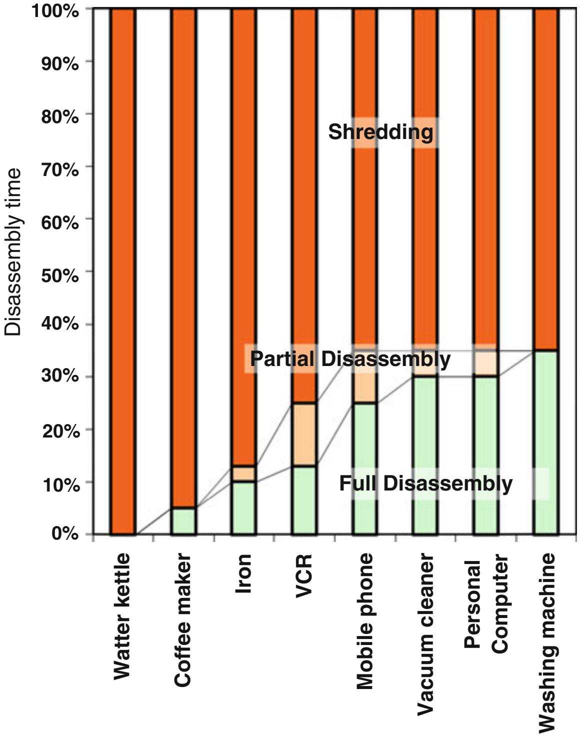

**Fig. 6** Dominant end-of-life treatment scenarios for different categories of consumer products as a function of required disassembly time (100 % corresponds to manual disassembly by an experienced operator) (Willems et al. 2006)

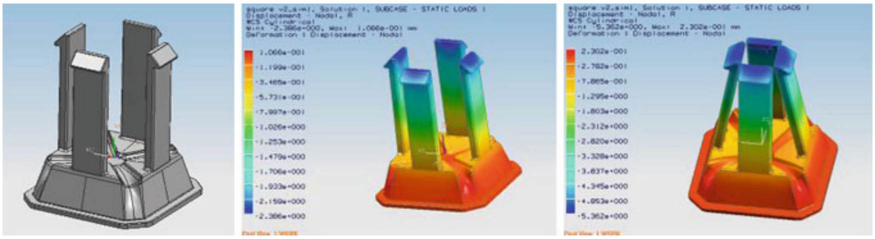

**Fig. 7** Optimised design and finite element simulation of the deformation of the pressure triggered EXTRACT fastener at, respectively, 4 bar (*middle*) and 7 bar ambient pressure (*right*) (Dewulf et al. 2009)

However, over the past 15 years a number of efforts have been reported to develop reversible joints that can facilitate systematic disassembly in an EOL stage. Reference (Duflou et al. 2005) contains a summary of early efforts in this direction. The most promising concepts can be described as 'externally triggered active' (EXTRACT) disassembly. Common characteristics of these concepts are the capability to disconnect fasteners by means of an external signal (such as a temperature, a pressure or a electromagnetic field profile, an atmospheric change or a dynamic excitation) that allows to trigger multiple connectors in simultaneously. This facilitates parallel batch processing of larger number of products with minimal operator involvement.

A recent development in this domain by KU Leuven in cooperation with Philips NV is illustrated in Fig. 7, showing a reversible snap fit design that is triggered by a pressure increase of a few bar (Dewulf et al. 2009). The chosen concept does not affect the functional integrity of electronic components and can support reuse as well as efficient separation of parts or components in support of pure material recycling. Industrial-scale testing of this and similar EXTRACT reversible joining solutions is ongoing and can be expected to become visible in commercial products in coming years if matching business models can assure closed loop product life cycle management.

## 5 Conclusions

The arguments developed in the previous sections illustrate that blind respect for dogmatic eco-design guidelines prescribing priorities for EOL treatment is not recommendable. Life time extension of products that consume energy and materials is often not ecologically justifiable, due to technological evolution of newer product generations and performance degradations of older types. As a matter of fact, limiting the functional life time of such products is typically part of strategies to minimise their total environmental impact. Similar arguments can be valid on the component level, inhibiting the reuse of certain parts of products from an environmental point of view.

Economic implications often form a barrier for the implementation of ecologically sound EOL treatment scenarios, illustrated by the historical neglect of most manufacturers for the EOL management of their products.

In the context of tightening legislation, the economic rationale of environmentally justified EOL treatment scenarios could improve though. The authors identify two trends that create new perspectives and opportunities for optimised EOL scenarios. On the one hand new business models (Product-Service Systems) are emerging in which manufacturers assume more responsibility over the life time of their products. On the other hand, the emergence of innovative technologies, such as the EXTRACT disassembly principle, improves the profitability of reuse or material separation techniques. Both scenarios bring component reuse and pure material recycling closer to reality and can significantly contribute to an improved sustainability of our manufacturing and consumption behaviour.

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# A New Methodology for Integration of End-of-Life Option Determination and Disassemblability Analysis

**Feri Afrinaldi, Muhamad Zameri Mat Saman**
**and Awalluddin Mohamad Shaharoun**

**Abstract** Nowadays many countries have developed new legislations which are aimed at greater emphasis to force manufacturers to reuse, recycle, recover, and remanufacture their products at the end of their life. However, an essential process for the recycling and/or reuse/remanufacturing of end-of-life products is product disassembly. This entails large amounts of capital expenditure, and most manufacturers would not like to even consider disassembling and remanufacturing unless capital costs are justified and financial gains assured. To enhance the recycling process, it is necessary to analyze the product from the end-of-life point of view. Without the understanding of end-of-life aspect, the ease of disassembly and recycling of a product can hardly be enhanced. Therefore, there is a strong need for developing a new methodology to evaluate the product disassemblability aspect and to determine its technological and economic impact at the end-of-life. This paper presents a new methodology to fulfill the above needs. It integrates the end-of-life option determination and disassemblability evaluation in one framework. The proposed methodology is divided into five stages: (1) Define the product; (2) Determine the end-of-life option and calculate the end-of-life value; (3) Evaluate the disassemblability and calculate the disassembly cost; (4) Calculate the recycling rate; and (5) Disassembly evaluation report. In order to show the application of the proposed methodology, a case study was conducted. The results of the case study prove that the methodology is able to show how economically efficient is it to disassemble a product and identify the opportunity of a component to be reused and/or recycled/remanufactured.

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**Keywords** Disassembly · Disassemblability · End-of-life · Recycling

# 1 Introduction

Laws in European Union, Japan, USA, and Australia require manufacturers to take back their products at the end of their useful life and recycle them. It is caused by the tremendous growth in the demand for consumer products that have a shortened lifespan compared with other products. At present, approximately 75–80 % of end-of-life vehicles in terms of weight, mostly metallic fractions, both ferrous and non ferrous are being recycled. The remaining 20–25 % in weight, consisting mainly of heterogeneous mix of materials such as resins, rubber, glass, textile, etc., is still being disposed (Toyota Motor Company 2005; The European Parliament and the Council of European Union 2000). In the case of electronic products, US Environmental Protection Agency (EPA), estimates about 40 million computers became obsolete in a year and only 18 % of them are recycled, the rests are still disposed of, primarily in landfills (EPA 2008). However, the number of landfills for disposal of end-of-life products has seen an exponential decrease (Desai 2002).

According to European Parliament and Council of European Union (2000, 2003a, b), requirements for recycling the end-of-life products and their components should be integrated in the design and development of new products. Manufacturers should ensure that products are designed and manufactured in such a way as to allow to quantified targets for reuse, recycle, and recovery to be achieved. Product manufacturers must endeavor to reduce the use of hazardous substances when designing products and increase the use of recycled materials in product manufacture.

Based on Desai (2002), before end-of-life products can be recycled, end-of-life disassembly mechanisms need to be in place. According to Kwak et al. (2009), to enhance the recycling process, it is necessary to analyze the product from the end-of-life point of view, without the understanding of end-of-life aspect, the ease of disassembly and recycling of a product can hardly be enhanced. Results of this analysis process will show how economically efficient it is to disassemble a product and identify the opportunity of a component to be recycled. This paper proposed a new methodology which integrates end-of-life option determination and disassemblability evaluation to assess the design of products for their technical and economic viability at end-of-life.

# 2 Related Study

## *2.1 End-of-Life Concept*

According to the Rose et al. (2000), end-of-life is the point in time when the product no longer satisfies the initial purchaser or first user. When a product reaches its end-of-life, it can be reused, remanufactured, recycled (primary or secondary), incinerated, or dumped in a landfill (Lee et al. 2001).

A bulk of research has been conducted to aid the product designers to select the appropriate end-of-life option of their product. Muller (1999) proposed a methodology to estimate end-of-life cost. The first step in this method is to analyze the end-of-life recycling. According to the author, it should be done by recycling experts. Rose et al. (2000) proposed End-of-Life Design Advisor to guide product developers to specify the appropriate end-of-life option based on the product characteristics. Rose and Stevels (2001) presented End-of-Life Strategy Environmental Impact Model. The environmental considerations are a factor that is considered in this method. A combination with product characteristics and cost analyses will make these methods more beneficial. Lye et al. (2002) designed Environmental Component Design Evaluation. It uses Analytical Hierarchy Process to compare criteria in assessing the environmental impact of a product. One of the criteria is end-of-life value. Lee et al. (2001) proposed a complete guideline for determining a feasible end-of-life option. The guideline was developed based on the material composition of the component. The decision to recycle (primary and secondary), dump to the landfill, or to handle with special means is made based on the material composition. The decision to reuse or remanufacture requires foreknowledge of the component manufacturing process undergone by the component, and its condition at the end-of-life. The decision can only be made by human intervention. For every option taken, the authors also proposed a method to calculate the end-of-life value of the product.

## *2.2 Design for Disassembly*

Desai and Mital (2005) defined disassembly, in the engineering context, as an organized process of taking apart a systematically assembled product (assembly of components). Products may be disassembled to enable maintenance, enhance serviceability, and/or to affect end-of-life objectives such as product reuse, remanufacture, and recycling.

Design for disassembly focuses on design efforts in order to improve the performance of a product with attention given to separation and sorting of waste in an effort to enhance the easiness of disassembly for product maintenance and/or end-of-life treatments (Jovane et al. 1993; Takeuchi and Saitou 2005). Based on the method for disassembly, disassembly process may clearly be split into two categories: destructive disassembly and non-destructive disassembly (Desai and Mital 2005).

Based on Mok et al. (1997), disassemblability is defined as the degree of easiness disassembly. Desai and Mital (2003) stated that use of force, mechanism of disassembly, use of tools, repetition of parts, recognizability of disassembly points, product structure, and use of toxic materials affect disassemblability.

Various methodologies have been developed to evaluate disassemblability of a product.

McGlothlin and Kroll (1995) designed a spread sheet-like chart to measure the ease of disassembly of a product. The authors measured the disassembly difficulties based on accessibility, positioning of tool, amount of force required to perform the disassembly task, time, and special (this is a provision to note special problems encountered that do not fit in any of other categories). Suga et al. (1996) proposed a method to evaluate disassembly evaluation by introducing two parameters, energy for disassembly and entropy for disassembly. Energy for disassembly is energy required to disconnect an interconnection and calculated for mechanical fasteners such as screw (release energy) and snap fit (elastic deformation energy). The concept of entropy for disassembly is based on idea that degree of difficulty of a disassembly depends on how many methods were used to make interconnections, as well as the number of different directions necessary to complete all disassembly operations.

Kroll and Hanft (1998) and Kroll and Carver (1999) presented a method for evaluating ease of disassembly of a product, proposed a catalog of task difficulty scores, and explained the derivation of difficulty scores. The method presented used a spreadsheet-like chart and a catalog of task difficulty scores. The scores are derived from work-measurement analyses of standard disassembly tasks. Yi et al. (2003) proposed a method for evaluating disassembly time. The aim of this method was to obtain an approximate disassembly time for the product to be disassembled by using a formula derived from information on the product's connecting parts without disassembling the product directly. In this method, authors divided disassembly time into preparation time, moving time, disassembly time, and postprocessing time. It is called as the base time. Each base time is influenced by factor time.

Desai and Mital (2005) presented a methodology to design products for disassembly. It would facilitate the end-of-life product disassembly with a view to maximize material usage in the supply chain at a reduced environmental effect. According to this, disassemblability of product is a function of several factors, such as effective tools placement, weight, size, material, and shape of the component being disassembled. The proposed methodology consists of two elements, a scoring system to evaluate the disassemblability and the systematic application of design for disassembly. In order to measure the disassembly time, the authors only focus on the operations which directly affect the disassembly efficiency. Design attributes and design parameters are provided in aiding the designers in selecting the disassembly score. The ergonomic considerations are also involved in developing the score. It is proposed for the high volume disassembly operations.

## 3 Proposed Methodology

The proposed methodology can be derived into five phases as shown in Fig. 1.

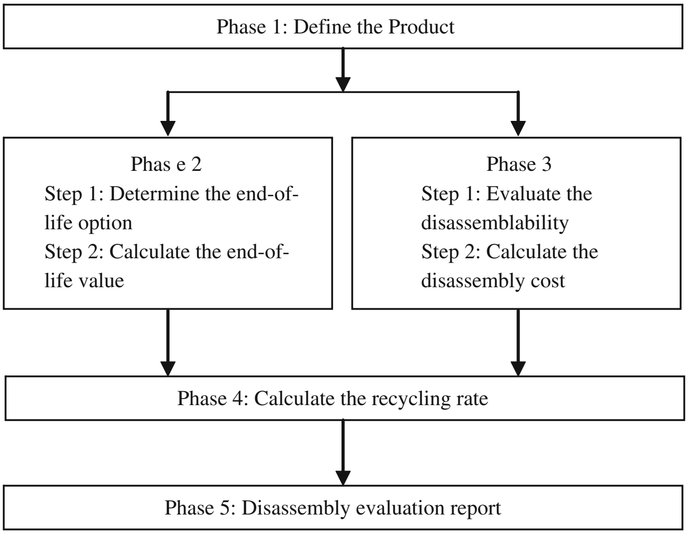


**Fig. 1** Proposed methodology

## *3.1 Phase 1 Define the Product*

Define the product means obtaining the type and quantity of fasteners among product's component, mass of subassemblies or components, materials used in subassemblies, and product's component and disassembly tasks required to take apart the components from subassemblies or product.

Connection information provides information about the construction of product and has a great significance in the application of materials not compatible with one another for recycling (Brouwers and Stevels 1995; BMW Group 2002). Material information is needed to calculate the costs or revenues of material for upgrading or for disposal. Mass of the product's parts is needed to calculate end-of-life processing costs and to calculate the revenues or costs of materials for upgrading or for disposal.

## *3.2 Phase 2 Determine the End-of-Life Option and Calculate the End-of-Life Value*

There are two steps involved in phase two, the end-of-life option determination and the end-of-life value calculation.

### 3.2.1 Step 1 Determine the End-of-Life Option

The most appropriate end-of-life option often depends on the nature of components in the product (Lee et al. 2001). In this work, the choosing of end-of-life options is based on the quality of end-of-life components and their material composition. The quality of components will be used to determine that the components will be reused or remanufactured, if the components are not appropriate to be reused or remanufactured so their material composition will be used to determine which options are more appropriate, recycled (primary or secondary recycling), incinerated, dumped to landfill, or specially handled (for toxic material). The method proposed in Lee et al. (2001) is adopted. If the component:

1. Is made from metal without any other alloy, primary recycling is recommended. If alloys are present, they alter the mechanical properties of the parent metal, so secondary recycling or landfill is more appropriate.
2. Is polymeric, primary recycling is recommended otherwise consider secondary recycling or incineration to recover its energy content.
3. Is made from ceramic, secondary recycling or landfill is recommended.
4. Is made from an elastomeric or is a composite material, secondary recycling or incineration is recommended, otherwise landfill.
5. Contains toxic or hazardous material, special handling is required.

### 3.2.2 Step 2 Calculate the End-of-Life Value

Because the proposed methodology is addressed to evaluate disassembly operation at the design stage of products so that all costs required in calculating end-of-life value must be forecasted for $t$ period of time, where $t$ is the estimated age of product. After end-of-life value is determined, this value is then converted to the present value amount. It is used to compare end-of-life value with design or redesign cost.

In order to estimate end-of-life cost, linear, logarithmic, exponential and power regression models are used, as shown in Eqs. (1–4) and least–square method is used to estimate $\hat{\beta}_0$ and $\hat{\beta}_1$.

$$\text{Cost} = \hat{\beta}_0 + \hat{\beta}_1\ t \tag{1}$$

$$\text{Cost} = \hat{\beta}_0 + \hat{\beta}_1\ \ln(t) \tag{2}$$

$$\text{Cost} = \hat{\beta}_0\ e^{\hat{\beta}_1\ t} \tag{3}$$

$$\text{Cost} = \hat{\beta}_0\ e^{\hat{\beta}_1\ t} \tag{4}$$

The Present value of each end-of-life cost is calculated by using Eq. (5).

$$PV = C_t \times \frac{1}{(1+d)^t} \tag{5}$$

where

$PV$ Present value

$C_t$ Future cost at the $t$ time period

$d$ Discount rate

$t$ Life of the product (year).

Equations (6–13) are used to calculate end-of-life value of each component Lee et al. 2001. All costs which are required to calculate the end-of-life value are in the present value amount.

$$\text{Reuse value} = \text{Cost of component (\$)} - \text{Miscellaneous (\$)} \tag{6}$$

$$\begin{aligned}\text{Remanufacture value} = &\text{Cost of component (\$)} - \text{Remanufacture Cost (\$)}\\ &- \text{Miscellaneous cost (\$)}\end{aligned} \tag{7}$$

$$\begin{aligned}\text{Primary recycle value} = &\text{Weight of component (kg)} \times \text{Market value of material (\$/kg)}\\ &- \text{Miscellaneous cost (\$)}\end{aligned} \tag{8}$$

$$\begin{aligned}\text{Secondary recycle value} = &\text{Weight of component (kg)} \times \text{Scrap value of material (\$/kg)}\\ &- \text{Miscellaneous cost(\$)}\end{aligned} \tag{9}$$

$$\begin{aligned}\text{Incinerate value} = &\text{Energy produced (KJ)} \times \text{Unit of energy (\$/KJ)}\\ &- \text{Miscellaneous cost}\end{aligned} \tag{10}$$

$$\begin{aligned}\text{Landfill cost} = &-(\text{Weight of component (kg)} \times \text{Cost of landfill (\$/kg)})\\ &- \text{Miscellaneous cost (\$)}\end{aligned} \tag{11}$$

$$\begin{aligned}\text{Special handing cost} = &-(\text{Weight of component (kg)} \times \text{Cost of special handling (\$/kg)})\\ &- \text{Miscellaneous cost (\$)}\end{aligned} \tag{12}$$

$$\text{Miscellaneous cost} = \text{Handling} + \text{Transportation} + \text{Storage} + \text{Re-processing} \tag{13}$$

## *3.3 Phase 3 Evaluate the Disassemblability and Calculate Disassembly Cost*

There are two steps involved in phase 3, the evaluation of disassemblability and the calculation of disassembly cost.

### 3.3.1 Step 1 Evaluate the Disassemblability

The evaluation method used in this research is disassemblability evaluation method proposed by Desai and Mital (2005). Desai and Mital (2005) subdivide the disassembly operation into the basic element tasks. As an example, a simple unscrew operation that may be subdivided into the following tasks (Desai and Mital 2005):

1. Constrain the product to prevent motion during disassembly.
2. Reach for tool (power screwdriver).
3. Grasp the tool.
4. Position the tool (accessibility of fastener).
5. Align the tool for commencement of operation (accessibility of fastener).
6. Perform disassembly (unscrew operation: force exertions in case of manual unscrew operation).
7. Put away the tool.
8. Remove screws and place them in a bin.
9. Remove the component and put it in a bin.

According to Desai and Mital (2005), task numbers 4, 5, 6, and 9 actually affect disassembly. Task numbers 1, 2, and 3 are preparatory tasks. Assuming operator dexterity, speed of operation, weight and size of tool, and workplace conditions remain constant, altering the preparatory tasks would have no effect on the efficiency of the disassembly process. Otherwise, the efficiency of the disassembly process can be directly attributed to task numbers 4, 5, 6, and 9. Task numbers 4, 5, 6, and 9 are directly affected by the design configuration of the product. For example, task number 9, the removal of the component is influenced by size, shape, weight, and material of the component. According to Desai and Mital (2005), large, unsymmetrical, and heavy components as well as small and sharp components are difficult to handle, and finally result in decrease in disassembly efficiency. Moreover, according to Desai and Mital (2005) if a large number of the above tasks are to be performed during the work shift (frequency of operations) and the worker is forced to adopt an unnatural posture resulting in the onset of static fatigue, the long-term effects can be devastating. Based on these, Desai and Mital (2005), address the following parameters as the parameters affecting the disassemblability:

1. Degree of accessibility of components and fasteners.
2. Amount of force (or torque) required for disengaging components (in case of snap fits) or unfastening fasteners.
3. Positioning.
4. Requirements of tools.
5. Design factors such as weight, shape and size of components being disassembled.

In order to determine the disassemblability score, Desai and Mital (2005) apply the Method Time Measurement (MTM) system. The simplest disassembly task of removing an easily grasped object without the exertion of much force by hand by a trained worker under average conditions has been considered as the basic disassembly task. A score of 73 TMUs was assigned to this task, which corresponded to time duration of approximately 2 s. Subsequent scores were assigned based on the detailed study of most commonly encountered disassembly operations. Table 1 shows the scoring system of numeric analysis of disassemblability.

### 3.3.2 Step 2 Calculate Disassembly Cost

The calculation of the disassembly cost is based on the disassembly operation rate per unit of time. Multiplying this rate with the disassembly time for each operation will result in the disassembly cost for each disassembly operation.

Disassembly time and disassembly cost for each task are defined as in Eqs. (14) and (15) (Desai and Mital 2005; Lambert and Gupta 2005)

$$\text{Disassembly time(in second)} = \text{Total disassembly score} \times 10 \times 0.036\,\text{s} \tag{14}$$

$$\begin{aligned}\text{Disassembly cost(\$)} = {} & \text{Disassembly time (second)} \\ & \times \text{Disassembly cost (\$/second)}.\end{aligned} \tag{15}$$

## *3.4 Phase 4 Calculate Recycling Rate*

To measure that current design meets or does not meet end-of-life directive in terms of the amount of material or parts that can be recycled, recyclability is used as the indicator. Based on the Manual for Recycling-Optimized Product Development (Lambert and Gupta 2005), the recycling rate is defined as:

$$R_Q = \frac{M_{\mathrm{R1}} + M_{\mathrm{R2}}}{M_{\mathrm{G}}} \times 100\,\% \tag{16}$$

| | |
|---|---|
| $M_{\mathrm{R1}}$, $M_{\mathrm{R2}}$ | Mass (kg) of materials in components in recycling rate categories R1 and R2. |
| $M_{\mathrm{G}}$ | Mass (kg) of product or subassembly. |

**Table 1** Scoring system of numeric analysis of disassemblability (Desai and Mital 2005)

| Design attribute | Design feature | Design parameters | Score | Interpretation |
|---|---|---|---|---|
| Disassembly force | Straight line motion without exertion of pressure | Push/pull operations with hand | 0.5 | Little effort required |
| | | | 1 | Moderate effort required |
| | | | 3 | Large amount of effort required |
| | Straight line and twisting motion without pressure | Twisting and push/pull operations with hand | 1 | Little effort required |
| | | | 2 | Moderate effort required |
| | | | 4 | Large amount of effort required |
| | Straight line motion with exertion of pressure | Inter-surface friction and/or wedging | 2.5 | Little effort required |
| | | | 3 | Moderate effort required |
| | | | 5 | Large amount of effort required |
| | Straight line and twisting motions with exertion of pressure | Inter-surface friction and/or wedging | 3 | Little effort required |
| | | | 3.5 | Moderate effort required |
| | | | 5.5 | Large amount of effort required |
| | Twisting motions with pressure exertion | Material stiffness | 3 | Little effort required |
| | | | 4.5 | Moderate effort required |
| | | | 6.5 | Large amount of effort required |
| Material handling | Component size | Component dimensions (very large or very small) | 2 | Easily grasped |
| | | | 3.5 | Moderately difficult to grasp |
| | | | 4 | Difficult to grasp |
| | | Magnitude of weight | 2 | Light (<7.5 lb) |
| | | | 2.5 | Moderately heavy (<17.5 lb) |
| | | | 3 | Very heavy (<27.5 lb) |
| | Component symmetry | Symmetric components are easy to handle | 0.8 | Light and symmetric |
| | | | 1.2 | Light and semi-symmetric |
| | | | 1.4 | Light and asymmetric |
| | | | 2 | Moderately heavy, symmetric |
| | | | 2.2 | Moderately heavy, semi-symmetric |
| | | | 2.4 | Moderately heavy, asymmetric |
| | | | 4.4 | Heavy and symmetric |
| | | | 4.6 | Heavy and semi-symmetric |
| | | | 5 | Heavy and asymmetric |
| Requirement of tools for disassembly | Exertion of force | | 1 | No tools required |
| | | | 2 | Common tools required |
| | | | 3 | Specialized tools required |
| | Exertion of torque | | 1 | No tools required |
| | | | 2 | Common tools required |
| | | | 3 | Specialized tools required |

(continued)

**Table 1** (continued)

| Design attribute | Design feature | Design parameters | Score | Interpretation |
|---|---|---|---|---|
| Accessibility of joints/grooves | Dimensions | Length, breadth, depth, radius, angle made with surface | 1 | Shallow and broad fastener recesses, large and readily visible slot/recess in case of snap fits |
| | | | 1.6 | Deep and narrow fastener recesses, obscure slot/recess in case of snap fits |
| | | | 2 | Very deep and very narrow fastener recesses, slot for prying open snap fits difficult to locate |
| | Location | On plane surface | 1 | Groove location allows easy access |
| | | On angular surface | 1.6 | Groove location is difficult to access. Some manipulation required |
| | | In a slot | 2 | Groove location very difficult to access |
| Positioning | Level of accuracy required to position the tool | Symmetry | 1.2 | No accuracy required |
| | | | 2 | Some accuracy required |
| | | | 5 | High accuracy required |
| | | Asymmetry | 1.6 | No accuracy required |
| | | | 2.5 | Some accuracy required |
| | | | 5.5 | High accuracy required |

Recycling categories (R1, R2, and R3) are defined as:

1. *R1* Component suitable for economic recycling with Suitability for Recycling $\geq$ 100 %.
2. *R2* Component suitable for economic recycling which has 80 % $\leq$ Suitability for Recycling < 100 %.
3. *R3* Not suitable for economic recycling with Suitability for Recycling < 80 %.

Suitability for recycling is calculated as follows:

$$\text{Suitability for recycling} = \frac{\text{Cost (equivalent new material} + \text{disposal)}}{\text{Cost (dismantling} + \text{re-processing} + \text{logistics)}} \times 100\,\% \tag{17}$$

Dismantling cost means disassembly cost and re-processing cost means cost required for upgrading the components based on its end-of-life option.

### *3.5 Phase 5 Disassemblability Evaluation Report*

In order to provide reports that can be used to make recommendation regarding improvement potentials, this methodology provides three potential improvements:

1. Improvement of product structure
   Based on the results of the numeric evaluation of disassemblability and end-of-life value for each component, a portfolio of disassembly time versus profit of single components gives a quick overview of weak points in the product structure. All components with high end-of-life profit and long disassembly time and all components with low end-of-life profit and short disassembly time have potential to be improved by repositioning them in the product hierarchy or by changing their joining technique.
2. Improvement of ease of disassembly
   By using disassemblability evaluation scores the designer also can identify which parameter of disassemblability has the highest contribution to the difficulties of the disassembly operation for a particular component. It shows the weaknesses of the design and it can be used as basis to suggest feasible design alternatives.
3. Improvement of material content
   Suitability for recycling and recycling rate indicates that current materials used are suitable or not for recycling in terms of economic consideration.

## 4 Assumption

The application of the above methodology is limited by several assumptions:

1. In computing the end-of-life value it is assumed that the recycling facility has 100 % efficiency.
2. The disassembly cost is assumed as the labor cost per unit of time.
3. As mentioned earlier that MTM System was used in estimating the disassembly time. Here, in using this method, it is assumed that the disassembly operations are performed sitting down at the bench level.
4. The operators doing the disassembly operations are assumed to have average skill and work in the normal condition.
5. The material of the components developing the product is known.

## 5 Case Study and Results

In order to illustrate the application of the proposed methodology, a hair clipper is used as a case study. The purposes of this case study are to measure the disassemblability, estimate the disassembly time, and compute the recyclability of the hair clipper. Hair clipper which is being analyzed consists of 13 main components. The detailed information about the hair clipper is shown in Fig. 2.

In Phase 1, the type and quantity of fasteners among hair clipper's component, mass of the components, materials used, and disassembly tasks required to take apart the components from the product are obtained. There are two types of fasteners used in the hair clipper, screw and snap fit. Screws are released by unscrewing them and snap fits are released by pulling them.

In Phase 2, the end-of-life option for the components is obtained and the end-of-life value is calculated. The end-of-life option determination is based on the guideline proposed by Lee et al. (2001). In order to calculate the end-of-life value, Eqs. (6–13) are used. The result of the end-of-life option determination and the calculation of the end-of-life value are shown in Table 2.

As an illustration, lower cutter is discussed. Based on the proposed methodology, feasible end-of-life option for sheet metal is primary recycling. The Market value of metal is 1.54 $/kg. Since miscellaneous costs are outside control of the designers, they are omitted from calculation. So,

$$\begin{aligned}\text{Primary recycling value} &= \text{Weight of component (kg)} \times \text{Market value of material (\$/kg)}\\ &\quad - \text{Miscellaneous cost (\$)} = 0.027\,\text{kg} \times 1.54\,\$/\text{kg} = \$0.04158.\end{aligned}$$

Table 2 shows that all components of the hair clipper give rise to a surplus and do not adversely impact the environment. A component which adversely impacts the environment will require special handling and the deficit incurred by special handling is indicated by the negative sign of the end-of-life value.

In Phase 3, the disassemblability is evaluated and then the disassembly cost is calculated. The scoring system proposed by Desai and Mital (2005) is applied. Table 3 shows numerical disassemblability analysis of unscrews operation for disassembling lower cutter and the calculation of disassembly cost in performing

**Fig. 2** Hair clipper. *1* Low cutter, *2* Upper cutter, *3* Tip, *4* Handle, *5* U-shape, *6* Upper cover, *7* Front part, *8* Magnet, *9* Coil, *10* Outer switch, *11* Inner switch, *12* Cable, *13* Lower cover

**Table 2** End-of-life option, disassemblability and recyclability evaluation result

| Number | Component | Task | Mass (kg) | Material | EOL option | EOL value ($) | Suitability for recycling (%) | Disassembly time (second) |
|---|---|---|---|---|---|---|---|---|
| 1 | Lower cutter | Unscrew | 0.027 | Sheet Metal | PR | 0.04158 | 230.77 | 9.36 |
| 2 | Upper cutter | Pull | 0.008 | Sheet Metal | PR | 0.01232 | 187.13 | 3.42 |
| 3 | Tip | Pull | 0.0005 | Polypropylene | SR | 0.00001 | 0.58 | 3.42 |
| 4 | Handle | Unscrew | 0.002 | Polypropylene | SR | 0.00004 | 1.59 | 5.04 |
| 5 | U-shape | Pull | 0.008 | Sheet Metal | PR | 0.01232 | 187.13 | 3.42 |
| 6 | Upper cover | Unscrew | 0.021 | Polypropylene | SR | 0.00042 | 4.49 | 18.72 |
| 7 | Front part | Unscrew | 0.002 | Sheet Metal | PR | 0.00308 | 17.09 | 9.36 |
| 8 | Magnet | Pull | 0.027 | Metal | PR | 0.04158 | 521.73 | 4.14 |
| 9 | Coil | Unscrew | 0.154 | Cooper | PR | 0.23716 | 1316.24 | 9.36 |
| 10 | Outer switch | Pull | 0.001 | Polypropylene | SR | 0.00002 | 1.17 | 3.42 |
| 11 | Inner switch | Pull | 0.004 | Polypropylene | SR | $8 \times 10^{-5}$ | 4.68 | 3.42 |
| 12 | Cable | Pull | 0.08 | Cooper | PR | 0.1232 | 1693.12 | 3.78 |
| 13 | Lower cover | Pull | 0.045 | Polypropylene | SR | 0.0009 | 47.62 | 3.78 |

*Note EOL* End-of-Life, *PR* Primary Recycling, and *SR* Secondary Recycling

**Table 3** Disassembly time computation of lower cutter

| Design attribute | Design attribute/parameter | Score |
|---|---|---|
| Force | Straight line and twisting motions with exertion of pressure/inter-surface friction and/or wedging | 3 |
| Material handling | Component dimensions | 2 |
| | Magnitude of weight | 2 |
| | Symmetric components are easy to handle | 0.8 |
| Requirement of tools | Exertion of torque | 2 |
| Accessibility | Dimensions/length, breadth, depth, radius, angle made with surface | 1 |
| | Location/on-plane surface | 1 |
| Positioning | Symmetry | 1.2 |
| Total | | 13 |

Disassembly time = number of screws × Total × 10 × 0.036 = 2 × 13 × 10 × 0.036 = 9.36 s
Disassembly cost = Disassembly time (second) × Labor cost ($/second) = 9.36 × 0.002 = $0.01872

the unscrew operation. Lower cutter has two identical screws which have to be removed so that the disassembly time of the door gear is 2 × 13 × 10 × 0.036 = 9.36 s. The labor cost is $0.002/s, so that Disassembly cost = 0.002 × 9.36 = $0.01872.

Table 3 shows the numerical disassemblability analysis of unscrews operation for disassembling the lower cutter which has two screws. From Table 3, it can be seen that force as the design attribute or parameter of design has the highest contribution to the duration of disassembly time of lower cutter. In order to reduce the exertion of force required to disengage the lower cutter, according to Desai and Mital (2005), appropriate materials for component bearing surfaces and/or fasteners should be selected to reduce inter-surface friction. Besides that the holding surfaces in component also needed to be redesigned. Developed software also provides redesign recommendations in order to increase the disassemblability of the product analyzed.

In Phase 4, recycling rate is determined. Before recycling rate can be calculated, Suitability for Recycling must be calculated earlier. As an example, suitability for recycling of lower cutter is explained. Cost of equivalent new material = mass (kg) × cost of equivalent new material of lower cutter ($/kg) = 0.027 × 1.54 = $0.04158, disposal cost = mass (kg) × disposal cost per kg ($/kg) = 0.027 × 0.06 = $0.00162, dismantling cost = disassembly time (second) × disassembly rate ($/second) = 9.36 × 0.002 = $0.01872, re-processing cost and logistic cost are omitted from the calculation because they are outside control of the designers. Then,

$$\text{Suitability for Recycling} = [(0.04158 + 0.00162)/0.01872] \times 100\,\% = 230.77\,\%.$$

Table 2 also shows Suitability for Recycling of all components of hair clipper. Based on recycling category of each component, recycling rate can be calculated. Total mass of hair clipper is 0.3795 kg and total mass of the components with R1 and R2 categories is 0.304 kg. Therefore,

$$\text{Recycling rate} = (0.304/0.3795) \times 100\,\% = 80.1\,\%$$

Based on the suitability recycling, lower cutter's suitability for recycling is 230.77 %, it means that if lower cutter is not recycled the total cost of new material for producing a new lower cutter plus cost required disposing the end-of-life lower cutter is 2.3077 times as much as total costs (disassembly, reconditioning and logistic) required if it is recycled. Based on this, it is better if lower cutter is recycled. Table 2 presents suitability for recycling of all components of hair clipper. The recycling rate calculation indicates that 80.1 % (in terms of weight) out of all materials used in the hair clipper can be recycled at feasible and reasonable expenditure.

In Phase 5, in order to show which components are having the potential to be redesigned, the portfolio of end-of-life value versus disassembly time and value return for removing component are provided, as shown in Figs. 3 and 4 respectively. Value return of removing is the ratio between end-of-life value and disassembly time of a component.

Based on Fig. 3, coil and upper cover have potential to be improved. These components have a high and low end-of-life values. They should be disassembled very easily. It can be solved by changing the joining technique or by repositioning

**Fig. 3** End-of-life values versus disassembly time

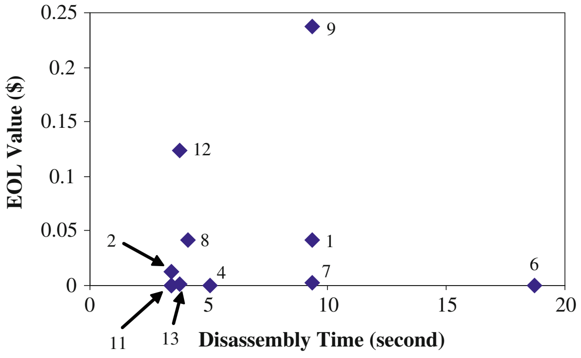
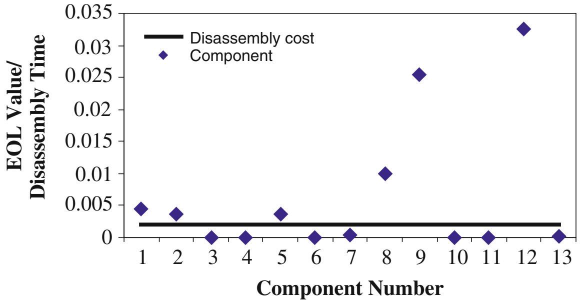


**Fig. 4** Return value of removing components



them in the product hierarchy. Based on Fig. 4, tip, handle, upper cover, outer switch, and inner switch are uneconomical to disassemble because their return value of removing is lower than the disassembly cost.

## 6 Discussion

This work integrated the two aspects of the end-of-life disassemblability and recyclability analysis in one framework. Those aspects are end-of-life option determination and disassemblability analysis. Those aspects are required to be analyzed to compromise the requirements of the legislation to take back and recycle the end-of-life product and the cost incurred for taking back, disassembling, and re-processing the end-of-life product.

The end-of-life option determination will guide the designers to choose the appropriate end-of-life option of a vehicle. The guideline was developed based on the material composition and condition of the end-of-life vehicle's component. The decision to recycle (primary and secondary), dump to the landfill, or special handling is made based on the material composition. The decision to reuse or remanufacture requires foreknowledge of the manufacturing process undergone by the component, and its condition at the end-of-life, the decision can only be made by human intervention.

For each end-of-life option the end-of-life value is computed. The end-of-life value will show profit or cost which can be achieved from the appropriate end-of-life option decided for each component. The end-of-life option, mass of the component, material type, and end-of-life cost are input for computing the end-of-life value. The end-of-life value can be used as the indicator to show whether a component adversely impacts the environment or not. A component which impacts the environment will require special handling and the deficit incurred by special handling is indicated by the negative sign of the end-of-life value.

The disassemblability evaluation will aid the designers in reducing disassembly difficultness, disassembly time, and disassembly cost required. The recyclability analysis will show that the design meets or does not meet the requirements legislated. Although the objective of the legislation is laudable and, theoretically all materials are recyclable, operating costs are still one of the primary concerns of manufacturers. Therefore, the economic aspects were involved in quantifying the recyclability. In order to determine that a component is suitable for recycling or not, suitability for recycling is used as the indicator. It is the ratio between the cost (in currency unit/kg) of a new material equivalent to the recycled material and the cost of disposal (on a landfill or through incineration) if the material is not recycled, versus the costs of disassembly, reconditioning, and logistics.

## 7 Conclusion

A very important contribution of this research is that the developed methodology integrates the end-of-life option determination and disassemblability evaluation in one framework. The end-of-life options determination and the disassemblability evaluation will show how economically efficient it is to disassemble an end-of-life vehicle and check the opportunity of a component to be recycled. Besides that, the disassemblability evaluation report provided by the methodology can be used by product designers to identify weaknesses of the design and do further improvement.

Due to broad scope of disassembly and recyclability analysis, the proposed methodology and software can be further improved as described below:

1. For determining the end-of-life option, the Multi-Criteria Decision Analysis can be integrated into the developed methodology to select the appropriate end-of-life option of the product's components because the selection of the end-of-life option is also subjected to the economic, environmental, and social factors. In this work, it is based on the material composition of the end-of-life components.
2. In order to estimate the disassembly time, the developed methodology only provides the disassemblability scoring system for manual disassembly operation.

In order to accommodate the disassembly operations which are not done manually, the database of the disassemblability scoring system can be enriched with database for estimating the disassembly duration of the automatic disassembly operation.

3. For a better cost and profit comparison, it will be more realistic if indirect costs are also considered in defining the disassembly cost. In the developed methodology, the disassembly cost is assumed equal to labor cost per unit of time.
4. Implementing this methodology to the computer program will make it a very useful tool for the product designers. It can provide assistance in making decisions at the early stage of the product design and development process in order to avoid the cost and time consumed through later redesign.

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# Sustainability Under Severe Uncertainty: A Probability-Bounds-Analysis-Based Approach

**Kailiang Zheng, Helen H. Lou and Yinlun Huang**

**Abstract** Sustainability is a vital issue for the long-term, healthy development of human society. In the methodological study on sustainability, one of the most challenging issues is how to deal with various types of uncertainties, since the available information and data are almost always incomplete and imprecise, and the possessed knowledge is usually insufficient and imperfect. In Probability bounds analysis (PBA) method, uncertainty is represented by probability box (p-box), which explicitly expresses both variability and imprecision. The important characteristics of a p-box are the probability bounds that define upper and lower bounds on the cumulative probability over the domain of the uncertain quantity. In this chapter, the PBA-based approach is introduced to gain a better understanding of its applicability and efficacy in solving a certain type of uncertainty problem in sustainable development. The most challenging issue in using PBA is how to model the propagation of uncertainty through complicated mathematical models in simulation and decision-making. Two types of p-box computational algorithms: the Dependency Bounds Convolution (DBC) method and the black-box compatible methods were studied. It was found that the DBC method can be used in simple algebraic-model-based simulation, but not in black-box models. On the other hand, the black-box compatible methods can be used in complicated models and they are applicable in optimization under uncertainty.

**Keywords** Uncertainty in sustainability · Probability-bounds analysis · Dependency bounds convolution method · Black-box compatible method · Optimization

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# 1 Introduction

Sustainability is a vital issue for long-term, healthy development of human society. As U.N. defined, "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). In the spatial domain, different types of sustainability systems can be recognized (Sikdar 2003). In the temporal domain, the study of sustainability requires not only the evaluation of the status quo, but also prediction and strategic decision-making for the future.

In sustainability, one of the most challenging tasks is how to cope with various types of uncertainties that are associated with available information and data (technical or non-technical), and possessed knowledge. It is also important to point out that uncertainties can propagate in many ways throughout system analysis design stages and decision-making. For example, due to the uncertainty of supply chain, a strategic planning of material and energy supplies could be very difficult (Bras 1997). This type of uncertainty may require other supply options that are related to the choice of end-of-life options: remanufacturing, reuse, or recycle, etc., which are frequently unstable.

Clearly, there is an urgent need of systematic methodologies and practical tools to help practitioners to handle uncertainties in a holistic way when studying a sustainability problem. It is known that a variety of uncertainty handling methodologies and techniques are available. In this chapter, we focus on one methodology, Probability Bounds Analysis (PBA). By resorting to the Imprecise Probability Theory (Walley 1991), PBA can provide a balance between the expressiveness of imprecision and the efficiency of computation. In this chapter, the PBA-based approach is introduced to gain a better understanding of its applicability and efficacy in solving a certain type of uncertainty problem in sustainable development. The following topics will be covered: (i) why PBA, (ii) how to use PBA to represent uncertainty, and (iii) how to compute p-boxes in modeling and decision-making. Several algorithms will be introduced and their applicability in modeling and decision-making will be discussed.

# 2 Why PBA

In this section, we will firstly introduce the general uncertainty classification method, and then describe the need of adopting an uncertainty representation approach, the so-called p-box method.

Uncertainty can be classified into two categories: aleatory and epistemic. Aleatory uncertainty, also called variability, refers to the inherent variation associated with physical systems or the involved environment. This type of uncertainty is objective and irreducible. Its representation is frequently made by a probability distribution function (Bruns 2006). Epistemic uncertainty is caused by the lack of knowledge or information (Parry 1996). It is subjective and irreducible. For example, Chlorofluorocarbon compounds were invented in 1930s, but their ozone depletion potential was not alerted until 1970s. It took mankind almost half a century to reduce this epistemic uncertainty. A standard representation of pure epistemic uncertainty is by the interval method (Kreinovich et al. 1999).

Sustainability science and engineering research is in its infancy, and much important information and knowledge are yet to be generated. Note that most of the quantification of sustainability status has been subjective so far. In sustainability modeling and decision-making, many times the modeler/decision-maker may encounter the following situations: the model needs $n$ number of parameters $A_i = \{A_1, A_2, \ldots, A_n\}$. It is most desirable to have at least $m$ number of data points for each parameter. Therefore $m \times n$ number of data points are needed in total. However, due to the difficulty in measurement or limitations in the knowledge domain, for some of the parameters $A_i$, there are only less than $m$ data points available. The incompleteness in knowledge domain and limitation of measurement will cause epistemic uncertainty. On the other hand, the randomness in measurement or judgment will cause aleatory uncertainty. How to deal with epistemic uncertainty and aleatory uncertainty simultaneously is an uncharted frontier. The negligence on either one may lead to a faulty judgment.

Various modeling approaches have been developed for uncertainty handling. Most of them are for the treatment of aleatory uncertainty, such as those statistical approaches. The three approaches that can handle severe uncertainty should be investigated for their applicability and effectiveness in sustainability study. They are (i) PBA (Ferson et al. 2003), (ii) Information Gap Theory (IGT) (Ben-Haim 2001), and (iii) the mathematically arguable but practically usable Fuzzy Arithmetic (Nguyen and Sugeno 1998). In this chapter, we will focus our study on PBA.

## 3 How to Use p-Box to Represent Uncertainty

In PBA, uncertainty is represented by probability boxes, or simply p-boxes (Ferson and Donald 1998). A p-box is a more expressive generalization of both probability distributions and interval representation. The p-box explicitly expresses both the variability (by the shapes of boundary cumulative distribution function (CDF)) and imprecision (by the separation between the upper and lower bounds).

The p-box is less general than imprecise probability, but the loss of generality can be compensated by the gained computational convenience. The important characteristics of a p-box are the probability bounds that define upper and lower bounds on the cumulative probability over the domain of the uncertain quantity. Let $X$ be a numerical random variable, $\mathbb{R}$ be the set of all real numbers, $x$ be any real number and $x \in \mathbb{R}$, then the CDF $F(x)$ of variable $X$ describes the probability for a realization of the variable $X$ to be less than $x$ for any $x \in \mathbb{R}$. This $F(x)$ is a non-decreasing function from 0 to 1 and is denoted as: $F(x) = P(X \leq x)$. Now, suppose

$X$ is an uncertain numerical variable, $\underline{F}(x)$ and $\bar{F}(x)$ are respectively, the lower and upper bounds of the CDF of variable $X$ from real number set $\mathbb{R}$ into $[0, 1]$, and $\underline{F}(x) \le \bar{F}(x)$ for all $x \in \mathbb{R}$, then let $[\underline{F}(x), \bar{F}(x)]$ denote the set of nondecreasing functions $F(x)$ from the reals into $[0, 1]$. The functions $\underline{F}(x)$ and $\bar{F}(x)$ circumscribe an imprecise probability distribution, which is called "probability box" or "p-box".

For example, if we have enough information to know that $X$ is normally distributed, however, based on the available information we can only characterize the mean $\mu$ and standard deviation $\sigma$ imprecisely by bonding them in the interval $\mu = [1, 4]$ and $\sigma = [1, 2]$. The uncertain variable $X$ can be expressed as: $X \sim \text{Normal}(\mu, \sigma) = \text{Normal}([1, 4], [1, 2])$.

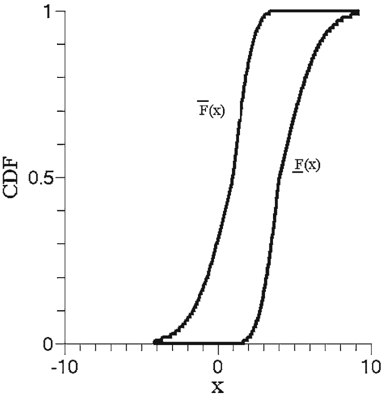
Using the available data, a p-box of variable $X$ can be constructed by software Risk Calc 4.0 (Ferson 2002) based on 95 % confidence level, which is preferred by most researchers. As illustrated in Fig. 1, the precise CDF of variable $X$ is unknown and constrained by the lower and upper CDF functions, i.e., $\underline{F}(x), \bar{F}(x)$. The case of a precise CDF distribution is a special case of a p-box. It needs to point out that there are several ways to construct p-boxes, depending on the type of information available (Ferson 2003a, b). For the details of how to construct p-boxes, please see reference (Ferson 2003a, b).

The p-box has a clear operational definition, which is "a rule which indicates how the mathematical notions are intended to be interpreted (Cooke 2004)". For the criticism of uncertainty models without clear operational definitions, please see reference (Cooke 2004).

## 4 How to Compute with p-Boxes

Some algorithms have already been developed to compute with p-boxes. Williamson and Downs (1990), Ferson (Ferson and Donald 1998, 2002), and Berleant et al. (2003) have done great work on algorithms to compute p-boxes. Two representative algorithms will be briefly described and compared below.

**Fig. 1** A p-box for $X \sim \text{Normal}([1, 4], [1, 2])$



## 4.1 Dependency Bounds Convolution (DBC) Methods for Simple Algebraic Models

After uncertain quantities are represented by p-boxes, the p-boxes can be computed through simple algebraic models by DBC method. This is a method for calculating uncertainties through mathematical models with only simple binary operations between the p-boxes of input variables. The DBC method is rigorous in the sense that the true probability distribution of the uncertain quantity is guaranteed to be included in the resultant probability bounds, no matter what the dependence relationship between the input variables will be, as long as the p-boxes of input variables were rigorously constructed (Bruns 2006). The resultant probability bounds are also best-possible, since they are as close together as possible to bound the resultant as precise as possible (Bruns 2006), given the information provided by the p-boxes of input variables. Any reduction of the bounds will result in the possible exclusion of the true distribution.

Williamson and Downs (1990), and Berleant et al. (2003) independently developed two algorithms for DBC. The work of Williamson and Downs was motivated to develop numerical methods for precise probabilistic arithmetic. Their method is implemented in the commercially available software, Risk Calc 4.0 (Ferson 2002). Berleant's approach is called the Distribution Envelope determination and implemented in the software, Statool (Berleant et al. 2003). Regan et al. (2004) have proved that the method of Williamson and Downs and method of Berleant are equivalent for binary operations of p-boxes defined on the positive real numbers.

The DBC method is not only suitable for statistically independent cases, but is also suitable for determining probability bounds when the dependence between the inputs is unknown.

## 4.2 Need for Alternative Methods to Treat Complex Black-Box Models

Though rigorous, the DBC method has two main drawbacks. First is about the repeated variables in the calculation. This method heavily depends on interval arithmetic, in which the repeated variables can generate overconservative solution bounds, which are not the best-possible and the most desired results. Second, the DBC method is not black-box compatible. It is only capable of calculating through algebraic models with simple binary operations and this is definitely insufficient for the complex calculations in most realistic problems.

The sustainable development of a complex industrial system (corporate, industrial ecosystem, region, zone, etc.) refers to a process of continuous improvement or advancement so as to create more value, wealth, and profits (economically viable dimension), provide cleaner products with less material/energy consumption and waste (environmentally compatible dimension), and implement more socially preferable products, services, and impacts (socially responsible dimension). The identification of an "optimal" solution means searching for the most efficient and effective approach for "improvement". This requires guidance for seeking ways of dealing with uncertainties in the complex sustainability hierarchy under different scenarios. Failure to account for such uncertainties (e.g. technical coefficients, product demands, kinetic constants, feed composition, etc.) can lead to non-optimal or infeasible decision results (Biegler and Grossman 2004). Optimization under severe uncertainty is an essential tool for decision-making toward sustainability. Beginning with the works of Beale (1955) and Bellman (1957), optimization under uncertainty has experienced rapid development in both theory and algorithms (Sahinidis 2004).

How to incorporate PBA with optimization techniques is a difficult task. Due to the two main reasons we mentioned before, DBC method is not able to handle optimization problems, when the uncertainty factors are expressed in p-boxes. In order to apply PBA method in sustainability related problems, we need to develop efficient approaches to compute uncertainty through black-box models. There are three black-box compatible methods, namely Double Loop Sampling (DLS), Optimized Parameter Sampling (OPS), and p-Box Convolution Sampling (PCS). They can be used to calculate uncertain inputs through structurally unknown or complex models. For the detailed comparison of these methods, please see reference (Bruns 2006). In the following section, we will introduce and discuss the efficacy of a DLS-based method, namely Double Loop Latin Hypercube Sampling (DLLHS), as a representative of black-box compatible methods.

## *4.3 Double Loop Latin Hypercube Sampling*

In this part, the concept of Latin Hypercube Sampling is introduced briefly, then a novel Double Loop Latin Hypercube Sampling (DLLHS) approach is described.

**Latin Hypercube Sampling (LHS)**. LHS was developed to generate a distribution of plausible collections of parameter values from a multi-dimensional distribution. It was proposed by McKay et al. (1979) and further developed by Iman et al. (1981).

In statistical sampling, a square grid containing sample positions is a Latin square, if and only if there is one sample in each row and each column. A Latin hypercube is a generalization of this concept to an arbitrary number of dimensions, where each sample is the only one in each axis-aligned hyperplane.

The difference between Monte Carlo (MC) random sampling and LHS method can be illustrated in the following two-dimensional case. For random sampling, new sample points are generated without considering the previously generated sample points. However, for LHS, one must know how many sample points are to be generated and remember in which row and column each sample is taken.

Figure 2 shows the difference of the two sampling methods, when they are applied to two uncertain factors, A and B.

The LHS method adopts a stratified-random procedure, which provides an efficient way of sampling variables from their distributions. The LHS involves sampling values from the prescribed distribution of each $k$ variable $x_1, x_2, \ldots, x_k$. The cumulative distribution for each variable is divided into $N$ intervals with the same probability and a value is randomly generated for each interval. The $N$ values obtained for each variable are paired randomly with the other variables. Unlike simple random sampling, this method ensures a full coverage of the range of each variable by maximally stratifying each marginal distribution. The LHS method can reliably sample the whole parameter space with less iteration, which can yield more precise estimation of the distributions.

**Double Loop Latin Hypercube Sampling (DLLHS)**. DLS (Hoffman and Hammonds 1994) is the most straightforward approach for calculating imprecise uncertainties through mathematical models and is applicable for black-box models with parameterized p-box. A parameterized p-box is the p-box generated for some uncertain variable with known distribution function, but with imprecisely known distribution parameters, just as the one illustrated in Fig. 1. DLS involves two layers of sampling: the outer loop sampling, which is associated with distribution parameters, and the inner loop sampling, which is associated with the distribution generated in the outer loop sampling. DLLHS integrates the DLS and the LHS methods by incorporating LHS in both the outer and inner sampling loops of DLS.

DLS involves sampling from distributions. Firstly, through the outer loop sampling (also called the parameter loop), samples for a set of distribution parameters of all of the uncertain factors can be generated. Then inner loop sampling (also called probability loop) needs to be conducted to obtain samples from the precise probability distribution functions, which are determined by the previous outer loop sampling.

For a problem involving $k$ uncertain variables $X_1, X_2, \ldots, X_k$, these variables are combined to a single super-vector $\boldsymbol{X}$ for notational convenience. It is assumed that a black-box model, $\boldsymbol{Y} = f(\boldsymbol{X})$, is available to map this vector of input variables $\boldsymbol{X}$ to the output vector $\boldsymbol{Y}$. To calculate the uncertainties through this model, the first step is to represent these variables in the form of p-box models as illustrated in Fig. 3.

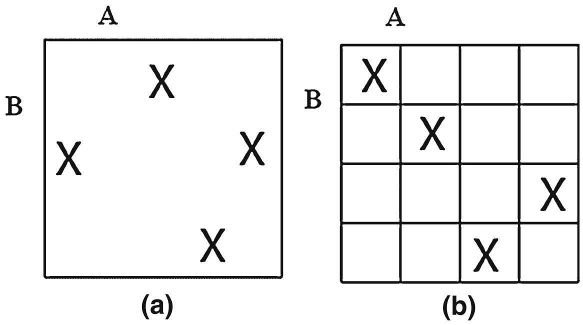


**Fig. 2** Comparison of MC and LHS methods: **a** MC random sampling, **b** Latin hypercube sampling

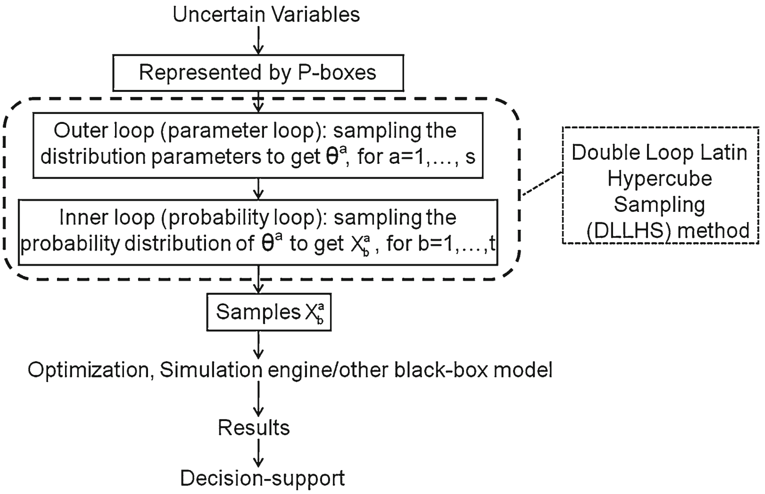


**Fig. 3** Schematic Diagram of DLLHS approach

For each variable $X_i$ $(i = 1, 2, \ldots, k)$, its p-box is associated with a set of imprecise parameters stored in the vector $\theta^i \in [\underline{\theta}^i, \bar{\theta}^i]$, where $\theta^i$ is the vector of distribution parameters that affect the shape or scale of the distribution function of $X_i$, and $[\underline{\theta}^i, \bar{\theta}^i]$ bounds the true distribution parameter vector within it.

For example, suppose it is known that variable $X_1$ is normally distributed with imprecise mean $\mu = [6, 8]$ and imprecise standard deviation $\sigma = [2, 3]$, $X_1$ can be described as $X_1 \sim \text{Normal}(\mu, \sigma) = \text{Normal}([6, 8], [2, 3])$. Then distribution parameter vector $\theta^1$ of $X_1$ is a $2 \times 1$ vector, $\underline{\theta}^1$ is $\begin{pmatrix} 6 \\ 2 \end{pmatrix}$ and $\bar{\theta}^1$ is $\begin{pmatrix} 8 \\ 3 \end{pmatrix}$. For notational convenience, it is desirable to combine these $\theta_i$ vectors into a single super-vector $\boldsymbol{\theta}$ to represent all the distribution parameters. Meanwhile, by extending from the lower and upper bounds of the sub-vectors $\theta_i$, the lower and upper bounds of this super-vector $\boldsymbol{\theta}$ can be obtained. Thus, the vector of distribution parameters for the super-vector $\mathbf{X}$ is constrained in $\theta \in [\underline{\theta}, \bar{\theta}]$.

In the parameter loop, the space of the parameter vector $\boldsymbol{\theta}$ is explored by LHS. For the $s$ number of samples generated in this sampling loop, each sampled point in the parameter space corresponds to a set of precise distribution parameters for all uncertain variables and is denoted as $\theta^a, a = 1, \ldots, s$.

The probability loop uses the precise distribution parameters attained from last step to solve a purely probabilistic sampling problem, i.e., using LHS for the corresponding distribution function. For each distribution function defined by $\theta^a$, a number of samples can be obtained and are denoted as $\boldsymbol{X}_b^a$, for $b = 1, \ldots, t$. Then $(s \times t)$ samples $\boldsymbol{X}_b^a$ of these uncertain variables can be obtained. These samples can be sent to optimization or simulation engine or other black-box models for the calculation. At last, the decision-maker can use these results to make his or her decision. A schematic diagram of the DLLHS approach is plotted in Fig. 4.

Comparison of LHS and MC sampling method was reported in literatures and the research proved that the LHS method is more efficient. Swidzinski and Chang (2000) stated that LHS could be nearly five times more effective in yielding estimation than traditional MC method. In DLLHS approach, a LHS method is used in each sampling loop. This indicates that DLLHS can be nearly 25 times more efficient than using traditional MC in DLS.

DLLHS is black-box compatible in that it can be used to calculate uncertain quantity through structurally unknown or complex models. All these black-box compatible methods, i.e., DLS, OPS, and PCS methods, in principle, should be applicable in optimization under uncertainty. In contrary, although DBC approach rigorously contains the true resultant p-box, it cannot compute p-boxes in black-box models; therefore it cannot be used in optimization.

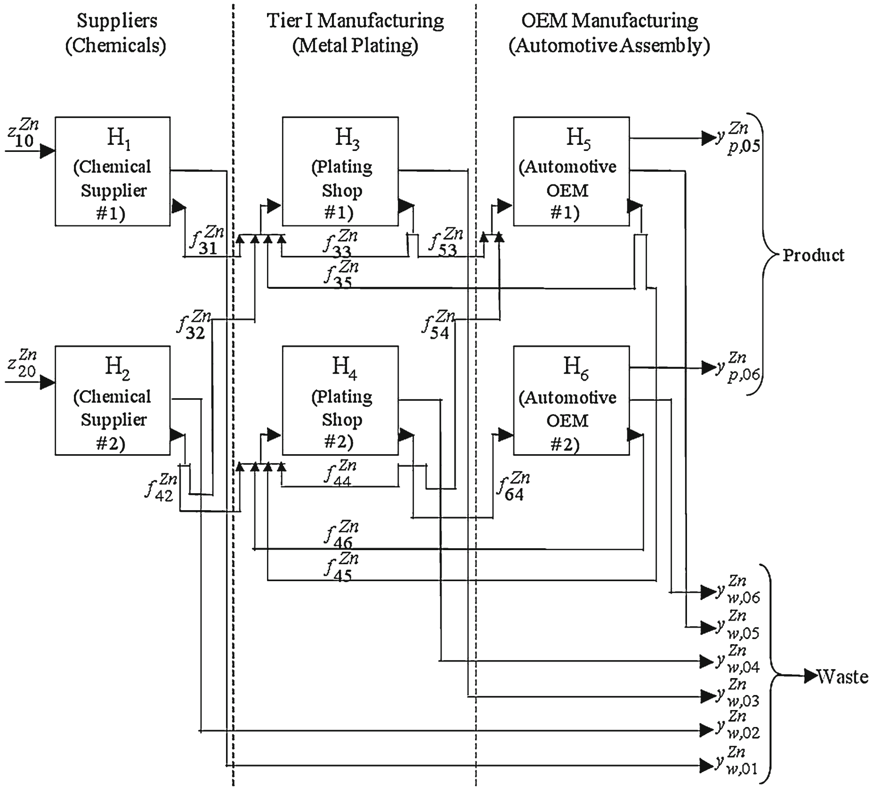


**Fig. 4** A schematic diagram of component-based electroplating supply network (Das and Dannis 1997)

## 4.4 Case Studies

In this section, the efficacy of DBC and DLLHS will be studied. In the first case, we will use DBC method, which is already incorporated in the commercial software Risk Calc, to analyze the effect of uncertainty propagation in a sustainability analysis problem of an industrial ecosystem. For the second case, DLLHS is applied to solve a simple numerical optimization problem under uncertainty. The second case study demonstrates that DLLHS method can be used in solving optimization under uncertainty problems, when the uncertain quantities are expressed in p-boxes.

### 4.4.1 Case 1: Application of DBC in Sustainability Analysis of an Industrial Ecosystem

Electroplating industry is facing great challenge due to global competition and its severe environmental issues. To survive and be profitable in the future, it must seek ways toward sustainable development. Cooperation and symbiosis efforts are necessary between the electroplating industry and its entire supply chain, i.e., the industry it serves (automotive, electronics, etc.) and the industry suppliers (chemicals, materials, etc.). Figure 4 presents the schematics of a component-based simplified electroplating supply network (Piluso et al. 2008), whereas the initial values of the stream flowrate in the base case are supplied in Table 1. This electroplating network consists of two chemical suppliers (H1 and H2), two electroplating shops (H3 and H4), and two end users (in this case, two original equipment manufacturers for the automotive industry (H5 and H6)).

The *AIChE* Mass Intensity (MI) metric, which is defined as total mass in/mass of product sold, is used as an index for environmental sustainability quantification. It is important to note that the smaller the MI metric, the better it is. The value of MI is the reciprocal of the value of "material efficiency," where the larger the better. Profit index is used as the economic indicator.

As reported by Piluso et al. (2008), in the deterministic base case, the MI of the whole system is 1.301 and the total profit is \$429,619/year. After aggregating the node-by-node models in the original literature, the simplified equations are presented below:

$$\text{MI(Mass Intensity)} = \frac{z_{10} + z_{20}}{y_{p,05} + y_{p,06}} = 1.301$$

$$\begin{aligned}\text{Profit} &= 2.93 \times y_{p,06} + 5.93 \times y_{p,05} - 0.25 \times y_{w,01} - 0.27 \times y_{w,02} - 0.29 \times y_{w,03}\\ &\quad - 0.29 \times y_{w,04} - 0.35 \times y_{w,05} - 0.35_{w,06} - 0.58 \times z_{10} - 0.55 \times z_{20}\\ &= \$429,619/\text{year}\end{aligned}$$

**Table 1** Plating network flow information (Das and Dannis 1997)

| Variable | Flowrate ($\times 10^3$ lbs/year) | Cost ($/lb) | Variable | Flowrate ($\times 10^3$ lbs/year) | Cost ($/lb) |
|---|---|---|---|---|---|
| $z_{10}$ | 50.000 | 0.58 | $f_{64}$ | 15.033 | 2.51 |
| $z_{20}$ | 70.000 | 0.55 | $f_{46}$ | 0.601 | 0.42 |
| $f_{31}$ | 46.500 | 0.89 | $y_{w,01}$ | 3.500 | 0.25 |
| $f_{32}$ | 27.720 | 0.88 | $y_{w,02}$ | 8.400 | 0.27 |
| $f_{42}$ | 33.880 | 0.88 | $y_{w,03}$ | 8.088 | 0.29 |
| $f_{33}$ | 4.044 | 0.40 | $y_{w,04}$ | 2.817 | 0.29 |
| $f_{44}$ | 4.025 | 0.45 | $y_{w,05}$ | 4.356 | 0.35 |
| $f_{53}$ | 68.746 | 2.93 | $y_{p,05}$ | 78.407 | 5.93 |
| $f_{35}$ | 2.614 | 0.35 | $y_{w,06}$ | 0.601 | 0.35 |
| $f_{54}$ | 18.373 | 2.51 | $y_{p,06}$ | 13.830 | 2.93 |
| $f_{45}$ | 1.742 | 0.37 | | | |

In the real world, production rate of a plant is influenced by many factors, such as the demand of the market. This could be a significant source of uncertainty. It is assumed that the product rates of plant $H_5$ and $H_6$, i.e., streams $y_{p,05}$ and $y_{p,06}$, suffer from the uncertainty aforementioned, and the flowrates of these two streams are denoted as variables $x_1$ and $x_2$, respectively. It is assumed that the value of $x_1$ follows a normal distribution, but we are not sure about the precise distribution parameters, only know that the mean value is within $[77.4, 79.4]$, and the standard deviation is within $[1, 1.5]$. Therefore, the value of $x_1$ can be denoted as a p-box: $x_1 \sim \text{Normal}\ ([77.4, 79.4], [1, 1.5])$. Similarly, the value of $x_2$ also follows a normal distribution but the precise distribution parameters are unknown. Its mean value is within $[12.8, 14.8]$, and standard deviation is within $[1, 2]$. Therefore, the value of $x_2$ can be represented as a p-box: $x_2 \sim \text{Normal}\ ([12.8, 14.8], [1, 2])$. These two p-boxes are shown in Fig. 5.

For each node of this supply network, there exists a mass balance between the input streams and output streams. From the deterministic case, the relative proportion of output streams from the same node can be calculated, which can be used to calculate the flowrates of all the intermediate streams in the uncertain situation. For briefness, the calculation details are omitted and only the final results are shown below. The MI and profit can be expressed by the following equations:

$$\text{MI} = 1.273096 + 0.186049/(1 + x_1/x_2)$$
$$\text{Profit} = 5111.277 \times x_1 + 2109.566_2$$

When introducing the DBC method, we mention that one of its drawbacks is the dependence on interval arithmetic, in which repeated parameters can generate overconservative results. In order to avoid the repeated parameters, the authors transformed the expression of MI as shown above. Using software Risk Calc 4.0, the sustainability performance of the overall system under uncertainty can be calculated. The results are shown with the corresponding p-boxes in Fig. 5.

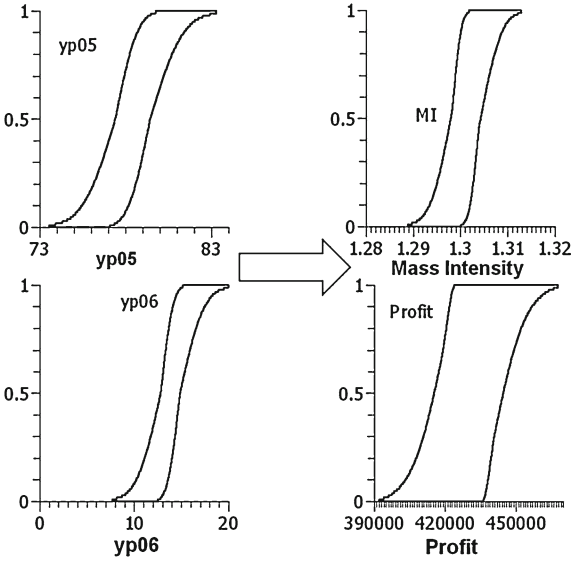


**Fig. 5** p-box representations of the values of inputs and outputs in Case 1

The characteristics of the sustainability of the industrial ecosystem are summarized below.

$$\begin{aligned}&\text{Mass intensity:}\\&\text{Mean} = [1.298, 1.305], \text{Median} = [1.298, 1.304],\\&\text{Range } = [1.289, 1.313], \text{Variance} = [1.577e-08, 4.014e-05].\end{aligned}$$

$$\begin{aligned}&\text{Profit (\$/year):}\\&\text{Mean} = [422615, 437057], \text{Median} = [421045, 438448],\\&\text{Range } = [391999, 467673], \text{Variance} = [3.058e+07, 7.658e+07].\end{aligned}$$

This case shows that DBC approach is effective in solving simple algebraic models. However, as we mentioned before, for black-box models or other complex models where the repeated parameters cannot be avoided, DBC approach is not applicable.

### 4.4.2 Case 2: Application of DLLHS Method in a NLP Optimization Problem

The following nonlinear optimization programming (NLP) problem was adopted from Das and Dannis' work (1997) to illustrate how to apply DLLHS method in NLP. The problem is stated as:

$$J = \min\left\{3x_1 + 2x_2 - \frac{3}{x_3} + 0.01(x_4 - x_5)^3\right\}, x \in \mathbb{R}^5,$$

subject to

$$\begin{aligned} x_1 + 2x_2 - x_3 - 0.5x_4 + x_5 - 2 &= 0, \\ 4x_1 - 2x_2 + 0.8x_3 + 0.6x_4 + 0.5x_5^2 &= 0, \\ x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 - 10 &\leq 0. \end{aligned}$$

In the deterministic case, the optimal solution is $f_{\min} = -4.0111$, when $x_1 = -0.9216, x_2 = -0.4741, x_3 = -0.6350, x_4 = -0.9461, x_5 = 2.761$. In this case study, it is assumed that the coefficient of $x_1$, which is denoted as $\alpha$, is uncertain. So the objective function can be rewritten as:

$$\min\left\{\alpha x_1 + 2x_2 - \frac{3}{x_3} + 0.01(x_4 - x_5)^3\right\}, x \in \mathbb{R}^5,$$

subject to

$$\begin{aligned} x_1 + 2x_2 - x_3 - 0.5x_4 + x_5 - 2 &= 0, \\ 4x_1 - 2x_2 + 0.8x_3 + 0.6x_4 + 0.5x_5^2 &= 0, \\ x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 - 10 &\leq 0. \end{aligned}$$

Based on the available, yet insufficient information, it is only known that $\alpha$ can be expressed as a normal distribution with the mean $\mu = (2.5, 3.5)$ and standard deviation $\sigma = (0.5, 1)$. Thus $\alpha$ can be denoted as $\alpha \sim$ Normal ([2.5, 3.5], [0.5, 1]). Under this circumstance, what will be the optimal value of the objective function?

To solve this problem, the DLLHS method was utilized to generate samples of $\alpha$, then these samples were sent to the optimization solver in Matlab. After the calculation using Matlab, the results were sent back to RiskCalc 4.0 to interpret the results in the form of a p-box. One hundred and one thousand samples were taken respectively for comparison. The distribution of the optimal solutions is expressed in Fig. 6.

It was found that the distribution of the minimal value of the objective function using 100 samples can be expressed as:

$$\text{Range} = [-5.976, -2.5004], \text{Mean} = [-4.43, -3.62], \text{Variance} = [0.12, 1.38].$$

While the distribution of the results using 1000 samples can be expressed as:

$$\text{Range} = [-7.1679, -1.9276], \text{Mean} = [-4.24, -3.83], \text{Variance} = [0.31, 1.26].$$

Comparing the results under different sample sizes, it is obvious that the range of mean and variance of the results using 1000 samples become narrower. This shows that if more samples are available, the degree of uncertainty can be decreased and the results will approach the solution in the deterministic case. Actually, the sample size required for a particular analysis depends on various

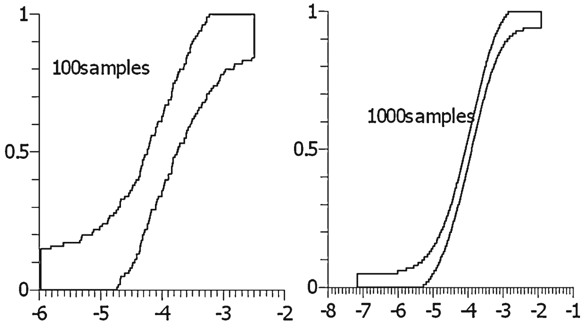


**Fig. 6** Comparison of minimization results at different sample sizes

factors, such as the model type, the random number generator adopted, type of uncertain distributions, and number of variables, and it cannot be determined universally (Wang et al. 2004). The general tendency is to reduce the sample size as much as possible without adverse effect on decision results.

## 5 Discussion

This case study demonstrates the applicability of using DLLHS method in solving optimization problems under uncertainty. It should be noted that the efficiency of this novel DLLHS method can be further improved. In this DLLHS method, LHS method was adopted in both the inner loop and the outer loop. More efficient sampling methods such as Hammersley Sequence Sampling (Diwekar and Kalagnanam 1997) could sample the p-box more efficiently and lower the computational cost even further. In the future work, the authors will try to utilize advanced sampling method to improve the computational efficiency.

In this case study, a single nonlinear objective optimization problem under uncertainty is solved. The principal aim of sustainable development is to achieve economic prosperity, environmental cleanness, and societal well-being simultaneously. In order to satisfy this “triple bottom line”, sustainable development becomes multi-dimensional in nature. The multi-objective decision-making becomes a vital issue in practical engineering fields. The authors view that the black-box compatible methods (DLS, OPS, and PCS), together with a multi-objective optimization algorithm, can be used to handle the challenging multi-objective optimization problems under severe uncertainty as well. The authors will work along this direction in the future.

## 6 Conclusion

In methodological study on sustainability, one of the most challenging issues is how to deal with various types of uncertainties. In PBA method, uncertainty is represented by probability box (p-box), which explicitly expresses both variability and imprecision. The most challenging issue in using PBA is how to model the propagation of uncertainty through complicated mathematical models in simulation and decision-making. In this chapter, two types of p-box computational algorithms: the DBC method and the black-box compatible methods (DLS, OPS and PCS) were studied. It was found that the DBC method can be used in simple algebraic-model-based simulation, but not in complicated models. On the other hand, the DLS, OPS, and PCS methods can be used in simulation-based complicated models and they are applicable in optimization under uncertainty.

However, PBA-based methods are not omnipotent. In PBA, the critical information about a specific uncertain quantity is the range and probability distributions of the p-box. Facing extremely severe uncertainty when even the bounds of probability are not available, or when only subjective value is available, the PBA-based methods will not be applicable. Under the circumstance when even the bounds of probability are not available, the IGT (Ben-Haim 2001) may be applicable. For the case of only subjective value is available, the fuzzy arithmetic method may be a good alternative (Liu et al. 2009).

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# Life Cycle Assessment (LCA): A Means to Optimise the Structure of Sustainable Industry

**Michael Narodoslawsky**

**Abstract** Sustainable development will become a forceful driver of re-structuring industry in the twenty-first century. As a comprehensive development concept, sustainability will influence all aspects of industrial processes, from their raw material base to their size and location to their interaction with each other and the environment and finally to their economic and social implications. This tall task requires completely new approaches to decision support. The methodology for the decision making process within the framework of sustainable development is still far from complete. Life Cycle Assessment (LCA) will, however, almost certainly become part of this process. This contribution explores the capacity of LCA to (and the requirements for LCA methods necessary to) solve questions of optimal process size, raw material base and structure. It will do so by using first-generation bioethanol processes and the interaction between an industrial and a municipal energy system as case studies, using the Sustainable Process Index as an LCA evaluation method.

**Keywords** LCA · Sustainable process index (SPI) · Sustainable industrial systems · Renewable resources

## 1 Introduction

The method of Life Cycle Assessment (LCA) has been developed over the last 20 years in order to generate a tool to report the environmental impact of human activities. As concern about environmental degradation entered political

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mainstream and more and more decisions in business and politics were influenced by environmental pressures, the necessity for a solid methodological base for societal discourse became evident.

The major innovation behind LCA was the recognition that the production of goods as well as the provision of services is, from an environmental point of view, always integrated in a chain of human activities that take resources from nature, processes them within society and eventually re-introduce these emissions and wastes created throughout this chain of activities into the biosphere. On top of material and energy exchange with the environment, each and every step along this chain creates additional impacts from influencing the habitat of other species to changing the species spectra of particular environs. Decisions about any step in the chain influence the impact of providing the good or service in question. Therefore meaningful discourse about the ecological impact of a given product or service can only be based on the information regarding the impact of the whole "life cycle" from "cradle to cradle". It goes without saying that this approach constitutes a major departure from the conventional way to assess especially economic activities that more or less concentrate on all activities that are within the direct responsibility of the producer or provider, leaving the assessment of the provision of resources as well as the use phase of a product to the respective responsibility of suppliers and consumers, with markets as regulatory instruments co-ordinating their decisions.

Besides the departure from the principle of individual responsibilities along the value chain LCA faced (and still faces) another formidable challenge. All assessment must be based on a value system in order to distinguish between the merits of different alternatives. Environmental assessment is no exception to that rule. We lack however a comprehensive and generally agreed upon value system for environmental impacts of human activities. Environmental impacts are either seen from the angle of a threat deemed to overshadow all other environmental impacts as with the carbon footprint (Wiedmann and Minx 2008) or described as diverse and incommensurable influences, leading to sets of unrelated indicators for each category of impact (Guinée 2002). The lack of an agreed measuring method requires a delicate approach towards standardisation of LCA. The ISO standards 14.040 (International Organisation of Standardisation 2006) to 14.048 (International Organisation of Standardisation 2002) therefore regulate procedural aspects of how to report and what to include into an LCA and are less specific when it comes to methodological approaches.

For the practical work of engineers life cycle thinking is becoming more and more instrumental. Engineers by definition cause environmental impacts in their professional activity. They are therefore at the forefront of changing society towards sustainability in ecological (as well as social and economical) ways. They need however operational methods to evaluate the impacts of technical processes and artefacts in order to generate sustainable technological solutions. This contribution will show ways how LCA may help engineers to meet the challenges of sustainability in the twenty-first century.

## 2 Background

Sustainable development will require major changes in the industrial fabric of society. Hence engineering work in the next decades will address questions that have been solved for the existing technological structure but that gain new importance. Among them are:

*Size and raw material*

Current engineering work is very much influenced by "economy of scale" considerations, leading to ever bigger technical structures. This approach however will be challenged as the raw material source of society changes from (scarce and polluting) fossil materials to renewable resources. Different structural approaches for the production of bioethanol, from conventional central bioethanol plants with natural gas as an energy source to integrated, more de-central solutions based on various possibilities to provide process heat on the base of renewable resources will exemplify this challenge. This analysis shows that with a change of the raw material base towards renewable resources, a completely new discourse about size, location and technology choices will be opened. Besides the concept of "economy of scale" the new concept of "ecology of scale" will become increasingly important.

*Integration of industry and societal needs*

A second major challenge lies in integrating industrial processes with societal material and energy systems in order to make more efficient use of scarce resources while strengthening economical co-operation on the local and regional level. Integrating industrial production and the societal demand for energy provision may be a common challenge for industrial engineers in future. Together with changing the raw material base to renewable resources high potential for reducing the overall environmental burden while generating positive societal results (jobs as well as regional added value) can be realised. This will be exemplified by a case of integrating the energy systems of a city and a brewery.

## 3 Objectives

The objective of this contribution is to highlight major engineering challenges that come with a larger role of renewable resources in industry as well as more integration of energy provision for industry and society (again considering renewable resources). This will be accomplished by analysing two case studies with a highly aggregated LCA evaluation method and drawing lessons from these case studies regarding the use of LCA for engineering purposes as well as for the re-structuring of industry in general.

In particular the objectives of this contribution will be to investigate the impact of size of plants and resources on the ecological impact of process industry. In addition to that the case studies will address the possible "integration dividend" from the ecological point of view when energy provision of an industrial installation and a city are integrated.

All case studies presented in this contribution are based on European (more specifically, Austrian) context. The lessons drawn from them with regard to what LCA can accomplish in planning industrial processes and what in turn must be the features of LCA methods when applied to technical planning as well as what will guide a future industrial structure are however more general and depend only to a small extent on the geographical context of the case studies.

## 4 The Sustainable Process Index as a Measure of Industrial Sustainability

Engineering requires making decisions and finding optimal solutions in a framework defined by demands from costumers, economical restrictions, safety risks and ecological constraints. Applying LCA to engineering tasks means that the methods employed must give answers to the questions asked by engineers during the planning process.

A major guideline for engineering work is the concept of "optimality". This requires an engineer to find a solution that minimises or maximises a certain value in the context of the project at hand. In particular this may ask an engineer to optimise profit while minimising ecological impact.

Optimality always requires a certain target function which is based on a quantifiable measure, e.g. profit. From the point of view of ecological impacts of industrial processes we here run into a conundrum: either we focus on one particular pressure (e.g. greenhouse gas emission from a process) risking to overlook dangerous risks or we look at the broader range of impacts from an industrial process and have to put up with a multitude of measures to be minimised. This is a particularly uncomfortable situation for engineers as minimising one ecological pressure may actually lead to an increase in another category of environmental impact.

A way out of this situation is the use of highly aggregated environmental evaluation methods like the Sustainable Process Index (SPI). Such measures allow including different ecological pressures and making them commensurable. Any aggregation however is based on a model for comparing different factors which in turn requires a value judgement. If a measure should be used by engineers, this value judgement must be based on a scientific reasoning and the measure as such thoroughly grounded in scientific logic and data.

The SPI was deliberately developed to meet these challenges as an engineering tool that includes LCA in planning and technology development (Krotscheck and Narodoslawsky 1996). It measures the area to integrate a certain process sustainably into the biosphere (hence the larger the SPI, the greater the ecological pressure exerted by the process) and is based on two principles translating sustainability in requirements for material flows:

*Principle* 1. Anthropogenic mass flows must not alter global material cycles; as in most global cycles (like the carbon cycle) the flow to long-term storage compartments is the rate defining step of these dynamic global systems, flows induced by human activities must be scaled against these flows to long-term stores.

*Principle* 2. Anthropogenic mass flows must not alter the quality of local environmental compartments; here the SPI method defines maximum allowable flows to the environment based on the natural (existing) qualities of the compartments and their replenishment rate per unit of area.

The SPI is based on the assumption that a sustainable economy builds only on solar radiation as natural income. Most natural processes are driven by this radiation on the earth's surface and for the conversion of radiation into useful energy (e.g. heat) and renewable resources (e.g. wood or crops) surface area is needed. Surface area is a limited resource in a sustainable economy because earth only offers a finite surface to utilise solar radiation. Therefore area is a convenient measure for the SPI, the more area a process needs to fulfil a service the more it 'costs' from an ecological sustainability point of view. This aligns the SPI with the general concept of ecological footprints (Stoeglehner and Narodoslawsky 2008).

Using the two principles and the basic assumption the SPI is capable of evaluating the life cycle of very different technologies and products from the viewpoint of ecological sustainability using a single measure without focusing on only one impact.

The SPI calculates a total area $A_{\mathrm{tot}}$ for embedding a process sustainably into the ecosphere. This total area is the sum of partial areas:

$$A_{tot} = A_R + A_E + A_I + A_{st} + A_P \left[m^2\right], \tag{1}$$

where $A_{\mathrm{R}}$ stands for the area necessary to produce raw materials, $A_{\mathrm{E}}$ represents the area requirement to provide process energy, $A_{\mathrm{I}}$ takes into account the area attached to physical installations, $A_{\mathrm{st}}$ is the area required for staff and $A_{\mathrm{P}}$ denotes the area to accommodate products and by-products in the ecosphere.

The SPI is able to compare processes based on different resources (fossil or renewable). A thorough list of publications describing the application of the SPI to different technologies as well as free software to use this method can be downloaded from the webpage www.spionexcel.tugraz.at.

# 5 The Case Studies

## *5.1 Bioethanol Production: The Influence of Size and Energy Base*

The first case study involves different ways to produce bioethanol. This case study is based on previous work (Friedl 2005, 2007; Gwehenberger et al. 2007). Though the original study included a broader range of renewable resources for the production of ethanol for fuel, the data analysed here will only pertain to corn as a raw material in order to highlight the influence of scale more clearly. Dealing with bioethanol production in this paper does however not mean that the author necessarily promotes biofuel as a wise alternative. The reader is kindly referred to the argumentation of (Wenzel 2009; Stoeglehner and Narodoslawsky 2009) for further insight into this matter.

The general set-up of this case study is to compare the ecological impact of different ways to provide bioethanol from corn de-centrally, using only renewable energy resources. Three different sizes are investigated, namely 1.000, 5.000 and 10.000 t/a of ethanol production, spanning the range from a small farm based unit to a moderately regional unit in the Central European context. The results of this evaluation are then compared to a 60.000 t/a unit that uses natural gas as a process energy source. Three different technological options to provide bioethanol are compared:

*Option 1: Ethanol production in combination with a biogas combined heat and power (CHP) plant:* heat and electricity from the biogas CHP are utilised for the ethanol production, the surplus electricity is supplied to the grid. The size of the biogas CHP is chosen such that its heat provision exactly covers the demand of the ethanol plant. It utilises as substrate a mixture that conforms to sustainable agricultural practice in crop rotation with corn (see Friedl 2007).

*Option 2: Ethanol production in combination with biogas production:* in this case the biogas is directly utilised to supply process heat for the ethanol production. The biogas unit utilises only the mash generated by the ethanol process. Excess biogas (in the cases with 5.000 and 10.000 t/a capacity) will be utilised to generate electricity via a small biogas CHP, any deficit in biogas will be filled by natural gas.

*Option 3: Ethanol production combined with straw combustion:* in these cases process heat is generated by burning a part (15–28 % depending on the size of the plant) of the straw produced for providing the input to the ethanol fermentation. Mash will in these cases be utilised as a fertiliser since drying and selling as distillers dried grains with solubles (DDGS) is not a viable option considering the large energy demand and the ever narrower market for DDGS as ethanol production increases globally.

The challenge for comparing the ecological impact for different technologies using various raw materials is to find a fair base for comparison. In this case study the base is the agricultural area necessary to provide raw material as well as energy for the bioethanol plant. This area obviously differs from option to option. The evaluation therefore has to take all agricultural and logistic activities (planting, tendering, harvesting, transport from the fields (of crops and by-products) as well as to the fields (of residues from the bioethanol process) into account. A sustainable crop rotation is supposed and all products generated on the area in question that are not utilised by the bioethanol plant render a SPI bonus, calculated by applying price allocation to the whole set of products produced from the system “bioethanol plant + agricultural area”. All results presented below refer to technological solutions that are optimally adapted to the size of the plant in order to provide a level field for comparison in economical terms, too.

Figure 1 summarises the cost per litre bioethanol for the respective options, including the 60.000 t/a reference. One can clearly see the influence of the economy of scale with a steep decrease of production costs per unit with increasing size of the plant. The difference between the de-central options is relatively minor compared to the influence of size, with slight disadvantages for option 2. As the size approaches 10.000 t/a the production cost per unit comes within 10 % of the 60.000 t/a reference plant (which is still small by industrial standards).

This points to the fact that increasing the size of a plant renders diminishing returns for cost reduction for larger units. What is quite interesting is that costs become already competitive for relatively small de-central solutions. A reason for this is that in the options analysed here energy provision is realised either by using waste heat (as in option 1, where the main product from the system is electricity) or by utilising by-products of agricultural production or the process itself.

Figure 2 contrasts the economical evaluation with the ecological pressures exerted by the different options. The first fact that can be seen from this figure is that the use of renewable resources not only as raw materials but also for the provision of process energy drastically reduces the ecological pressure (by a factor of 2–4, depending on size and option), mainly due to the lower greenhouse gas emissions associated with renewable resources.

An interesting feature of this figure is that options 2 and 3 have almost the same values for the ecological pressure for the sizes 5.000 and 10.000 t/a although they employ very different technologies. The higher value of the SPI for the smallest size (1.000 t/a bioethanol) of option 2 results from the fact that in this case the

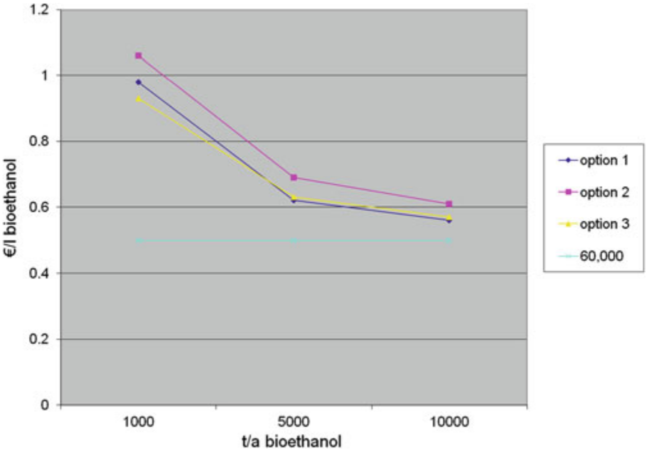

**Fig. 1** Cost to produce one litre bioethanol for different options

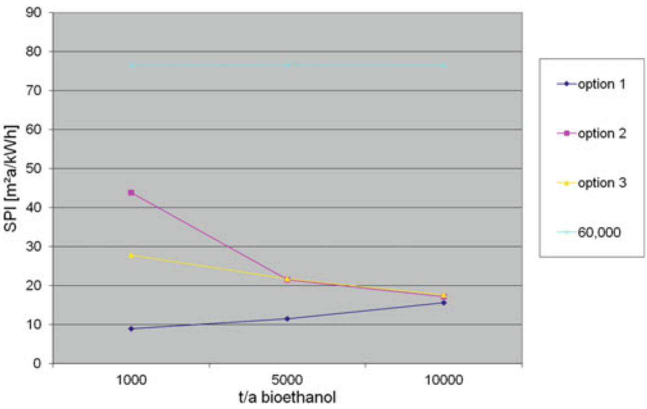

**Fig. 2** Ecological pressure calculated with the SPI method for different options

mash produced by the fermentation is not sufficient to supply enough biogas for process heat and therefore additional natural gas has to be used to supply heat.

Option 1 has a consistently lower ecological pressure than all other options. This results from the fact that in this case the main product is electricity and the bioethanol plant uses the excess heat to drive the process. It is also interesting that this option exhibits a contrary trend regarding the ecological footprint versus size of the plant compared to the others. While the SPI value decreases for options 2 and 3 due to higher efficiency of larger plants, option 1 shows an increasing ecological footprint, mainly due to the excessive transport necessary to return biogas manure to the fields as the plant size increases.

It should be noted that in the case of most options depicted in Fig. 2 the main impact still comes from greenhouse gases, as the assumption here is that agriculture and transport still use fossil fuel. There is also a shift in the respective importance of the steps along the life cycle as shown in Figs. 3 and 4.

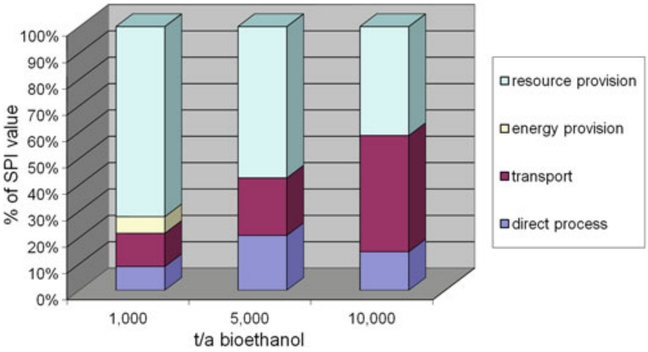

**Fig. 3** Contribution of different factors to the ecological pressure for option 1

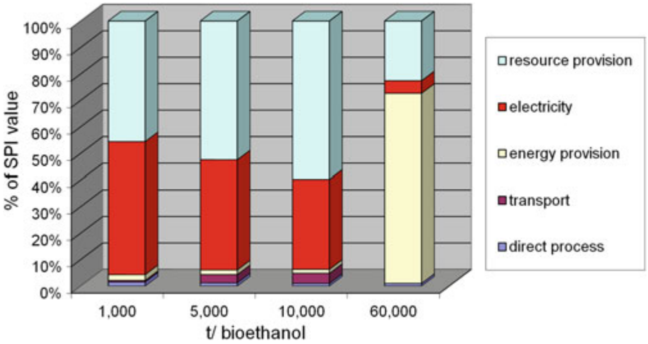

**Fig. 4** Contribution of different factors to the ecological pressure for option 2 and 60.000 t/a reference plant

In option 1 resource provision (and hence agriculture) clearly dominates the ecological pressure. Transport gains importance when the plant becomes bigger as the biogas manure has to be transported back to the fields.

In option 2 the electricity demand becomes important (as this must now be taken from the grid, with considerable fossil contribution to the electricity production, based on the Austrian context). Resource provision by agriculture is the second important factor.

For the reference plant process energy is by far the most important factor for the ecological pressure. This is due to the fully fossil provision of process heat (using natural gas).

## 5.2 *Brewery Heats Town: The Influence of Integrating Industry into Energy Provision for Society*

The second case study deals with the city of Freistadt in Upper Austria. This city of 7.500 inhabitants hosts a brewery that is located close to the historic city centre that is entirely under monument preservation. The latter fact does not allow any changes to the buildings e.g. for increasing their energy efficiency such as insulation or the installation of solar heating.

In the current situation (business as usual, BAU) the brewery employs an oil furnace and electrical chilling with a yearly total energy consumption of 4.700 MWh. The historic city is mainly heated by fossil resources with a yearly consumption of 13.000 MWh heat.

In the course of revamping the brewery and installing a new energy system the city (who actually owns the brewery based on a contract dating from the Middle Ages) contemplates an integration of the brewery and the historic city in one energy system while at the same time switching totally to renewable energy sources. In a detailed study commissioned by the city and the Austrian research programme “Energy for Tomorrow” (sponsored by the Ministry of Transport, Innovation and Technology) optimal energy systems scenarios for just revamping the brewery as well as integrating brewery and city were generated using Process Network Synthesis methodology (Friedler et al. 1995).

Figure 5 shows the results for the cost per MWh as well as the SPI value per MWh for the most interesting scenarios generated in this study.

The left-hand side three scenarios depict solutions for the brewery alone. The scenario at the left represents BAU, with an heavy oil furnace providing process heat and natural gas providing room heat in the brewery. The second scenario includes a micro gas turbine, utilising biogas from a nearby biogas plant with a wood chip furnace providing additional heat for process and room heating, the third scenario only provides process heat from a wood chip burner. In all cases chilling remains based on electricity. In the second scenario 25 % of the energy generated comes in the form of electricity that is sold to the grid.

Changing to renewable resources clearly reduces the ecological pressure dramatically by more than 50 %. Interestingly enough it also reduces costs by up to a factor of 3. The second scenario clearly comes out on top on both counts.

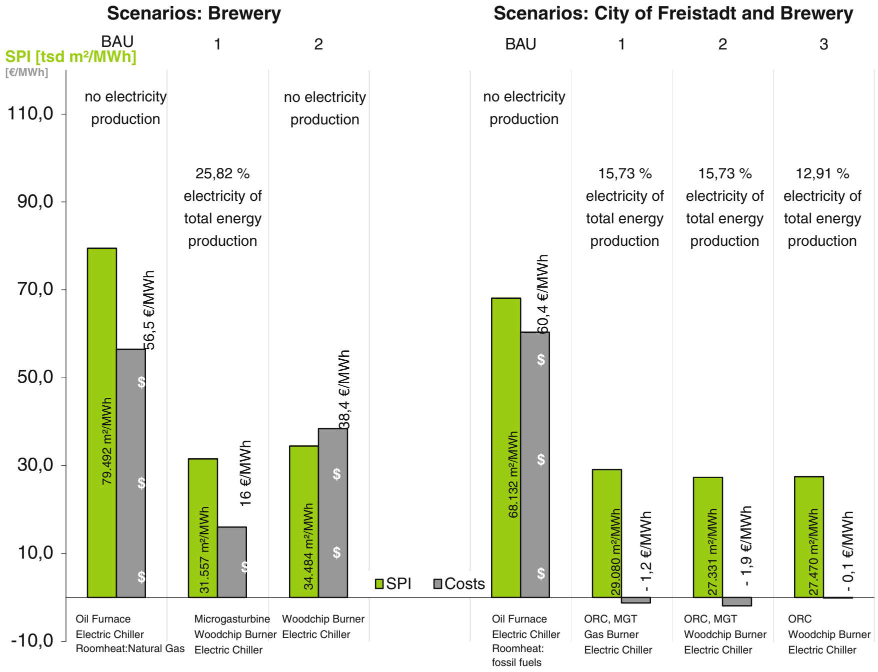

**Fig. 5** Costs and SPI value per MWh for different scenarios of energy provision for brewery and city of Freistadt

The four scenarios on the right-hand side represent the integration of brewery and city, with the most left scenario showing BAU for the brewery and the historic city. Scenarios 1, 2 and 3 (counted from BAU of city and brewery) are totally based on renewables, with scenario 1 utilising biogas in a micro gas turbine and a gas burner, supplementing heat from an Organic Rankine Cycle (ORC) plant operated with wood chips. Scenario 2 supplants the gas burner with a wood chip burner while scenario 3 does not use any biogas and provides heat by ORC and wood chip burner. The technology mix is in all scenarios adapted to the differing demand over the year, with some elements (e.g. ORC) supplying base load and others generating necessary peak load.

Again, in all scenarios based on renewable resources for supplying city and brewery, the ecological footprint calculated for the whole life cycle (including agriculture and forestry when applicable as well as all emissions) per MWh is lower by more than 50 % compared to the BAU scenario and consistently lower than any scenario where the brewery "goes it alone". What is astonishing however is that the cost per MWh for integrated systems may even become negative. This is due to the favourable feed-in tariffs for electricity from renewable resources that make the overall system a bargain as electricity is sold to the grid.

## 6 Conclusions

The case studies show that sustainability requires a profound re-structuring of industry as economic optimisation is not the only aspect that will shape industrial processes. The integration of environmental (and social) considerations into the decision making process will affect the raw material base, size and structure of the industry in the twenty-first century. As a rule process industry will be faced with the necessity to optimise not only single production lines but more complex, network-like structures, where de-central and central facilities will operate and provide services in terms of energy provision and regional value added besides the provision of goods.

Some tenets of process industry will have to be changed if sustainability is taken seriously. Economy of scale may have to be balanced by ecology of scale when renewable resources come into play and questions of the ecological pressure of transport become more relevant due to low transport densities and high water content of both bio-resources and residues. The case study on bioethanol production shows that neither the totally de-central small-scale solutions nor central large-scale plants offer the "sustainability optimum" of low cost paired with low environmental pressure. New compromises of "regional, medium-scale" industries that pair high efficiency of scale with acceptable transport will carry the day when renewable resources become more dominant.

The case study on integrated industry/society solutions points to the fact that the higher the level of integration the lower the ecological pressure of the system becomes. It also points out that major economic advantages may be generated by integration of industry and communities regarding energy provision.

The case study on bioethanol production has clearly shown that the distribution of ecological pressures along the life cycle may change dramatically when de-centralised solutions based on renewable resources are employed. The more de-centralised and the more dependent an industrial system becomes on renewable resources, the larger will be the ecological impact of providing the resources. It may therefore be more efficient to address ecological problems of the resource sector (agriculture and forestry) as well as the transport sector. As a rule, processes that are predominantly based on renewable resources will benefit more from an overall system change towards sustainability than processes based on fossil resources.

LCA will play a prominent role in the optimisation of such sustainable industrial systems. In order to support decisions in the future, LCA evaluation methods have to fulfil certain requirements: they must be able to distinguish between different raw material and energy systems (especially to distinguish between fossil and renewable resources) and they must provide easy-to-read information for decision makers (preferably via aggregated measures). On top of that they must be able to evaluate networks of technologies rather than single technologies and provide a clear indication about ecological "hot spots" within technology networks as well as information about the effect of logistics and transport on the overall ecological pressure of industrial systems.

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# Practical Approaches to Sustainability: iSUSTAIN® Tool for Green Chemistry Case Study

Karen Koster and Martin Cohen

**Abstract** This chapter illustrates one approach in the development of a green chemistry scoring tool developed in the chemicals industry. In a collaboration between Cytec Industries Inc. (Cytec or the Company) and the Beyond Benign organization, a green chemistry tool, called iSUSTAIN®, was developed. The tool provides a means to measure the relative sustainability of a product, based upon the *Twelve Principles of Green Chemistry*. Each of the *Twelve Principles*, which range from atom economy to reduced energy and process hazard safety, has been included in the tool. The tool provides a definitive measure of the sustainability of products and processes, enabling the development of an initial sustainability baseline and guidance for improvement, and acts as a learning tool for the technical community to gain an appreciation of the factors within their control that can affect the overall green chemistry aspects of their processes. This tool was developed to serve as a metric to assess the relative "greenness" of both new product ideas and existing commercial products. In addition, the tool was made available for public use. By making this tool available at no cost to academic and public users, it was intended to foster learning and change the mindset of scientists at universities so future generations of researchers will have these principles of sustainability well ingrained in their thinking.

**Keywords** Green chemistry · Green chemistry tool · Twelve principles of green chemistry

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# 1 Introduction

Over the past decade, companies have progressed in their efforts to actively support principles of sustainable development.[1] These efforts typically begin with "footprint" type programs, such as efforts to reduce waste and energy usage, and then look at other opportunities across the value chain to make improvements in the environmental, health, safety, or social impacts of an enterprise. There is growing pressure for companies to have definitive measures in sustainability performance.[2] As a result, more and more companies are reviewing their sustainability approach to determine how they can begin to address the broad issues of environmental and social aspects of their business. One difficulty in approaching an implementation strategy for sustainability is defining the scope and addressing the complexity inherent in addressing environmental and social aspects of complex operations and systems. Moreover, it is difficult to articulate and measure sustainability in a way that will resonate with employees at all levels of an organization, and which will change behaviors and outcomes.

Having made other efforts to measure the environmental impacts of operations, such as waste and energy usage, the Company shifted its focus to its products. Thus work began to develop a "practical" tool to measure the sustainability of products. The level of complexity of the Company's product mix and process chemistries made the use of simple formulation based approaches to measuring the sustainability of a product impractical. However, there was a need to develop a tool to measure sustainability that was capable of being used by bench chemists and which would not require a team of experts to implement. Therefore, over the course of two years, the Company developed a tool, called the iSUSTAIN® Green Chemistry Index (or the Index), based on the *Twelve Principles* to accomplish this objective. In this case study, we will describe the approach and efforts to develop the tool, provide detail on the tool, and provide an analysis of the benefits and potential use.

## *1.1 Objective*

The objective of the tool is to measure the relative sustainability or "greenness" of a product, using one methodology. In assessing the need, teams within the Company determined that the tool needed to be flexible enough to apply to monomers, oligomers, polymers, bonded materials, and articles. In addition, they found that the

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[1] Sustainable Development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987).

[2] For instance, the Global Reporting Initiative (GRI) is a network-based organization that provides a framework for best practice in sustainability reporting, and the number of companies reporting using GRI framework has increased over time (Global Reporting Initiative 2012).

tool needed to be capable of addressing all the key elements of green chemistry, and needed to be simple enough for bench chemists and researchers to use in their work. Benefits of development of the tool included being able to compare sustainability of products within a portfolio, or compare one product versus the next generation product; to assess the environmental, health, and safety aspects of the substitution of a raw material, catalyst, or solvent in a product; and to begin to develop a database that could be used in life-cycle analysis (LCA) for a product or product portfolio. Ultimately the tool could be used to drive the development of greener products, benefiting all stakeholders.[3]

### *1.2 Green Chemistry Defined*

Green Chemistry is the design of chemical products and processes that reduce and/or eliminate the use and/or the generation of hazardous substances (Anastas and Warner 1998). This approach requires an open and interdisciplinary view of material and product design, applying the principle that it is better to consider waste prevention options during the design and development phase, rather than disposing or treating waste after a process or material has been developed. Through a principle-based approach, green chemistry results in increased efficiency, reduced hazards, and the elimination of waste. Green Chemistry in practice implies designing safer, economical, and efficacious processes and products. All of these aspects are indicative of good product design and good manufacturing processes and can result in economic benefit for institutions that implement these practices. Green Chemistry offers a concrete path to achieve sustainable and safe laboratory practices. The *Twelve Principles of Green Chemistry* establish a framework for practicing chemists to follow along this path.

### *1.3 Description of the Work*

Work commenced on the iSUSTAIN® Green Chemistry Index as part of an effort to develop a method to measure the sustainability of products. The Company worked with initial input from Dr. John Warner (Warner-Babcock Institute of Green Chemistry, and the Beyond Benign organization), who provided guidance

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[3] The iSUSTAIN® Index provides the user with a respected way to articulate the environmental performance aspects of a process up and down the customer supply chain. From a technical perspective it can be an invaluable design tool. From a marketing perspective it can help communicate the true value of a process to internal and external clients. From any perspective the iSUSTAIN® Green Chemistry Index provides an objective assessment to effectively plan efforts across an organization while not inhibiting the existing structure (Warner 2009, private communication).

on the use of the *Twelve Principles of Green Chemistry* (Anastas and Warner 1998) as a foundation for the Index and provided a basic framework around which to build it. Formulation of the basic metrics included in the Index was completed, and software design on a Web-based interface and system began. By the end of the first year of the project, a trial development version of iSUSTAIN® was available on the intranet. The first version of the web-based application was rolled out in the first quarter of the second year with training for about 60 internal project leaders in the use of the tool. Since the development, the tool was made publicly available.

Methodologies to provide qualitative and quantitative measures of the impact of production and use of manufactured items to human health and the environment go back many years but reached more general public awareness through publication of the United Nations Brundtland Commission Report in 1987 (United Nations 1987). Activities in developing metrics increased dramatically from that point (Curzons et al. 2001). Sustainability metrics reported in the literature run the gamut from the laboratory-based EcoScale (Van Aken et al. 2006), to full cradle-to-grave life-cycle assessments.[4] The former has a limited application scope of the laboratory, while the latter requires considerable training to execute and a formidable amount of information, most of which is not readily available. In order to develop a practical approach to measuring sustainability of products, a number of obstacles were addressed. First was availability of product-related data. While many regulated companies have data warehouses of compositional data to support product registration and hazard communication efforts, having data available on each of the *Twelve Principles* would require considerable effort. A second challenge was development of tools that can measure green chemistry elements. While the *Twelve Principles* provide a solid basis for defining green chemistry, each element would need to be defined in a way that could be measured. As a final obstacle, the team needed to develop a practical tool that could be rolled up and used by research chemists with a system that is easy to use and does not require special expertise.

Making the tool publicly available was an additional decision that was made. Many industry developed green chemistry tools are being used internally in product assessments and are not generally available. In addition, there is not an industry recognized metric for green chemistry. In this case, it was decided to make the tool publicly available to provide a mechanism for the software to be maintained, and to further promote the use of the *Twelve Principles* as a way to define the green chemistry of products. It was the further hope that if a consensus standard is ultimately developed, that this methodology could be used as a basis of a consensus standard. Finally, as regulators begin to expect companies to provide data behind their marketing materials on green products, having an externally recognized tool for measuring product sustainability should support compliance with regulations and stakeholder expectations.

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[4] See (Azapagic et al. 2006) for an example of excellent development of an LCA.

Faced with a lack of a metric that met internal needs, the Company embarked on the development of the metric. The tool would provide a wider scope than the simpler metrics but use currently more readily available information than that which is required for a full “cradle-to grave” life-cycle assessment (see United States Environmental Protection Agency 2010 and Tester et al. 2005). In this regard, the tool incorporated the green chemistry aspects of raw materials, but focused on the sustainability attributes of the product being made by the Company, i.e., a “cradle-to-gate” analysis. However, efforts will continue to expand the tool to look at sustainability impacts by the customer over time through dialogues and workshops with like minded customers.

In summary, there were three main goals for the metric: (1) To afford a measure of the sustainability of our products and processes through initial laboratory development to commercialization, allowing for an initial sustainability baseline and guidance for improvement, (2) to act as a learning tool for the technical community to gain an appreciation of the factor within their control that can affect the overall sustainability of the products and processes, and (3) to allow development of summary statistics on sustainability and track performance against corporate goals. These goals, if achieved, would enable the Company to measure its sustainability performance of its products through the application of green chemistry.

## 2 Development of the iSUSTAIN® Green Chemistry Tool

### *2.1 Science and Innovation*

The iSUSTAIN® Green Chemistry index was designed to actualize use of the Twelve Principles of Green Chemistry. For each principle of green chemistry, there is a metric (calculation) that will measure the principle. These are detailed in Table 1.

Output from use of the Index for evaluation of a coatings product example is shown below (note that all scores range from 0 to 100 with 100 being the best performance).

### *2.2 Using the Index*

To use the iSUSTAIN® Index, the user generates a scenario. The scenario contains information on the materials going into a process (the Bill of Materials In or “BOM In”), the materials out of a process (the product and any waste streams—the Bill of Materials Out or “BOM Out”), and the conditions used for the various steps in a process (the Process Steps). Several alternative scenarios can be generated for the same product/process, making changes within them to evaluate their effect on the overall sustainability score, thus allowing the user to do a “what-if” analysis.

**Table 1** Green chemistry index

| Principle of Green Chemistry | Metric | Source |
|---|---|---|
| 1. Waste prevention | E-factor (modified from standard form) | Industry standard |
| 2. Atom economy | Reaction mass efficiency (RME) | Industry standard |
| 3. Less hazardous chemical synthesis | Uses safety, health, environmental impact, and regulatory status scores developed in the Raw Materials database to provide an overall impact for the raw materials used | Original metric |
| 4. Designing safer chemicals | Uses aquatic toxicity and human toxicity assessed through modeling (EPA's ECOSAR program and others) or actual experimental data where available | Mixed metric |
| 5. Safer solvents and auxiliaries | Uses safety, health, environmental impact and regulatory status scores developed in the Raw Materials database to provide an overall impact, for the solvents and auxiliary materials used | Original metric |
| 6. Design for energy efficiency | Uses time, temperature, pressure, and mass information for individual process steps to provide a rough assessment of the overall energy use | Original metric |
| 7. Use of renewable feedstocks | Uses the common industry practice of the sum of the weight of renewable raw materials in a product per weight of product | Industry practice |
| 8. Reduce derivatives | Uses the complexity of the process train to develop a quantitative measure | Original metric |
| 9. Catalysis | A qualitative metric is used to note if a catalyst is employed or not | Original metric |
| 10. Design for degradation | Uses the EPA's assignment of biodegradability assessed through modeling (EPA's BIOWIN [a] program) or actual experimental data where available | Mixed metric |
| 11. Real-time analysis for pollution prevention | A questionnaire-based assessment of the degree to which appropriate engineering controls have been applied to a process | Original metric |
| 12. Inherently safer chemistry for accident prevention | A table-based assessment of a number of common hazard areas for the process (extreme conditions, exothermicity, flammability, etc.) | Original metric |

[a] Part of the EPA Sustainable Futures EPM (TM) suite of software (United States Environmental Protection Agency 2012)

In the Internet-based system, the user generates a scenario for the process of interest as follows. Next the user inputs the data relevant to the assessment. The instructions are based on a set example from the chemical industry.[5]

### 2.2.1 Bill of Material In

The BOM In table is a listing of all raw materials, diluents (water or solvent that also are part of the product), other solvents, and auxiliary materials (catalysts, initiators, acids, bases, etc.) that go into the process of making the material under consideration. The material can be a mixture or be created using chemical synthesis. The user decides on a particular scale for the process and lists the amounts of each material according to that scale. Raw materials are substances that exit the process as part of the final product. Diluents are water or other solvents that also are part of the product. Materials designated as solvents are those that are not part of the product, including solvents used for washes and cleanouts. Everything else that does not end up in the product is classified as an auxiliary material. The user lists the percent of each particular material that is from a renewable resource to the best of their knowledge. In this regard, the Company provides a definition of renewable raw materials (RRMs) and the researcher can check the material against the definition, or refer to a listing of materials known to be renewable based on the definition. Scoring for the material for Safety, Health, Environmental Impact and Regulatory Status is provided from the iSUSTAIN® Raw Materials database. Note that all final scores used and generated by the iSUSTAIN® Index are scaled between zero (the lowest) and 100 (the best).

### 2.2.2 Bill of Materials Out

The BOM Out table is a listing of ALL materials coming out of the process, which includes the Product and all of the separate waste streams, with the amounts listed using the same scale as used in the BOM In table. "% Diluents" is defined as the (sum of all diluent weights)/(full product weight). To input materials into the BOM Out table, the user inputs the Product name, weight, and "% Diluents". In addition, special instructions for human toxicity, aquatic toxicity, and ultimate biodegradation are provided.

### 2.2.3 Process Steps

The Process Steps table collects data on the process to allow an assessment of the complexity and potential hazards of the process as well as the energy used by the

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[5] Synthesis of isopropyl lactate, freely adapted from Blatt (1943).

process. Both are relatively simple calculations to facilitate their use. For Process Complexity, one aim is to count the different unique pieces of equipment that the process uses, whether at lab scale, plant scale, or somewhere between. The second aim is to count how many times material is either added to or removed from any piece of equipment while the process is running (additions of any materials, distillation, removal of a split, aqueous washes—which would be both an addition and a removal, etc.). Initial feeds of materials to an empty reactor at the start of the process are not counted.

For rough quantification of energy use, the process should be broken up into steps where there is a substantial change in temperature, pressure, or equipment used, and these are entered into the Process Steps table along with duration in hours, total weight, and heat capacity of the process mixture for each step.

### 2.2.4 Principles of Green Chemistry as Applied in the Index

The following are the metrics developed in alignment with the *Twelve Principles of Green Chemistry*. The final score for each metric is scaled between 0 (the lowest) and 100 (the best). In some cases this scaling requires use of a normalization algorithm. Lastly, all final values are rounded to the nearest 5, recognizing the variability in any of the assessments.

In developing the scaling for each metric, a number of considerations were addressed. Some metrics, such as Metric 3, Safe Raw Materials, by their method of calculation inherently scale between 0 and 100. These are left as is, of course. Others, such as Metric 6, Energy Efficiency (EE), are unbounded on the high end. For these, an "s"-shaped normalization algorithm was applied that reflected the anticipated range of the particular metrics within the chemical industry. Taking Metric 6 as an example, there are some very simple formulation processes that literally require no more than mixing of components at ambient temperature. On the other hand, there are synthetic processes like the production of ammonia from nitrogen that requires a great deal of energy. The goal was one index system that could accommodate this wide range of processes, requiring in the end a subjective decision as to how to shape the normalization function.

A second complication is that different industries within the chemical enterprise may have greatly different ranges for some of the metrics. A notable example here is Metric 1, Waste Prevention, which uses a modification of the industry-standard E-factor, the total of wastes produced in a process divided by the amount of product. For the specialty chemical industry, this metric typically can range between 0.5 and 5, meaning that for every pound of product produced, 0.5–5 pounds of waste are also produced. For the pharmaceutical industry, however, E-factors as high as 100 are not unusual. Once again, the desire was to accommodate both industries, with the result that for the coatings formulation industry, energy and waste will score near 100 (the best) and for the pharmaceutical industry, waste may score near 0 (the lowest).

The next section will go through each green chemistry principle and detail the metric calculation.

# 3 The Principles of Green Chemistry

## 3.1 Waste Prevention

*Principle* 1: *It is better to prevent waste than to treat or clean up waste after it is formed.*

*Wastes are assigned to severity classes. The* $E^+$*-factor is the sum of each weight of generated waste times its severity class, all divided by the total weight of the end product (on a neat basis—diluent not included in the weight of the final product) and is modified from the form initially suggested by* Sheldon (1992). *It is a useful tool for rapid evaluation of processes based on overall generated waste. Wastes that are used elsewhere to derive some benefit (burning to produce power, byproduct synergy—used as a raw material in another process) are not counted as wastes herein.*

The severity class Table 2 is a means to recognize that some wastes are worse than others. The user assigns the various wastes generated in the process to these classes using best judgment or with guidance from a process engineer. The equation below is then used to generate the $E^+$-factor and finally the normalization algorithm shown is applied to scale the value between 0 and 100.

Metric Scaling Range (Table 3).

Example Data and Output (Table 4).

$$\mathrm{E^+\text{- Factor(Environmental factor)}} = \frac{\sum_i (\mathrm{Wt\ Waste_i})(\mathrm{Severity\ Waste_i})}{(\mathrm{Wt.\ Desired\ Product})(1 - \%\ \mathrm{Diluents}/100)} = 3.08$$

$$\text{Normalized } \mathrm{E^+}\text{-Factor} = 70.$$

**Table 2** Severity class and environmental fate

| Severity class and environmental fate | Severity multiplier |
|---|---|
| 1. (Semi)Solid hazardous waste land disposal/containment | 10 |
| 2. (Semi)Solid hazardous waste incineration | 4 |
| 3. (Semi)Solid non-hazardous waste landfill | 2 |
| 4. Waste water (appropriate to send to treatment plant) | 0.5 |

**Table 3** Metric scaling range waste

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 0 | 0.4 | 6 | 50 | Unbounded (200) |

**Table 4** Example data and output

| Bill of Materials Out | Type of material | Weight/ batch | % diluents | Severity multiplier | Weight times severity |
|---|---|---|---|---|---|
| Isopropyl Lactate | Product | 360 | 50 | | |
| Azeotrope water | Waste Class 4 | 25 | | 0.5 | 12 |
| Sodium sulfate filter solids | Waste Class 3 | 13 | | 2 | 26 |
| Reactors wash | Waste Class 2 | 129 | | 4 | 516 |

## 3.2 Atom Economy

*Principle* 2: *Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.*

Reaction Mass Efficiency (Trost 1991 and Constable et al. 2002) is formally the ratio of the moles of product times the formula weight of the product divided by the sum of the moles of each reactant times their formula weights. This metric measures the efficiency of utilization of raw materials into the product, with 100 being the highest possible (all starting materials entirely incorporated into product—e.g., a ring opening polymerization) (Tables 5, 6, 7).

$$\mathrm{RME} = \frac{(\mathrm{Wt.\ Desired\ Product})(1 - \%\ \mathrm{Diluents}/100)}{\sum its_{\mathrm{i}}(\mathrm{Wt\ Raw\ Material_i})(1 - \%\ \mathrm{Recycle_i}/100)} = 70.$$

**Table 5** Metric scaling range RME

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | >0 | 25 | 60 | 85 | 100 |

**Table 6** Example data RME

| Bill of Materials In | Type of material | Weight/ batch | Est. % recycle | % renewable | Catalyst mole % |
|---|---|---|---|---|---|
| Lactic acid 50 % (2-hydroxypropionic acid) | Raw | 212 | 20 | 100 | 0 |
| Isopropanol | Raw | 450 | 80 | 0 | 0 |

**Table 7** Example output RME

| Bill of Materials Out | Type of material | Weight/batch | % diluents |
|---|---|---|---|
| Isopropyl lactate | Product | 360 | 50 |

**Table 8** Metric scaling range less hazardous chemical synthesis

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | >0 | 30 | 70 | 90 | 100 |

## *3.3 Less Hazardous Chemical Synthesis*

*Principle* 3: *Whenever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.*

Based on available safety, health, and LCA information, scorings for these impacts and regulatory status for many common raw materials have been developed. These separate scorings are combined into a single Raw Material Impact number for each material according to the formula, which are combined for all of the raw materials in the process according to the equation below to give a final Total Process Raw Material Impact score. If a portion of a material is recycled, then that portion is not counted in this tally (Tables 8, 9).

$$\text{Total Process Raw Material Impact} = \frac{\sum_i (\text{MatImp}_i)(\text{Wt Raw Material}_i)(100 - \%\,\text{Recycle}_i)}{\sum_i (\text{Wt Raw Material}_i)(100 - \%\,\text{Recycle}_i)} = 85.$$

## *3.4 Designing Safer Chemicals (DSfC)*

*Principle* 4: *Chemical products should be designed to preserve efficacy of the function while reducing toxicity*

For this metric, aquatic and human toxicity of the product is determined as follows:

For products with available European Risk Phrases,[6] the human and aquatic toxicity concerns are determined using the algorithms in the Raw Materials Database where Health is used for human toxicity and Environmental Impact is used for aquatic toxicity, respectively (Table 10).

The aquatic toxicity concern for discrete substances without assigned European Risk Phrases is determined using available or modeled data (U.S. EPA ECOSAR program or the appropriate module from the OECD QSAR Toolbox) (United States Environmental Protection Agency 2012 and OECD 2012) and the following guidelines.

U.S. EPA Aquatic Toxicity Guidelines (Table 11).

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[6] R-phrases (short for Risk Phrases) are defined in (European Agency for Safety and Health at Work—Directive 67/548/EEC 1967) Annex III.

**Table 9** Example data and output less hazardous chemical synthesis

| Bill of Materials In | Material type | Weight/ batch | Est. % recycle | % renewable | Catalyst mole % | Usage weight/ weight | Safety | Health | Environmental impact | Regular status | Mat Imp | % of total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lactic acid 50 % (2-hydroxypropionic acid) | Raw | 212 | 20 | 100 | 0 | 0.942 | 100 | 55 | 100 | 100 | 85 | 32 |
| Isopropanol | Raw | 450 | 80 | 0 | 0 | 0.500 | 55 | 80 | 100 | 100 | 78 | 17 |

**Table 10** Risk phrase scores

| Risk phrase score | Concern |
|---|---|
| 1 | Low |
| 2 | Moderate |
| 3 | High |
| 4 | High |
| 4.5 | High |

**Table 11** U.S. EPA aquatic toxicity guidelines

| Toxicity concern | Experimental or ECOSAR results |
|---|---|
| Low | All three acute values are >100 mg/L, and all three chronic values are >10.0 mg/L, or there are "No Effects at Saturation" (or NES). NES occurs when a chemical is not soluble enough to reach the effect concentration, i.e., the water solubility is *lower* than an effect concentration, or, for liquids, when $K_{ow}$ criteria are exceeded for an endpoint. For solids, NES is expected if $K_{ow}$ exceeds the specific SAR $K_{ow}$ cutoffs, or the effect concentration is more than one order of magnitude (≥10x) less than water solubility |
| Moderate | Any of the three acute values is >1.0 mg/L and <100 mg/L, or any of the chronic values is >0.1 mg/L and <10.0 mg/L |
| High | Any of the three acute values is <1.0 mg/L, or any of the chronic values is <0.1 mg/L |

The aquatic toxicity concern for mixtures is based on the concern level of the individual components using the criteria given in Table 12.

The human toxicity concern for discrete substances without assigned European Risk Phrases is determined by the following procedure:

1. Conduct a literature search for the following acute toxicity endpoints:

   - Oral $LD_{50}$
   - Dermal $LD_{50}$
   - Inhalation $LC_{50}$ (4 h)
   - Skin and Eye Irritation
   - Sensitization

   a. The human acute toxicity concern level is assigned using the criteria given in Table 13.

2. Conduct a literature search for any chronic effects such as mutagenicity, teratogenicity, carcinogenicity.

   a. Chronic health hazard concern levels are assigned by component concentration and mixture concern (Table 14).

3. The final value for the human toxicity concern level is the higher concern level of the acute and chronic values.

**Table 12** Aquatic toxicity concern

| Component concern | Component concentration (%) | Mixture concern |
|---|---|---|
| High | $\geq 25$ | High |
| High | $\geq 2.5$ | Moderate |
| Moderate | $\geq 25$ | Moderate |

**Table 13** Human acute toxicity concern level

| Endpoint | Level | Concern |
|---|---|---|
| Oral $LD_{50}$ | $\leq 50$ mg/kg | High |
| | $>50$ to $<2000$ mg/kg | Moderate |
| | $\geq 2000$ mg/kg | Low |
| Dermal $LD_{50}$ | $\leq 200$ mg/kg | High |
| | $>200$ to $<2000$ mg/kg | Moderate |
| | $\geq 2000$ mg/kg | Low |
| Inhalation $LC_{50}$ | $>100$ to $\leq 500$ ppm (gases)<br>$>0.5$ to $<2.0$ mg/L (vapors)<br>$>0.05$ to $\leq 0.5$ mg/L (dust/mist) | High |
| | $>500$ to $\leq 5000$ ppm (gases)<br>2.0 to $\leq 20$ mg/L (vapors)<br>0.5 to $\leq 5$ mg/L (dust/mist) | Moderate |
| | $>5000$ ppm (gases)<br>$>20$ mg/L (vapors)<br>$>5$ mg/L (dust/mist) | Low |
| Skin Irritation | Corrosive | High |
| | Irritating (Draize score: $\geq 2.3$ $<4.0$) | Moderate |
| | Mild Irritation (Draize score: $\geq 1.5$ $<2.3$) | Low |
| Eye Irritation | Serious (irreversible damage) | High |
| | Reversible irritation | Moderate |
| | Mild Irritation | Low |
| Sensitization | Skin sensitizer | Moderate |
| | Inhalation sensitizer | High |

**Table 14** Chronic health hazard concern levels

| Chronic effects: mutagenic, teratogenic, carcinogenic | Concern |
|---|---|
| Known, suspected, or probable cause of chronic effect in humans | High |
| Possible chronic effect in humans based on animal data | Moderate |
| Limited evidence of chronic effects in humans based on animal data | Moderate |
| Inconclusive evidence of chronic effects based on animal data | Low |

The DSfC scoring for Metric 4 is then determined from the human and aquatic toxicity concern levels (Table 15).

Metric Scaling Range (Table 16).

Example Data and Output (Table 17).

$$\text{DSfC (Design of Safer Chemicals)} = 100.$$

**Table 15** Designing safer chemicals Metric 4 scoring

| Human toxicity concern | Aquatic toxicity concern | DSfC score |
|---|---|---|
| Low | Low | 100 |
| Low | Moderate | 75 |
| Moderate | Low | |
| Low | High | 50 |
| High | Low | |
| Moderate | Moderate | 50 |
| Moderate | High | 25 |
| High | Moderate | |
| High | High | 0 |

**Table 16** Metric scaling range DSfC

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 0 | 25 | 50 | 75 | 100 |

**Table 17** Example data and output DSfC

| Bill of Materials Out | Human toxicity | Aquatic toxicity |
|---|---|---|
| Isopropyl lactate | Low | Low |

## 3.5 Safer Solvents and Auxiliaries

*Principle* 5: *The use of auxiliary substances (solvents, separation agents, etc.) should be minimized whenever possible and, when used, be innocuous.*

As for raw materials, based on available safety, health, and LCA information, scorings for these impacts and regulatory status for many common solvents, diluents, and other auxiliary materials have been developed and provided as available into the iSUSTAIN® Raw Material database. These separate scorings are combined into a single Auxiliary Material Impact number for each material according to the formula, which in turn are combined for all of the auxiliary materials in the process according to the equation below to give a final Total Process Auxiliary Material Impact score. If a portion of a material is recycled, then that portion is not counted in this tally.

Metric Scaling Range (Table 18).

Example Data and Output (Table 19).

$$\text{Total Process Auxiliary Material Impact} = \frac{\sum_i (\text{MatImp}_i)(\text{Wt Material}_i)(100 - \%\,\text{Recycle}_i)}{\sum_i (\text{Wt Material}_i)(100 - \%\,\text{Recycle}_i)} = 75.$$

**Table 18** Metric scaling range safer solvents

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | >0 | 30 | 70 | 90 | 100 |

**Table 19** Example data and output safer solvents

| Bill of Materials In | Type of material | Weight/ batch | % recycle | % renewable | Catalyst mode | Usage weight/ weight | Safety | Health | Environmental impact | Mat Imp | % total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sulfuric acid | Auxiliary | 9 | 0 | 0 | 5 | 0.026 | 100 | 35 | 100 | 78 | 2 |
| Benzene | Solvent | 874 | 98 | 0 | 0 | 0.049 | 55 | 0 | 100 | 0 | 3 |
| Sodium carbonate | Auxiliary | 11 | 0 | 0 | 0 | 0.029 | 100 | 80 | 100 | 93 | 2 |
| Isopropanol | Diluent | 180 | 0 | 0 | 0 | 0.050 | 55 | 80 | 100 | 78 | 34 |
| Isopropanol | Solvent | 50 | 0 | 0 | 0 | 0.139 | 55 | 80 | 100 | 78 | 9 |

### *3.6 Design for Energy Efficiency*

*Principle* 6: *Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.*

EE roughly accounts for energy usage during heating and cooling and for application of high pressure or vacuum. This has to be assessed for each step of an overall process. This is captured in the Temperature Factor Table 20. This factor is summed with a pressure contribution (high or low pressure) and then multiplied by the average time for application of the temperature, total weight of materials, and approximate average heat capacity for each process step, all of which is then divided by the total product weight (diluents included) as in the equation below. If the process step is exothermic, then the time used should only be the heating time until onset of the exotherm. For the heat capacity, a rough weighted average of the aqueous and organic portions is adequate, using 4.2 J/gm°K for aqueous and roughly 2.0 J/gm°K for organic portions of the reaction mixture. This metric is only meant to be an approximate, but at least semi-quantitative, estimation of energy usage.

Step EE values are summed for the entire process and then normalized using the algorithm shown below.

$$l\text{Step EE (Energy Efficiency)} = \frac{(f_T + |1 - \text{Pressure(atm)}|) * \text{time(hrs)} * \text{Weight} * \text{Heat Capacity}\left(\frac{\text{J}}{\text{gm}} * {}^\circ\text{K}\right)}{\text{Wt. Desired Product}}$$

Metric Scaling Range (Table 21).

Example Data and Output (Table 22).

$$\text{Total EE (Energy Efficiency)} = \sum\nolimits_i \text{Step EE}_i = 77.$$

$$\text{Normalized Total EE} = 75.$$

**Table 20** Temperature factors

| Temperature ranges (°C) | Temperature factor ($f_T$) |
|---|---|
| <−20 | 5 |
| −20 to 0 (technical cooling) | 3 |
| 0–10 (ice cooling) | 2 |
| 10–20 (water cooling) | 1 |
| 20–30 (room temperature) | 0 |
| 30–90 (hot water heating) | 1 |
| 90–160 (steam heating) | 2 |
| 160–280 (hot oil or electrical heating) | 3 |
| >280 | 5 |

**Table 21** Metric scaling range EE

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | >0 | 25 | 200 | 650 | Unbounded (1200) |

**Table 22** Example data and output EE

| Process step | Temperature (°C) | Time (hour) | Pressure (atm.) | Total weight | Average heat capacity | Step EE |
|---|---|---|---|---|---|---|
| 1. Charge reagents and heat | 80 | 1 | 1 | 1,545 | 2.0 | 8.6 |
| 2. Heat and separate azeotropically | 85 | 6 | 1 | 1,521 | 2.0 | 56 |
| 3. Neutralize and distill benzene | 85 | 2 | 1 | 315 | 2.0 | 3.9 |
| 4. Filter mixture | 60 | 1 | 1 | 301 | 2.0 | 1.0 |
| 5. Vacuum, distill unreacted lactic acid to recycling and then product to dilution tank | 100 | 3 | 0.04 | 180 | 2.0 | 7.1 |
| 6. Dilute product to final concentration | 40 | 0.5 | 1 | 360 | 2.0 | 0.2 |
| 7. Dispense product to drums | 40 | 1 | 1 | 360 | 2.0 | 0.4 |
| 8. Rinse process reactors, filter, and tank | 25 | 0.5 | 1 | 129 | 2.0 | 0.0 |

## *3.7 Use of Renewable Feedstock*

*Principle 7: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practical.*

**Definition**: A RRM is a raw material from a renewable natural resource. A natural resource qualifies as a renewable resource if it is replenished by natural processes of growth at a rate comparable to or greater than its rate of consumption.

Renewable feedstocks are often made from agricultural products. Depleting feedstocks are typically made from fossil fuels or are mined. A depleting or limited resource is also defined by how quickly it can become depleted (several generations) and whether the heavy use of a finite supply creates adverse economic pressures. Use of a renewable feedstock should be sustainable and there should be no adverse and accumulative direct or indirect environmental and/or human health effects from its use.

Metric Scaling Range (Table 23).

Example Data and Output (Tables 24, 25).

$$\begin{aligned}&\%\,\text{RRM (as sold basis) – includes diluents}\\&\quad=\frac{\sum_{\text{i}}(\text{Wt RRM}_{\text{i}})(1-\%\,\text{Recycle}_{\text{i}}/100)(\%\ \text{Renewable}_{\text{i}})}{\text{Wt Product}}=45\\&\%\,\text{RRM (neat basis) – excludes diluents}\\&\quad=\frac{\sum_{\text{i}}(\text{Wt RRM}_{\text{i}})(1-\%\,\text{Recycle}_{\text{i}}/100)(\%\,\text{Renewable}_{\text{i}})}{(\text{Wt Product})(1-\%\,\text{Diluents}/100)}=95.\end{aligned}$$

**Table 23** Metric scaling range renewable feedstock

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 0 | 10 | 40 | 75 | 100 |

**Table 24** Example data and output renewable feedstock

| Bill of Materials In | Type of material | Weight/batch | % recycle | % renewable | % of total |
|---|---|---|---|---|---|
| Lactic acid 50 % | Raw | 212 | 20 | 100 | 32 |
| Isopropanol | Raw | 450 | 80 | 0 | 17 |
| Sulfuric acid | Auxiliary | 9.2 | 0 | 0 | 2 |
| Benzene | Solvent | 874 | 98 | 0 | 3 |
| Sodium carbonate | Auxiliary | 10.5 | 0 | 0 | 2 |
| Isopropanol | Diluent | 180 | 0 | 0 | 34 |
| Isopropanol | Solvent | 50 | 0 | 0 | 9 |

**Table 25** Example output renewable feedstock

| Bill of Materials Out | Type of material | Weight/batch | % diluents |
|---|---|---|---|
| Isopropyl lactate | Product | 360 | 50 |

## *3.8 Reduce Derivatives (Process Complexity)*

*Principle* 8: *Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.*

Reduced derivatization is accompanied by a reduction in both the process equipment used and the number of in-process additions and removals of materials. So this parameter may also be looked upon as aiming toward a streamlined process. It is calculated as the sum of the number of reactors and other primary equipment that the bulk of the process stream passes through (filters, columns, centrifuges, pastillators, etc.) plus all in-process additions or removals (addition of reagents or other process streams, removals by distillation, aqueous splits, etc., excluding the initial loadings to an empty reactor). This sum is then normalized to be between 0 and 100 using the algorithm shown below. This addresses both excessive process complexity (number of pieces of equipment) and derivatization (in-process additions or removals), as well as the safety concerns of too complex a process.

Metric Scaling Range (Table 26).

Example Data and Output (Table 27).

**Table 26** Metric scaling range derivatives

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 1 | 5 | 15 | 30 | Unbounded (50) |

**Table 27** Example Data Derivatives

| Process steps | | Reactors, etc. | Asset count | In-process add/ remove |
|---|---|---|---|---|
| Step 1 | Charge reagents and heat-up | Reactor 1 | 1 | 0 |
| Step 2 | Heat and separate water azeotropically | Reactor 1 | 0 | 1 |
| Step 3 | Neutralize and distill off benzene and excess isopropanol | Reactor 1 | 0 | 2 |
| Step 4 | Filter mixture | Reactor 1→Filter Reactor | 2 | 1 |
| Step 5 | Vacuum distill off unreacted lactic acid to recycle and then product to the dilution tank | Reactor 2→Dilution tank | 1 | 1 |
| Step 6 | Dilute product to final concentration | Dilution tank | 0 | 1 |
| Step 7 | Dispense product to drums | Dilution tank→drums | 1 | 1 |
| Step 8 | Rinse out process reactors, filter, and tank | Reactors 1 and 2, filter and dilution tank | 0 | 1 |

$$\text{Reduce Derivatives Score} = (\text{Pieces of Equipment}) + (\#\text{ of In-Process Additions/Removals}) = 13$$

$$\text{Normalized Reduce Derivatives Score} = 60.$$

## 3.9 Catalysis

*Principle* 9: *Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.*

Use of catalysts by their very nature results in the lowering of the activation energy required for a particular reaction to proceed. Typically, a catalyzed reaction also produces the desired product with greater selectivity and yield and concomitantly less waste.

This metric is based on the mole % of the catalyst, calculated as indicated in the equation below. The limiting reagent is the raw material of which there are fewer or equal moles to the proportion required for the reaction. If several catalysts are

**Table 28** Metric scaling range catalysis

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 0 | 1 | 10 | 50 | 100 |

**Table 29** Example data catalysis

| Bill of Materials In | Material type | Weight/ batch | Est. % recycle | % renewable | Catalyst mole % |
|---|---|---|---|---|---|
| Lactic Acid 50 % (2-hydroxy propionic acid) | Raw | 212 | 20 | 100 | 0 |
| Isopropanol | Raw | 450 | 80 | 0 | 0 |
| Sulfuric acid | Auxiliary | 9.2 | 0 | 0 | 5 |
| Benzene | Solvent | 874 | 98 | 0 | 0 |
| Sodium carbonate (soda ash) | Auxiliary | 10.5 | 0 | 0 | 0 |
| Isopropanol | Diluent | 180 | 0 | 0 | 0 |
| Isopropanol | Solvent | 50 | 0 | 0 | 0 |

used, this metric is calculated based on the one with the lowest mole %. This value is then normalized between 0 and 100 using the algorithm shown below.

$$\text{Catalyst Mole }\% = 100 * (\text{moles of catalyst})/(\text{moles of limiting reagent upon which it acts})$$

Metric Scaling Range (Table 28).
Example Data and Output (Table 29).

$$\text{Minimum Catalyst Mole }\% = 5$$

$$\text{Normalized Catalysis Score} = 95.$$

## *3.10 Design for Degradation*

*Principle* 10: *Chemical products should be designed so that at the end of their function they do not persist in the environment and instead break down into innocuous degradation products.*

For this metric, biodegradation of the product is based on the scale used by the U.S. EPA BIOWIN program Expert Survey Biodegradation model and is shown in Table 30. The appropriate module from the OECD QSAR Toolbox may also be used. The biodegradation score for mixtures is determined from the weighted biodegradation score based on % composition of each component. These models will not run for polymers (MW > 1,000), however, the structure may be approximated by choosing several molecular fragments to represent the polymer and running each separately. An average of the results may be used as a rough biodegradation value. In lieu of this, a default rating of 2.0 is used for polymers. Note that water in the product is ignored.

**Table 30** Biodegradation half-life

| Biodegradation half-life | Ultimate biodegradation |
|---|---|
| Hours | 5.0 |
| Hours (days) (biodegradation >50 % in 28 days) | 4.5 |
| Days | 4.0 |
| Days (weeks) | 3.5 |
| Weeks (biodegradation ~20–30 % in 28 days) | 3.0 |
| Weeks (months) | 2.5 |
| Months (slow to very slow biodegradation) | 2.0 |
| Longer (biodegradation issue—toxic, persistent) | 1.0 |

**Table 31** Metric scaling range degradation

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 1 | 1 | 2 | 3.5 | 5 |

**Table 32** Example data output degradation

| Bill of Materials Out | Ultimate biodegradation[a] |
|---|---|
| Isopropyl lactate | 3 |

[a] Ultimate biodegradation is the complete conversion of the molecule to $CO_2$ and $H_20$

Metric Scaling Range (Table 31).
Example Data and Output (Table 32).

$$\text{Normalized Biodegradation} = (\text{Ultimate Biodegradability} - 1) * 25 = 50.$$

## 3.11 Real-Time Analysis for in-Process Monitoring and Control (Pollution Prevention)

*Principle* 11: *Analytical methodologies need to be further developed to allow for real-time in-process monitoring and control prior to the formation of hazardous substances.*

If a process does not run correctly, the potential exists for formation of off-grade product and/or unwanted side-products. At the very least, these constitute waste and necessitate additional action to properly handle them. The possibility may also exist that the side-products are hazardous and present additional risks over simple waste. In any event, formation of these materials should be avoided and appropriate process controls should be in place to ensure this.

The following questions are designed to assess the level of hazard and control. Of importance is whether the process is capable of forming hazardous side-products and whether there are adequate controls, with an estimation of the extent (in the view of the user or process engineer). More controls should be necessary if

**Table 33** Metric scaling range in-process monitoring

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | 0 | 20 | 50 | 90 | 100 |

**Table 34** Example data in-process monitoring

| Question | Answer | Points |
|---|---|---|
| Does the potential exist in this process for the formation of hazardous side-products? | No | 30 |
| Are adequate monitoring and control apparatus in place to quickly detect excursions in reactors and storage vessels? | Yes | 25 |
| Is the process common practice and/or in the scale-up or commercialization stages of production? | Yes | 0 |
| Is there a regularly scheduled audit or check of this equipment? | Yes | 10 |
| Do formal (written) catastrophe plans and emergency measures exist? | Yes | 10 |

hazardous side-products can be formed. Lastly, if the process is commercial, then there should be provision for equipment audits and emergency plans. The overall score is the sum of these points.

Metric Scaling Range (Table 33).

Example Data and Output (Table 34).

Total Real-time Analysis Score = 75.

## *3.12 Inherently Safer Chemistry for Accident Prevention*

*Principle* 12: *Substance and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires.*

For this metric, the following questions are used to assess the risks inherent in the process under consideration. Full point values are given for 'Yes' answers and the overall score is then 100 minus the sum of these points (note that the sum of point values can be greater than 100 in extreme cases).

Metric Scaling Range (Table 35).

Example Data and Output (Table 36).

Total Yes answer points = 15.

**Table 35** Metric scaling range inherently safer chemistry

| | Minimum | Low | Moderate | Large | Maximum |
|---|---|---|---|---|---|
| Expected range | −40 | 20 | 50 | 85 | 100 |

**Table 36** Example data in output safer chemistry

| Question | Risk | Answer | Points |
|---|---|---|---|
| Are any extreme conditions (pressure >10 atm, temp >200 °C or <78 °C) used in the process? | High | No | 0 |
| Does the potential exist for a runaway exotherm under the process or upset conditions (including violent polymerization)? | High | No | 0 |
| Do any of the process materials or mixtures present an explosion hazard (contact, dust, and/or peroxide-forming)? | High | No | 0 |
| Are there any process materials present initially or formed during this process that might restrict or exclude its use in the intended production facility (other high hazards than mentioned above, strong odor, etc.) | High | No | 0 |
| Is pressure between 1.0 and 10 atm or less than 20 mm of Hg used in this process (other than process steps for which Q1 may be true)? | Medium | No | 0 |
| Are temperatures ranging from 150 to 199 °C or −50 to −78 °C used in this process (other than process steps for which Q1 may be true)? | Medium | No | 0 |
| Is the reaction mixture flammable? | Medium | Yes | 10 |
| Are any of the process mixtures pyrophoric or hypergolic? | Medium | No | 0 |
| Do any of the process mixtures react violently with water? | Mild | No | 0 |
| Is a gas generated in any part of this process? | Mild | Yes | 5 |
| Are any of the process mixtures corrosive (pH <2 or >12)? | Mild | No | 0 |
| Are any of the process mixtures irritants or lachrymators? | Mild | No | 0 |

$$\text{Safer Chemistry Score} = 100 - \text{Total Points} = 85.$$

## 4 Final Outcome

Once each element of the green chemistry index is identified, the data for a product can be rolled up for a complete weighted score on the sustainability of the product. Elements can also be grouped into subcategories to assess environmental, health, and safety aspects, and scored by group. For instance, if a product had a low health score, researchers could work on improving that element, to reduce the potential occupational exposure of a product or material.

Comparative data can be shown as in Tables 37 and 38, showing a comparison of Product A to Product B

This type of comparison can point researchers in the right direction to improving a product to be greener, focused on a specific set of attributes. Over time, as products are developed with improvements in green chemistry attributes, the portfolio will be more sustainable in the long run.

**Table 37** Final metrics Product A

| Metric | Product A |
|---|---|
| 1. Waste prevention | 95 |
| 2. Atom economy | 100 |
| 3. Safe raw materials | 95 |
| 4. Safe product | 75 |
| 5. Safe solvents | 80 |
| 6. Energy efficiency | 80 |
| 7. Renewables | 0 |
| 8. Process complexity | 35 |
| 9. Catalysis | 95 |
| 10. Biodegradability | 30 |
| 11. Process control | 60 |
| 12. Safe process | 85 |

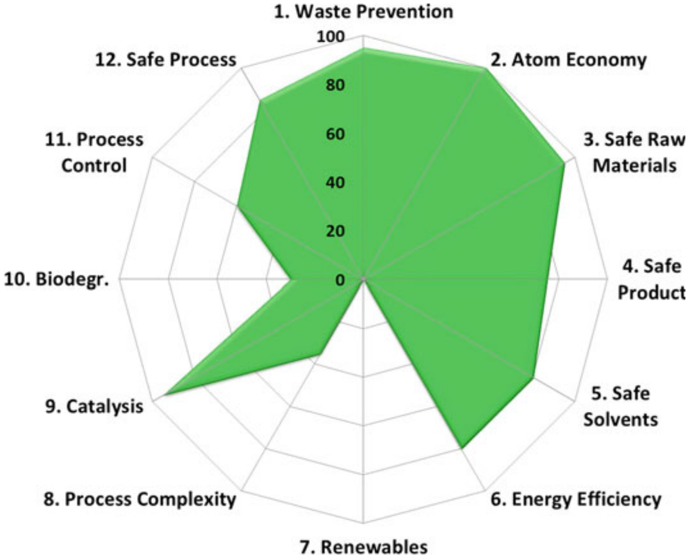
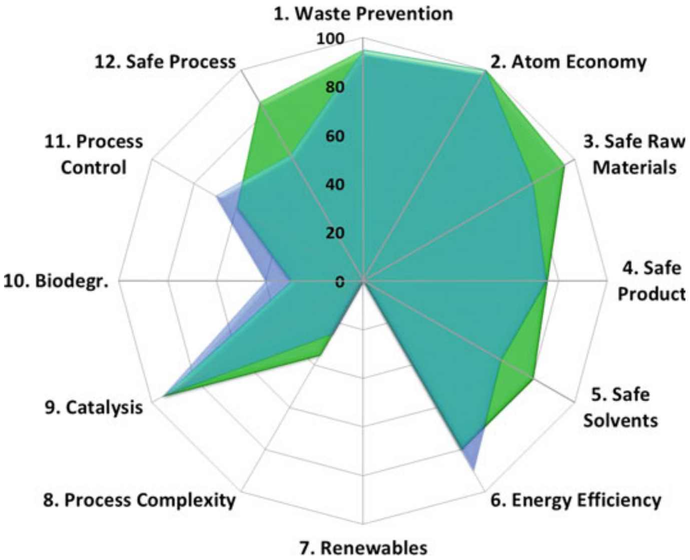


**Table 38** Final metrics Products A and B

| Metric | Product A | Product B |
|---|---|---|
| 1. Waste prevention | 95 | 95 |
| 2. Atom economy | 100 | 100 |
| 3. Safe raw materials | 95 | 80 |
| 4. Safe product | 75 | 75 |
| 5. Safe solvents | 80 | 65 |
| 6. Energy efficiency | 80 | 90 |
| 7. Renewables | 0 | 0 |
| 8. Process complexity | 35 | 25 |
| 9. Catalysis | 95 | 95 |
| 10. Biodegradability | 30 | 40 |
| 11. Process control | 60 | 70 |
| 12. Safe process | 85 | 60 |



## 4.1 Value of the iSUSTAIN® Tool

The iSUSTAIN® Green Chemistry Index provides researchers with a tool to measure the degree of sustainability of products and processes, based on the *Twelve Principles of Green Chemistry*. This tool gives the researchers information on factors within their control that can be used to improve the overall sustainability of the new product and process and enables them to make assessments at the earliest stages of product development. In addition, the tool provides the means to track performance against established sustainability goals. In this regard, organizations that use the Index will be able to set targets around development of greener or more sustainable products using actual data that provides a basis for continuous improvement. The tool can be further used to assess sustainability by users of the materials being assessed, providing a mechanism to generate a more complete life-cycle assessment. The tool offers much greater transparency around green marketing, and will prevent "green washing" claims. That is; the Index will provide a basis for marketing a product as sustainable using data and a method that has been made available to the public. This will foster transparency and dialogue around what is green in the industry. Further, by making this tool available at no cost to academic and public users, it will foster learning and change the mindset of scientists at universities so future generations of researchers will have these principles of sustainability well ingrained in their thinking.

## 4.2 Considerations in Implementation

There are numerous challenges to design and implementation of a green chemistry metric such as iSUSTAIN®. The first is development of a simple, practical tool, given the multiple variables and aspects that require review. Along the same lines, balancing simplicity against accuracy of the tool requires serious consideration. It is important to ensure that the application can be used by the user community and not just by a team of experts. In this case, development of training and tools that can be used from the bench chemist to the research scientist is critical to the success. To that end, a complex tool would not be used by the scientific and commercial teams and they would not see any value in using it. Business buy-into use of a product sustainability tool is a critical success factor. In this regard, promoting the use of the tool within an organization requires a well thought out training and communications plan with clear links to the business strategy. Finally the decision whether to use the tool internally or make available to the outside world requires careful consideration. In this case, the clear benefit to making the tool available to the public outweighed the burden of maintaining and keeping the tool proprietary. All in all, the efforts for this undertaking will be rewarded by a deeper understanding of green chemistry, within the product development process, and hopefully across the industry over time.

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# Part II
# Sustainability Metrics and Analysis

# Measuring Sustainability: Deriving Metrics from a Secure Human-Environment Relationship

**Verle Hansen**

**Abstract** The ability of individuals and institutions to take actions that would achieve sustainability is often lost in rhetoric about what it is or isn't and how to measure progress. Typically, sustainability is viewed as an objective and in this capacity efforts are made to identify indicators and to manage the environment to save it from civilization or to minimize human impact upon it. However, our intention to measure sustainability as an objective sets us in the wrong direction. Indicators of this objective measure deviations of the human or environmental condition from sustainability, but to sustain requires that no appreciable deviation has occurred. Viewed from this perspective, sustainability must be redefined and a new set of metrics must be identified to guide actions that avoid losses. These metrics must define the boundaries of human activities relative to environmental capabilities and to provide early warning signs of conditions that would be unfavorable to human life and signal a need to change. Once established, these metrics can be used as planning criteria so that they inform and become a measure of human actions. This enables progress toward civilization within the context of an environment that is able to sustain human life and is itself able to be sustained.

**Keywords** Sustainability metrics • Environmental capabilities • Planning criteria • Human-environment relationship

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## 1 Introduction

Since the concept of sustainability was introduced in the Brundtland Commission report (WCED 1987), attempts have been made to measure progress toward this end (UN 1992, 1996, 2001). Indicators of social, environmental, economic, and institutional systems were among the first metrics of sustainability (UN 2001) and measure status at prescribed times and places. They can show whether progress was made relative to a particular objective, or state a condition of being that is unrelated to an objective. In this capacity, indicators do not adequately measure sustainability because they measure deviations from it and provide little guidance to change actions to move toward it.

According to the Encyclopedia of Earth,[1] on 3 December 1984, 27 tons of methyl isocyanate gas leaked from a pesticide plant in Bhopal, India causing sudden and devastating effects on human health and life. Related deaths were estimated to exceed 6,000 people by 1994 and are currently between 15,000 and 20,000. A settlement of $470 million was paid by Union Carbide to compensate 554,895 people with injuries and 15,310 survivors of people who died.

These indicators expressed in terms of losses did not sustain the lives of anyone affected by this chemical release. Our concern for sustaining human life requires that its measures should not be in terms of losses, but should be in terms of assurances that losses are avoided.

Indicators expressed in terms of costs give little direction to sustain human life and health from future incidents. In the Bhopal case, the number of chemical releases per year, number of injuries, number of deaths, amounts of money paid to injured persons or beneficiaries, and/or impact on profits, provide insufficient support for making decisions that would have avoided the release. Such inadequacy of indicators can be illustrated by using examples of sustainability indicators from the UN Commission on Sustainable Development (UN 2001) and the US Environmental Protection Agency:

(1) *Percent of population living below poverty line* (Sect. 4.3.1 Equity): This indicator must be taken at a point in time. That portion of the population included in this percentage was living in poverty at the time of measurement and not adequately sustained. Keeping people above poverty, i.e., sustained, requires a socio-economic objective and making decisions that meet that objective.

(2) *Nutritional status of children* (Sect. 4.3.2 Health): To be sustained, all children need adequate nutrition. However, the number of children that did not receive adequate nutrition at the time of measurement is not sustained. This indicator gives the status of current conditions for children, but without enough information to make decisions so that in the future all children will have adequate nutrition.

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[1] http://www.eoearth.org/article/Bhopal,_India

(3) *Emissions of Greenhouse Gases* (Sect. 4.3.7 Atmosphere): This indicator measures the quantity of greenhouse gases emitted, but it does nothing to prevent the emissions from occurring and its resulting climate change.

(4) *Proportion of population with access to an improved water source in a dwelling or located within a convenient distance from the user's dwelling. (p. 89)*: If 85 % of the population has access to sufficient water, the 15 % that do not have access are not sustained. It indicates that work needs to be done; however, it has not produced the water to 15 % of the people when they needed it or informed human activities so that all people will have the water they need within limited water resources.

(5) *Tons of solid waste generated and solid waste recycled per capita* (USEPA 2009). Any waste from a finite system subtracts from resource availability so that demand relative to usable resource is increasing. If this demand and waste continue, demand will eventually outstrip availability. A statement that waste is not generated would be a better indicator and would enable all activities to be tested before enactment.

(6) *Percentage of area of assessed rivers and streams that do not meet state and federal water quality standards* (USEPA 2009). Any percentage greater than zero indicates failure. Assuming they are correct and sufficient, the standards themselves are the sustainability indicators. They provide targets that must be achieved to be sustainable and enable all proposed human activities to be assessed prior to enactment.

To sustain means to keep in existence; therefore, measurements of deviation reveal how much was not sustained and hint that our understanding of sustainability is faulty. These indicators are inadequate precisely because failure is not an option. Moreover, they do not provide the ability to plan so that sustainability is assured. True indicators of sustainability should measure possible projected capabilities of the systems to meet human needs and provide quality of life within the physiological limitations of human life. This is what every responsible sailor does before venturing to sea. Before hoisting anchor, every possible consideration is given to the capacity of the vessel and its systems to confront the capricious pelagic environment, survive, and sustain the vessel's occupants. Is the boat adequately provisioned to meet occupant needs during the planned and unplanned time of the voyage? Are precautions and emergency procedures in place to address any risk to human life, i.e., overboard recovery, hypo- and hyperthermia, illness, and injury? Are the skillsets, tools, parts, and equipment on board to restore any system that fails? Are there redundant systems and skills to account for system failure or knowledge gaps? Measures of these abilities would give warning that proposed human activities that would place these systems at risk can be scrubbed and new alternatives developed and evaluated before losses are incurred.

To understand the word sustainable it is useful to examine other suffixes that include the word *able*. It is clear that they are not objectives, but are tests of whether objectives are met. Words, e.g., readable, negotiable, adaptable, accountable, affordable, admirable, agreeable, and cleanable, tell us how to measure something, i.e., they take on meaning relative to a subject or object. Is the book readable? Are his behaviors readable? Are two personalities compatible? Is the music danceable? Are Euros and Dollars comparable and interchangeable? Are chemicals containable? Broken apart, such words reveal their intent. Is a book able to be read? Are the financial records able to account? Is my shirt able to be cleaned? Similarly, the word *sustainable* asks a question. In environmental terms, questions of sustain-able are related to human interests on one hand and those related to environmental qualities on the other. Is the environment able to sustain human life? Is the environment able to be sustained? In this capacity, they establish two categories of sustainability metrics: (1) those that measure whether human life is secured; and (2) those that measure whether the environment that sustains life can endure.

## 2 The Human Metrics of Sustainability

*Measure 1: Does Earth's natural systems remain on a natural trajectory unaffected by humanity*? Only one species, *Homo sapiens,* is concerned with sustainability. The United Nations (2001) identified 15 themes to which sustainability should apply, e.g., equity, health, education, housing, security, etc. All are related to human well-being. Sustainability is important to people because the conditions within which humanity thrives are unique in our solar system, and may be rare and inaccessible in the universe. Therefore, we want some assurance that planet Earth will provide options when resource availability and demands for them do not coincide and that opportunities to make a living will allow us to remain and adapt in-place (Benyus 1997). Unfortunately, there are no assurances because humanity is vulnerable to Nature's capriciousness. Therefore, the assurance we seek is that we do not become the cause of our demise. Considering that we are the product of natural systems and evolutionary processes that we did not create and cannot control, this assurance is linked with (a) functioning natural systems that provide services to humanity, (b) fail-safe systems, and (c) redundancies of systems components.

*Measure 2: Are human activities managed with regard to self-directing natural systems*? Assurances can be provided if we have the ability to alter human activities while we are participating in the use of natural capital. We live within a dependent and non-negotiable relationship with Nature. The only option we have in maintaining this relationship is to alter human activities relative to the state of the environment that must exist to sustain human life. Built-in lag times between natural systems showing stress and their collapse require measures of sustainability that provide the ability to anticipate system weaknesses and adjust human behaviors accordingly. Responding to these objectives within these conditions modifies human activities to align with conditions of functioning natural systems.

*Measure 3: Is human use of natural capital always within capacities of ecosystems to regenerate*? Human life cannot exist unless water quantity is replenished at rates greater or equivalent to use. This is a precondition of human existence and, therefore, is a measure of sustainability. Humanity can respond by limiting water use within rates of replenishment, using water more efficiently, and/or developing technologies that replace or create water supplies that match excessive uses. However, such technologies cannot replace natural capital today to meet needs of yesterday.

*Measure 4: Does adequate information to align human land-use decisions with ecosystem integrity exist today*? Human stresses on ecosystems are largely the outcome of changing land-uses to meet human needs without considering the natural structures, functions, and processes that meet human needs, or how natural systems work.

> On January 31, soon after sunrise, 133 individuals from [their offices in] Boston, Maryland, Hawaii, Canada, Mexico, Japan, the Netherlands, the Philippines, and elsewhere[2] began to transform the 60 city blocks east of Dodger Stadium in Los Angeles. A day later, they left behind 420 buildings, encompassing 54,755,153 square feet.[3]

Land-use change to meet human needs has been ongoing for thousands of years, but dramatically accelerated around the year 1950 due to human population increase that is predicted to peak around year 2075 (US Census 2002) with 90 % of this increase to occur by year 2050. Population growth to 6.8 billion in year 2009 has more than tripled the 1950 population and land-use change is still not aligned with ecosystem integrity. The virtual tools used in the demonstration described above illustrate the increasing pace of land-use change and amplify the need to account for the integrity of systems before losses are severe. If we fail to align development with ecosystem integrity during the next 40 years, we will have lost more of the environment in one century than during all of human history. Because we want to sustain ecosystem services during this period of land-use change and the science of these systems is incomplete, land-use change must be informed by environmental qualities that secure human life.

*Measure 5: Is every effect of land-use change on natural systems systematically counteracted*? Land-use decisions are predominantly made within the context of a bounded parcel of land. LEED[4] Green Globes,[5] Sustainable Sites Initiative,[6] New

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[2] http://bimstorm.com/LAX/play

[3] http://aec.cadalyst.com/aec/Features/The-Summer-of-BIM-Tech-Trends-Column/ArticleStandard/Article/detail/507889?ref=25

[4] Leadership in Energy and Environmental Design is a green building program by the US Green Building Council. http://www.usgbc.org/.

[5] Green Globes is a green building program by the Canadian equivalent of the LEED program (see above). http://www.greenglobes.com/design/homeca.asp.

[6] Sustainable Sites Initiative is a program by the American Society of Landscape Architects, the Lady Bird Johnson Wildflower Center, and the US Botanic Garden to measure how a site can protect, restore and regenerate ecosystem services. http://www.sustainablesites.org/report/.

Urbanism,[7] Smart Growth,[8] and similar programs provide decision support tools that minimize the impact of land-use decisions on the environment at, and to a lesser extent, beyond the site. Although impacts can be minimized by such programs, they cannot be eliminated and will incrementally and cumulatively affect broader scales of the finite environment. Reducing the impacts of agriculture and development accepts that losses will occur. If this environmental footprint is greater than renewable natural capital, these losses accumulate so that natural systems will be weakened and fewer ecosystem services will be available. Therefore, using resources "smarter" is necessary, but if they are to be sustained, losses must be linked with resource renewal.

*Measure 6: Are ecosystem structures, functions, and processes providing goods and services that sustain human life*? The need for natural systems to be viable is rooted in human dependency upon them. According to the Millennium Ecosystem Assessment (2005), ecosystems services essential to human life are:

1. Provisioning services—food stocks, water, fiber, timber, cotton, hemp, silk, fuel, genetic resources, biochemicals, natural medicines, and pharmaceuticals.
2. Regulating services—air quality, atmospheric gas, climate, chemical cycling,[9] water cycling, water purification, erosion, disease, pollination, and natural hazards.
3. Cultural services—cultural diversity, spiritual and religious values, knowledge systems, inspiration and esthetic values, sense of place, cultural heritage, recreation and renewal, and social relations.
4. Supporting services—geochemical cycling and flux, mineral-gaseous cycles, water–air quality maintenance, soil formation, hydrologic flux and cycling, primary production, nutrient cycling, energy flux, energy dissipation and climate modulation, absorbing/buffering/diluting/detoxifying pollutants-xenobiotics, and biological productivity maintenance.

Because an environment that is able to sustain human life must supply these services, the measures of their being functional and viable are measures of sustainability.

*Measure 7: Are fail-safe and emergency procedures in place that will provide uninterrupted services to meet human needs*? The intent of achieving sustainability, discussed earlier in this chapter, is to provide some assurance that this planet will be able to sustain human life. Because human life depends upon uninterrupted ecosystem services, it is essential to consider their thresholds, plan strategies to address potential failures, and to adjust human activities/behaviors to

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[7] The Congress of New Urbanism is establishing new standards for green design at the neighborhood. http://www.cnu.org/.

[8] The Smart Growth Network uses a partnership between the US EPA and several non-profit and government organizations to encourage development that serves the economy, community, and the environment. http://www.smartgrowth.org/about/default.asp.

[9] Carbon, Nitrogen, and Phosphorus.

avoid failure. Sustainability for any life is about being able to make a living on a continual basis. Meeting sustainability objectives tomorrow will not help survive today.

*Measure 8: Do people have opportunities to meet individual needs*? Meeting base human needs is critical to survival of individuals, but higher needs are achieved as opportunities are presented and individuals are personally motivated. The definitions of sustainability that were used in the Introduction refer to human development and quality of life that occurs at all levels of human needs. The concept of development, therefore, requires that individuals have opportunities to meet their needs at all levels. Four preconditions will determine whether this measure will be met: (a) institutions must allow and enable individual choices/action; (b) natural resources must be available; (c) natural resources must be accessible; and (d) equitable use of the commons must be enforced.

*Measure 9: Are people able to remain and adapt in-place*? Ultimately the measure of sustainability is whether people can remain on this planet and continue to adapt and evolve. Our ability to remain is contingent upon all systems working as identified above.

The above measures place human activities/actions/decisions within the context of the systems that make human life possible. These metrics provide the most assurance possible that human needs can be met and the systems that sustain human life will be sustained. These two aspects of sustainability will be explored in environmental metrics.

## 3 Environmental Metrics of Sustainability

There are no true measures of environmental sustainability because the environment is a composite of reactions to the amount of solar energy, the climates that this energy spawns, the life forms that utilize this energy, and their interactions with materials that make up this planet. Our use of energy and materials can cause Earth to react by changing phases to lesser productive, but complete ecosystems, e.g., from grassland to desert. Although the productivity of these ecosystems differs significantly, Nature makes no distinction whether one is better than another. Such distinctions are made by people because differences in environmental performance can affect human existence. This establishes a conditional relationship[10] between humanity that relies upon natural resources and the ecosystems that provide them.

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[10] This conditional relationship is well established in much of the literature:

> …development that meets the needs of the present generation *without compromising* the ability of future generations to meet their own needs (WCED 1987).
>
> …development that improves the quality of human life *while living within* the capacity of supporting ecosystems (IUCN 1997; Bell and Morse 1998).

The fundamental limit of this conditional relationship is that "Human society shall not co-opt so much of Earth's energy that ecosystems can neither furnish services nor endure for substantial periods of time" (Cairns 1997). The problem is that humanity does co-opt much of these services with few measures of how much can be taken without degrading ecosystem services. If we expect ecosystem services to fulfill human needs, the environment must retain certain qualities. Therefore, metrics of environmental sustainability are the environmental qualities that make human life possible.

These qualities set us in a different direction from current practices. Rather than trying to manage the environment to protect it from us, this strategy recognizes that:

1. The only party to human-environment relationships that can intentionally change its actions is us.
2. The most assurance that humanity will be sustained is when natural systems retain their integrity.

The human role in this relationship is not to conserve nature from encroaching civilization, but to make certain that all attributes of functioning natural systems exist so that Nature can react without losing environmental qualities that sustain human life. This will require that we know the preconditions of fully functioning natural systems so that human activities can change to make those functions possible. A process to identify these measures follows.

A pivotal condition of functioning natural systems is that the visible spectrum of solar energy between ultraviolet and infrared light (136 and $1 \times 10^6$ Å) reaches the surface of Earth. This portion of the electromagnetic spectrum is the key energy for life processes (Kormondy et al. 1977). Although human activity does not control how much energy is emitted by the Sun, the amount of pollution we cause in the atmosphere can affect how much of this energy reaches the surface of Earth. Therefore, this electromagnetic spectrum is a fundamental metric of sustainability that can affect human actions and be measured. However, its value is limited because this measure is also affected by latitude, altitude, season, and time of day; and most of the variables are not determined by human actions. The challenge in identifying metrics of sustainable environments is to find conditions

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(Footnote 10 continued)

> …development that delivers basic environmental, social, and economic services to all *without threatening* the viability of the natural, built, and social systems upon which these services depend (Brugmann 1996).
>
> …economic development to be *compatible with* constraints set by the natural environment… (Leisinger 1995).
>
> …global development that can be *maintained across* generations in an environmentally and socially acceptable way (Umweldbundesamt 1997).
>
> …maximizing the net benefits of economic development, *subject to maintaining* the services and quality of natural resources over time (Bell and Morse 1998).

of the human-environment relationship that a change in human activities can affect.

The following quote reveals conditional human-environment relationships. "The integrity of interactions between species is critical for the long-term preservation of human food production on land and in the sea (MEA 2005)." If preconditions of this integrity can be identified, they can be used as planning criteria. In this role, these preconditions both inform proposed land uses and measure whether such land uses are sustainable with regard to systems as a whole.[11] Although humanity does not control how species interact, the ways we use land can affect whether such interactions are possible. Two preconditions of interactions between species are revealed: (1) habitats must exist that will sustain minimum viable and effective populations of native species; and (2) connectivity between these habitats must exist to maintain genetic variability and to repopulate habitats where native populations have declined. After native species are identified, it is possible for people to make land-use decisions to ensure that habitats and connectivity that meet the needs of these populations exist concurrently with land uses and other human activities. Each of these preconditions describes a quality of the environment that must be maintained to enable the environment to sustain human life. As such, they are measures of sustainable environments.

The Natural Step[12] program identifies four limitations of human-environment relationships:

1. Nature cannot be subjected to systematic concentrations of substances extracted from the earth's crust.
2. Nature cannot be subjected to systematic concentrations of substances produced by society.
3. Nature cannot be degraded by physical means.
4. People cannot be subjected to conditions that systematically undermine their ability to meet individual and collective needs.

These general measures can guide human activities, e.g., creation, production, use, processing, dispensing, elimination, and transformation of chemicals; and move us toward sustain-able environments, societies, and economies. However, they are too general to inform human actions relative to specific environmental qualities that human life and/or functioning systems require.

Presuming that the environment would continue to function without human presence, it should also function with human presence as long as these systems retain their integrity. If "A system with ecological integrity has near-natural conditions for…productivity, biodiversity, soil, and water (Forman 1995)", then we need to know the preconditions for maintaining ecosystem integrity under the

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[11] These conditions and preconditions individually constitute measures of sustainable environments and function as sheet music does for a musician, i.e., they inform how to perform, and collectively they measure the quality of the performance.

[12] http://www.naturalstepusa.org/principles-of-sustainability/

weight of human actions. Progressively peeling back layers of preconditions of functioning natural systems will reveal other preconditions that can provide a measure of sustainable environments. Table 1 is a sample of this search for preconditions of near-natural productivity and illustrates one of several possible routes to determine the qualities that describe a sustainable environment.

The environmental characteristic, or objective, in the left column is possible if the increasingly narrowing preconditions stated in the next three columns are met. Although these could be measures of sustainability, they are difficult to measure and more importantly give little direction to human actions. Land uses, for example, can affect whether soil organisms can exist, but do not control what they do, i.e., decompose. Measures stated in the column at the far right begin to describe things that human actions can affect and measure. Near-natural productivity is still the objective, but what we affect are land uses where ground cover fits the natural environment. It is possible to measure whether vegetation that is proposed for a site will exist in the natural environment, soil chemistry fits native organisms, plants are characteristic of the area, and native and non-native plants are separated. Similarly, searches for preconditions of near-natural biodiversity can be identified as illustrated in Table 2.

**Table 1** Preconditions of productivity

| Environmental characteristic | Precondition of column 1 | Second level precondition | Third level precondition | Measures of sustainable environments |
|---|---|---|---|---|
| Near-natural productivity | Average biomass of an area remains near levels that would exist on undisturbed land. This is a natural adaptation to the local climate and is most likely to be sustained | Plant biomass must have soil nutrients<br>Plant biomass must have soil moisture<br>Plants biomass must have adequate $CO_2$<br>Plant biomass must have solar energy input | Soil parent material provides new materials and minerals<br>Soil organisms (fungi and bacteria) exist to decompose organic and inorganic matter<br>Plant materials exist to be decomposed and become food for new growth | Ground cover mimics that which would typically exist in the area so soil moisture is not reduced or increased<br>Soil chemistry and pH matches that which native soil organisms and plants have adapted<br>Plants adapted to the location are indigenous to the area<br>Non-native plants and animals are separated from native communities |

Knowledge of these preconditions provides a vision of environmental qualities that, by hind-casting, can be used to identify human activities and land uses that meet these preconditions to make it possible for the systems upon which we depend to remain operational. This can be illustrated in the following example. Baby turtles hatch on beaches at night and race to the sea to avoid predation on land. They identify the direction of the sea because the night sky is lighter over the sea (Pough et al. 1996). However, light pollution near human developed areas makes the night sky over land brighter than over water causing baby turtles to head in the wrong direction. A human concern for systems, to which baby turtles are a part, requires that human activities that affect baby turtles be modified. Light pollution over land should be eliminated during the hatching season. Where motor vehicles contribute to light pollution, roads could be planned well inland to minimize sky light over land; or all lighting should be screened and nearby materials should be kept dark to minimize reflected light; or new technologies might be developed where light pollution is not a byproduct of seeing at night.

A fully functioning environment depends upon its parts and interactions. Human actions cannot control whether the interactions will exist, but their actions can make certain that its parts exist and that interactions are possible. Table 3 is an attempt to develop a parts list.

Application of these measures is governed by four considerations: (a) human life uses and relies upon the existence of natural goods and services; (b) Nature is a non-negotiating partner in the human-environment relationship; (c) Nature is not concerned whether humanity survives; and (d) the only variables over which humanity has some control are human activities. Therefore, human activities must be adjusted on the basis of the desired qualities of these systems. Using these criteria in the planning/design process serves to instruct human activities/behaviors relative to functioning natural systems and they measure how well those activities/behaviors are performed. They are measures of sustainability because they provide the ability to plan or evaluate alternative decisions that modify proposed human activities/behaviors relative to a sustainable environment objective.

Whether these conditions are sufficient to inform human activities/behaviors is arguable and unknowable until these measures are applied. Applications of these measures would enable human decisions relative to environmental qualities, and provide living laboratories to test these conditions so that the science of human-environment relationships can be advanced. The measures established herein may be incomplete, but they provide the ability to consider the environment and its relationship to human existence immediately and the opportunity to refine and improve them. Our ability to measure proposed activities/decisions relative to preferential environmental conditions makes it possible for natural systems to continue on their own evolutionary trajectories, but does not guarantee it. We cannot predict nature's capriciousness and we may not be able to predict how humanity will affect the environment, but measuring our actions/decisions relative to environmental qualities that are required to sustain human life will make it possible for natural structures, functions, and processes to continue.

Table 2 Preconditions of biodiversity

| Environmental characteristic | First level precondition | Second level precondition | Third level precondition | Measures of sustainable environments |
|---|---|---|---|---|
| Near-natural biodiversity | Native species exist in minimum effective populations (MEP) and minimum viable populations (MVP) and in native communities and obligate species interactions and dependencies | Enough genetic variability exists in a population to be effective<br>Births equal or exceed mortality due to all causes, but total population never exceeds carrying capacity of available habitat<br>Sufficient numbers of individuals exist in an area to be viable<br>Species have the mobility to reach any particular area<br>Once a species has arrived in an area, resources are sufficient for their survival<br>Interactions between species exist | Species with obligate relationships exist in the same area<br>Complete trophic regimes exist to sustain any population and community | Native and non-native genetic material remain isolated from each other<br>Habitats exist in sufficient sizes, locations, and distributions to sustain MEP and MVP of native species<br>Habitats contain essential resources to sustain stable populations and communities<br>Spawning, nesting, and birthing sites characteristic of species requirements are available with resources adequate to maintain the populations of all native resident and migratory species. These sites must be accessible<br>Resources needed by native migratory species must be available<br>Habitats must be connected<br>Connectivity must be redundant but must also challenge species<br>The general character of the landscape must be appropriate for native species and communities |

**Table 3** Criteria for sustainable natural systems

| Human intentions | Preconditions | Actionable Preconditions or measures of being sustainable |
|---|---|---|
| The environment is able to secure human life, provide options and opportunities for people to fulfill their needs; and to enable human life to remain and adapt in place (Benyus 1997) | "The integrity of interactions between species is critical for the long-term preservation of human food production on land and in the sea (MEA 2005)"<br>Soil regeneration and renewal $\geq$ erosion + depletion<br>Water quality and quantity are sufficient to replenish living cells with nutrients, regulate temperature, renew body fluids, and remove wastes<br>Damaging forces of water are mediated<br>Earth forming sculpting process is maintained<br>Energy can be translated and moderated (Mollison 2001)<br>Natural quantities of hydroxyl radicals exist in the atmosphere to convert pollutants into less harmful chemicals (MEA 2005)<br>Photosynthesizing plants are able to convert $CO_2$ into carbohydrates and release as $O_2$<br>Autotrophs are able to produce organic compounds using $CO_2$ from air or water<br>Nitrogen compounds (proteins and nucleic acids) are available to all living things within their tolerances. Nitrogen is incorporated into compounds<br>Others…… | 1. Habitats exist that will sustain minimum viable populations (MVP) and minimum effective populations (MEP) of native species<br>2. Connectivity between habitats exists<br>3. Connectivity between habitats is redundant and general character of the landscape is appropriate for native species and communities<br>4. Habitats are distributed widely enough so that MVP and MEP are beyond the reach of any multiple or widespread natural disturbance regimes<br>5. Flowering crops are accessible by pollinating insects<br>6. Birthing, spawning, nursery, and maturing habitats are usable and accessible<br>7. Migratory routes and habitats for all native transitory animals are open, accessible, and secure<br>8. Distribution of redundant species is maintained across multiple time and space scales (Alberti 2005)<br>9. Complete native trophic regimes exist in any location<br>10. Ground cover mimics that which would typically exist in the area so soil moisture is not reduced or increased<br>11. Plants adapted to the location are characteristic to the area<br>12. Non-native plants and animals are separated from native communities<br>13. Unique environments and the species that depend upon them are protected<br>14. Natural disturbance regimes exist or are simulated where human life and property would be endangered<br>15. Soil parent material is deposited on site<br>16. Soil chemistry and pH matches that which native soil organisms and plants have adapted |

(continued)

**Table 3** (continued)

| Human intentions | Preconditions | Actionable Preconditions or measures of being sustainable |
|---|---|---|
| | | 17. Plant roots anchor soils (Prugh et al. 1999) |
| | | 18. Soil compaction and soil cover do not increase runoff above background levels |
| | | 19. Projected water demand is limited to availability |
| | | 20. Trees/plants break the force of falling rain and loosen soil to allow absorption and slow runoff (Prugh et al. 1999) |
| | | 21. Avenues for water recharge are clean |
| | | 22. Water quantity and speed of surface flows meet historic cycles, durations, and intensities |
| | | 23. Hydric soils and plants exist to process water |
| | | 24. Forests exist in sufficient contiguous sizes to translate and moderate solar energy and the energy gradients it creates |
| | | 25. Sufficient forests exist to generate hydroxyl radicals to process atmospheric pollutant levels |
| | | 26. New deciduous forests and crops exist in higher latitudes, and old forests exist to consume $CO_2$ |
| | | 24. Native forests remain sufficiently intact to store 86 % of the plant's above ground carbon and 73 % of the planet's soil carbon (http://en.wikipedia.org/wiki/Carbon_cycle) |
| | | 27. Air and water are clean enough for autotrophs to live |
| | | 28. Water chemistry of sea-water is sufficient to maintain photosynthesizing plankton |
| | | 29. Plant and animal wastes are abundant, and the soil remains clean enough for soil organisms that process this waste to exist |
| | | 30. The atmosphere shields life from harmful radiation |

## 4 Conclusion

Sustainability is a question. It is a test of all that we propose and do relative to the systems that sustain human life. It is the long-term perspective of human existence, and it is a measure of our willingness to change ourselves and our actions to ensure our future. Sustainability need not be some ethereal complex undefinable objective that cannot be measured. The conditional relationship between human needs/ objectives and the natural systems that meet those needs/objectives establishes a basis for these measures and gives meaning to sustainability. When sustainability indicators are identified with regard to maintaining this conditional relationship, they give direction to decisions and activities and measure whether proposed decisions and activities are acceptable and workable. In this form, sustainability indicators double as criteria that enable us to: plan and evaluate land-use change and other human activities; prevent environmental problems without having to allocate time and money to solve them after they are created; avoid repugnant losses of life and allow us to align the way we live with our values and ethics; provide a keel for the development of environmental, social, economic, and energy policies; envision the future we want rather than accept the one that looms at the horizon; and identify scientific questions and design scientific studies. The question whether the systems that meet human needs are able to remain viable and able to sustain human life not only measures what we do, it guides what we consider. These abilities to measure what we have not yet lost align humanity with the systems that sustain us and provide the most assurance possible that we will be able to remain and adapt in place.

**Disclaimer** This chapter has not been subjected to internal policy review. Therefore, the research results presented herein do not, necessarily, reflect the views of theAgency or its policy. Mention of trade names or commercial products does notconstitute endorsement or recommendation for use.

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# Science-Based Metrics for Product Sustainability Assessment

## Barbara C. Lippiatt

**Abstract** Consumers and manufacturers need compelling metrics, tools, and data supporting investments in sustainable products. Today's marketplace is fraught with sustainability claims that are often based on incomplete, anecdotal evidence that is difficult to reproduce and defend. The claims suffer from two main weaknesses: (1) products upon which claims are based are not necessarily "green" in a science-based; life-cycle assessment (LCA) sense and (2) their measures of cost-effectiveness often are not based on standard methods for measuring economic worth. The problem is hard to solve because methods, tools, and robust data for sustainability performance measurement are not widely available. The National Institute of Standards and Technology (NIST) is addressing these needs by developing rigorous metrics and tools for scientifically assessing the life-cycle economic and environmental performance of products. Economic performance is measured using standard life-cycle costing methods. Environmental performance is measured using LCA methods that assess the "carbon footprint" of products as well as 11 other sustainability metrics including fossil fuel depletion, smog, water use, habitat alteration, indoor air quality, and human health. These environmental and economic performance metrics are applied to assess the sustainability of 230 building products in the NIST Building for Environmental and Economic Sustainability (BEES) tool. The approach is illustrated with a BEES case study of five floor covering products.

**Keywords** Sustainability metrics · Product sustainability assessment · Building for environmental and economic sustainability

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## 1 Introduction

An environmentally conscious consuming public is demanding products that are more sustainable. Manufacturers are seeking to meet the expectations of consumers and the demands of regulators while becoming more environmentally responsible (European Parliament 2003a, b; 107th Congress 2002). For consumers, regulators, and manufacturers alike, this requires that credible processes be implemented to accurately measure the environmental impacts of products.

Yet consumers are not willing to purchase environmentally sustainable products at any cost. The economic dimension of sustainability will always be a factor in purchasing decisions. However, while a given product might be either less or more costly than its competitor when purchased, what really matters is the cost comparison over the life of the product. Though more expensive to purchase, one product might well have a longer useful life and have lower maintenance and disposal costs than a competing product, thus offsetting a higher initial purchase price. Hence product costs measured over a product's useful life provide the most appropriate measure of a product's economic sustainability.

This chapter focuses on the development of sustainability performance metrics to support sound decisions by industry and consumers in the selection and use of sustainable products. These metrics consider both the environmental and economic dimensions of sustainability. They are based on sound science that is translated into performance scores that can be understood by scientists and non-scientists alike, thus providing useful information to inform product selection decisions.

## 2 Background

The National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce, is the U.S. national measurement institute. NIST develops unbiased, state-of-the-art measurement science that advances the nation's technology infrastructure and is needed by industry to continually improve products and services. With this mission in mind, the agency began the Building for Environmental and Economic Sustainability (BEES) program in 1994, with the goal of developing a rational, systematic technique for selecting environmentally preferred, cost-effective products. The BEES software, which applies the technique to 230 building products, is in widespread use today, with more than 24,000 users in over 80 countries (Lippiatt et al. 2010).

The BEES approach attracted the attention of the U.S. Environmental Protection Agency's Environmentally Preferable Purchasing (EPP) Program in 1997. With EPP support, the tool was further developed and recommended by EPP for cost-effective, environmentally preferable federal purchasing. Since 2002, NIST has further developed BEES in support of the USDA BioPreferred Program, a preferred purchasing program established by the 2002 Farm Bill that requires BEES performance evaluation (107th Congress 2002).

## 3 Objectives

The BEES analytical technique takes a multidimensional, life cycle approach. That is, it considers multiple environmental and economic impacts over the entire life of a product. Considering multiple impacts and life cycle stages is necessary because product selection decisions based on single impacts or stages could obscure other impacts or stages that might cause equal or greater damage. In other words, a multidimensional approach is necessary for a comprehensive, balanced analysis of environmental and economic impact.

It is relatively straightforward to select products based on minimum life cycle economic impacts because products are bought and sold in the marketplace. But how does one consider environmental impacts in purchase decisions? Impacts such as global warming, water pollution, and resource depletion are for the most part economic externalities. That is, their costs are not reflected in the market prices of the products that generated the impacts. Moreover, even if there were a mandate today to include environmental "costs" in market prices, it would be nearly impossible to do so due to difficulties in assessing these impacts in economic terms. How does one put a price on clean air and clean water? What is the value of human life? Economists have debated these questions for decades, and consensus does not appear likely.

While environmental performance cannot be measured on a monetary scale, it can be quantified using the multi-disciplinary approach known as environmental life cycle assessment (LCA). The BEES approach measures environmental performance using an LCA approach, following guidance in the International Organization for Standardization (ISO) 14040 standard for LCA (ISO 2006). An ASTM International standard for Multi-Attribute Decision Analysis also is followed in order to synthesize LCA results across multiple impacts into a single, decision-enabling environmental performance score (ASTM International 2002). Economic performance is separately measured using the ASTM International standard life cycle cost (LCC) approach (ASTM International 2005).

Environmental life cycle assessment is a "cradle-to-grave," systems approach for measuring environmental performance. The approach is based on the belief that all stages in the life of a product generate environmental impacts and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, use, and ultimately waste management. An analysis that excludes any of these stages is limited because it ignores the full range of upstream and downstream impacts of stage-specific processes.

The strength of environmental life cycle assessment is its comprehensive scope. Many environmental claims and strategies today are based on a single life cycle stage or a single environmental impact. A product is claimed to be "green" because it has recycled or bio based content, or criticized of not being green because its manufacture contributes to air pollution. These single-attribute claims may be misleading because they ignore the possibility that other life cycle stages, or other environmental impacts, may yield offsetting impacts. For example, an LCA for a recycled content product will account for replacement of raw materials with recycled inputs, meaning there are no longer environmental burdens associated with the replaced raw materials. Yet recycled inputs are not burden-free, so the LCA will now include *other* burdens—those associated with collection, transportation, and processing of the recycled input into a form suitable for product production. Whether the old burdens are worse than the new ones cannot be assumed a priori: The replaced material may be quite benign, while the recycled content product may have high embodied energy content, leading to fossil fuel depletion, global warming, and acid rain impacts during the raw materials acquisition, manufacturing, and transportation life cycle stages. LCA thus broadens the environmental discussion by accounting for shifts of environmental impacts from one life cycle stage to another, or one environmental medium (land, air, water) to another. The benefit of the LCA approach is in implementing a tradeoff analysis to achieve a genuine reduction in overall environmental impact, rather than a simple shift of impact.

# 4 Description of Work

## *4.1 Environmental Performance Measurement*

The general LCA methodology involves four steps. The *goal and scope definition* step spells out the purpose of the analysis and its breadth and depth. The *inventory analysis* step identifies and quantifies the environmental inputs and outputs associated with a product over its entire life cycle. As shown in Fig. 1, environmental

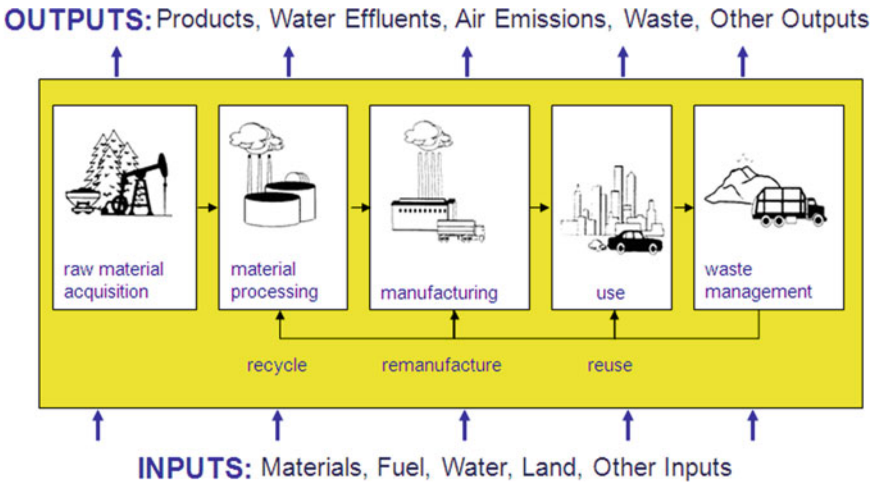


**Fig. 1** Framework for life cycle inventory analysis

inputs include use of materials, fuel, water, land, and other resources; outputs include releases to air, land, and water. However, it is not these inputs and outputs, or *inventory flows,* which are of primary interest. Of more interest are their consequences, or impacts on the environment. Thus, the next LCA step, *impact assessment*, characterizes these inventory flows in relation to a set of environmental impacts. For example, the impact assessment step might relate carbon dioxide emissions, a *flow*, to global warming, an *impact*. Finally, the *interpretation* step combines the environmental impacts in accordance with the goals of the LCA study.

While this chapter focuses primarily on the BEES life cycle impact assessment and interpretation approaches, it is important to note that rigorous, consistent life cycle scoping and inventory analysis are critical for credible LCAs. For example, the BEES goal and scoping phase sets consistent boundaries for all product systems under study, whereby all life cycle industrial processes that meet either mass or energy contribution criteria are included in the analysis. Some additional processes are included based on their cost contribution, even if they do not meet established mass or energy criteria, because a significant cost may indicate scarce natural resources or numerous subsidiary industrial processes potentially involving high energy consumption. For more on BEES' consistent scoping and inventory analysis criteria, refer to the BEES technical documentation (Lippiatt et al. 2010).

The impact assessment step of LCA quantifies the potential contribution of a product's inventory flows to a range of environmental impacts. There are several well-known LCA impact assessment approaches.

Direct Use of Inventories. In the most straightforward approach to LCA, the impact assessment step is skipped, and the life cycle inventory results are used as-is in the final interpretation step to help identify opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. However, this approach in effect gives the same weight to all inventory flows (e.g., carbon dioxide emissions and lead releases). For most products, equal weighting of flows is unrealistic.

Ecological Scarcity (Switzerland). With this approach, "Eco-Points" are calculated for a product, using the "Eco-Factor" determined for each inventory flow (Frischknecht et al. 2009). Eco-Factors are based on current annual flows relative to target maximum annual flows for the geographic area considered. The Eco-Points for all inventory flows are added together to give one single, final measure of impact. While appealing, the concept has a number of difficulties, such as being valid only in a specific geographical area, problems in estimating target flows, and that the scientific calculation of environmental impacts is inextricably combined with political and subjective judgment. The preferred approach is to separate the life cycle impact and interpretation steps.

Environmental Priorities System (Sweden). The Environmental Priority Strategies in Product Development System, the EPS System, takes an economic approach to assessing environmental impacts (Steen 1999). The basis for the evaluation is the Environmental Load Unit, which corresponds to the willingness to pay 1 European Currency Unit. The final result of the EPS system is a single number summarizing all environmental impacts, based on society's judgment of the importance of each environmental impact, its intensity, frequency, location and timing, the contribution of each flow to the impact, and the cost of decreasing each inventory flow by one weight unit. Although this methodology is popular in Sweden, its use is criticized due to its lack of transparency and the quantity and quality of the model's underlying assumptions.

- Eco-Indicator 99/ReCiPe. The Eco-Indicator 99 method is a "damage-oriented" approach to life cycle impact assessment developed in The Netherlands (Goedkoop and Spriensma 2000). It is appealing for its emphasis on simplifying the subsequent life cycle assessment step, namely, the weighting of the relative importance of environmental impacts. To this end, a very limited number of environmental damage categories, or "endpoints," are evaluated: Human Health, Ecosystem Quality, and Resources. Damage models are used to evaluate products in relation to these three damage categories. While the Eco-Indicator 99 method offers promise for the future—and recently has been updated and repackaged into the ReCiPe method—it continues to be criticized for the many scientific assessment gaps in the underlying damage models. (http://www.lcia-recipe.net/).

Environmental Problems. The Environmental Problems approach to impact assessment was developed within the Society for Environmental Toxicology and Chemistry (SETAC) (Guinée et al. 2001). It involves a two-step process:

- Classification of inventory flows that contribute to specific environmental impacts. For example, greenhouse gases such as carbon dioxide, methane, and nitrous oxide are classified as contributing to global warming.
- Characterization of the potential contribution of each classified inventory flow to the corresponding environmental impact. This results in a set of indices, one for each impact, which is obtained by weighting each classified inventory flow by its relative contribution to the impact. For instance, the Global Warming Potential index is derived by expressing each greenhouse gas in terms of its equivalent amount of carbon dioxide heat trapping potential.

The Environmental Problems approach does not offer the same degree of relevance for all environmental impacts. For global and regional effects (e.g., global warming and acidification) the method provides an accurate description of the potential impact. For impacts dependent upon local conditions (e.g., smog), it may result in an oversimplification of the actual impacts because the indices are not tailored to localities.

The Environmental Problems approach is preferred by most LCA practitioners and scientists today. For this reason, BEES uses the approach where possible. The U.S. EPA Office of Research and Development has developed TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), a set of state-of-the-art, peer-reviewed U.S. life cycle impact assessment methods that has been adopted in BEES (Bare 2002). Ten of the 11 TRACI 1.0 impacts follow the Environmental Problems approach: Global Warming Potential, Acidification Potential, Eutrophication Potential (a water pollution indicator), Fossil Fuel

Depletion, Habitat Alteration/Land Use, Criteria Air Pollutants, Human Health, Smog, Ozone Depletion, and Ecological Toxicity. Water Use is assessed in TRACI 1.0 using the Direct Use of Inventories Approach, as is Indoor Air Quality, the twelfth and final BEES impact. For more on the 12 BEES environmental impacts, refer to the BEES technical documentation (Lippiatt et al. 2010).

At the LCA interpretation step, the normalized impact assessment results are evaluated. Few products are likely to dominate competing products in all BEES impact categories. Rather, one product may outperform the competition relative to fossil fuel depletion and habitat alteration, fall short relative to global warming and acidification, and fall somewhere in the middle relative to indoor air quality and eutrophication. To compare the overall environmental performance of competing products, the performance scores for all impact categories may be synthesized. Note that in the BEES online software, synthesis of impact scores is optional.

Impact scores may be synthesized by weighting each impact category by its relative importance to overall environmental performance, then computing the weighted average impact score. In the BEES software, the set of importance weights is selected by the user. Several alternative weight sets are provided as guidance and may be either used directly or as a starting point for developing user-defined weights. The alternative weights sets are based on an EPA Science Advisory Board study, a 2006 BEES Stakeholder Panel's structured judgments, and a set of equal weights, representing a spectrum of ways in which people value diverse aspects of the environment (Gloria et al. 2007).

To simplify decision-making and facilitate purchasing, BEES summarizes life cycle environmental performance results as single scores based on the selected weight set. For the sake of transparency and to highlight the underlying tradeoffs among and within impacts, BEES also reports the contribution of each individual environmental impact to this score, as well as the contribution of each individual environmental flow to each individual environmental impact.

## 4.2 Economic Performance Measurement

BEES measures a product's economic performance using the ASTM International life cycle cost (LCC) method (ASTM International 2005). Economic performance is evaluated over a fixed period (known as the study period) that begins with the purchase of the product and ends at some point in the future. Over this period, the LCC method evaluates both "first costs" and "future costs." For consumable products for which future costs are irrelevant, the study period is set at zero and economic performance is measured on a first cost basis alone. For durable products such as equipment and building products, the LCC study period length depends upon the decision maker. For a private investor, its length is set at the period of product ownership. For society as a whole, the study period length is often set at the useful life of the longest-lived alternative in a product category.

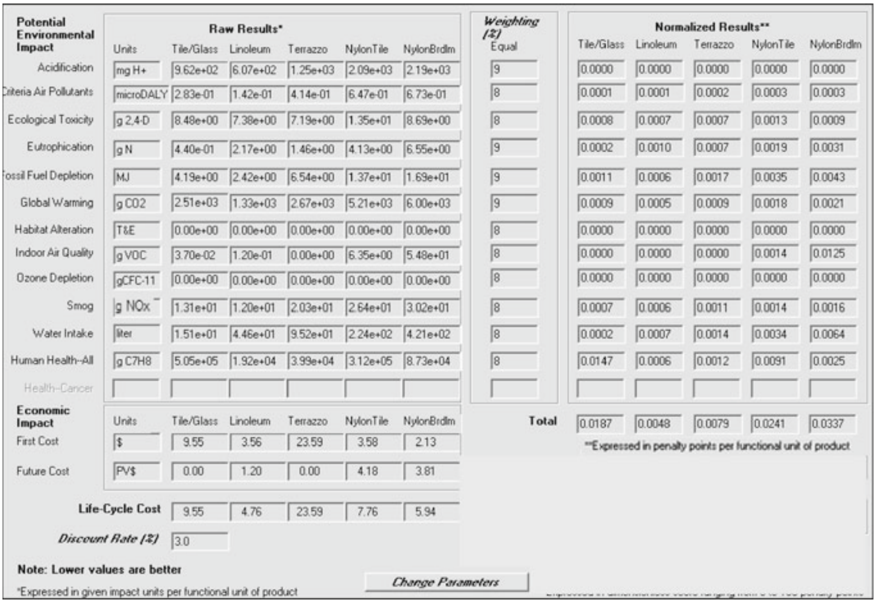
The same study period length is used to evaluate all products in a category to account for the fact that different products have different useful lives. BEES takes the societal perspective, setting the study period length for most durable products at the useful life of the longest-lived alternative. If an alternative lasts more than 50 years, however, the study period is limited to 50 years because technological obsolescence becomes an issue, data become too uncertain, and the farther in the future, the less important the costs. The BEES study period for building products is set at 50 years.

The LCC method sums over the study period all relevant costs associated with a product. Alternative products for the same functional product category, say floor covering, can then be compared on the basis of their LCCs to determine which is the least-cost means of fulfilling that function over the study period. Categories of cost typically include costs for purchase, installation, operation, maintenance, repair, replacement, and disposal. A negative cost item is the residual value, or the product value remaining at the end of the study period.

The LCC method accounts for the time value of money by using a discount rate to convert all future costs to their equivalent present value. Future costs must be expressed in terms consistent with the discount rate used. There are two approaches. First, a *real* discount rate may be used with constant-dollar (e.g., 2007) costs. Real discount rates reflect that portion of the time value of money attributable to the real earning power of money over time and not to general price inflation. Even if all future costs are expressed in constant dollars, they must be discounted to reflect this portion of the time value of money. Second, a *market* discount rate may be used with current-dollar amounts (e.g., actual future prices). Market discount rates reflect the time value of money stemming from both inflation and the real earning power of money over time. When applied properly, both approaches yield the same LCC results. BEES computes LCCs using constant year dollars and that year's prevailing real discount rate (3 % in 2007) mandated by the U.S. Office of Management and Budget (OMB) for most Federal analyses (U.S. OMB 2007).

## 5 Results and Analysis

The following figures and table illustrate the output from a BEES analysis of environmental impacts and life-cycle costs of five selected floor coverings. The environmental impact scores and life-cycle costs for ceramic tile with recycled glass content, linoleum flooring, terrazzo, nylon carpet tile, and nylon broadloom carpet are presented in Fig. 2. Values are given on an equivalent functional unit basis: covering one square foot of floor surface over 50 years of use (including product replacements and disposal). The lower the values, the more preferable the product would be from an environmental and cost perspective.



| Potential Environmental Impact | Raw Results* | | | | | | Weighting (%) | Normalized Results** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Units | Tile/Glass | Linoleum | Terrazzo | NylonTile | NylonBrdlm | Equal | Tile/Glass | Linoleum | Terrazzo | NylonTile | NylonBrdlm |
| Acidification | mg H+ | 9.62e+02 | 6.07e+02 | 1.25e+03 | 2.09e+03 | 2.19e+03 | 9 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| riteria Air Pollutants | microDALY | 2.83e-01 | 1.42e-01 | 4.14e-01 | 6.47e-01 | 6.73e-01 | 8 | 0.0001 | 0.0001 | 0.0002 | 0.0003 | 0.0003 |
| Ecological Toxicity | g 2,4-D | 8.48e+00 | 7.38e+00 | 7.19e+00 | 1.35e+01 | 8.69e+00 | 8 | 0.0008 | 0.0007 | 0.0007 | 0.0013 | 0.0009 |
| Eutrophication | g N | 4.40e-01 | 2.17e+00 | 1.46e+00 | 4.13e+00 | 6.55e+00 | 9 | 0.0002 | 0.0010 | 0.0007 | 0.0019 | 0.0031 |
| ossil Fuel Depletion | MJ | 4.19e+00 | 2.42e+00 | 6.54e+00 | 1.37e+01 | 1.69e+01 | 9 | 0.0011 | 0.0006 | 0.0017 | 0.0035 | 0.0043 |
| Global Warming | g CO2 | 2.51e+03 | 1.33e+03 | 2.67e+03 | 5.21e+03 | 6.00e+03 | 9 | 0.0009 | 0.0005 | 0.0009 | 0.0018 | 0.0021 |
| Habitat Alteration | T&E | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 8 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Indoor Air Quality | g VOC | 3.70e-02 | 1.20e-01 | 0.00e+00 | 6.35e+00 | 5.48e+01 | 8 | 0.0000 | 0.0000 | 0.0000 | 0.0014 | 0.0125 |
| Ozone Depletion | gCFC-11 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 0.00e+00 | 8 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Smog | g NOx | 1.31e+01 | 1.20e+01 | 2.03e+01 | 2.64e+01 | 3.02e+01 | 8 | 0.0007 | 0.0006 | 0.0011 | 0.0014 | 0.0016 |
| Water Intake | liter | 1.51e+01 | 4.46e+01 | 9.52e+01 | 2.24e+02 | 4.21e+02 | 8 | 0.0002 | 0.0007 | 0.0014 | 0.0034 | 0.0064 |
| Human Health--All | g C7H8 | 5.05e+05 | 1.92e+04 | 3.99e+04 | 3.12e+05 | 8.73e+04 | 8 | 0.0147 | 0.0006 | 0.0012 | 0.0091 | 0.0025 |
| Health--Cancer | | | | | | | | | | | | |
| | | | | | | | Total | 0.0187 | 0.0048 | 0.0079 | 0.0241 | 0.0337 |

**Economic Impact**

| Economic Impact | Units | Tile/Glass | Linoleum | Terrazzo | NylonTile | NylonBrdlm |
|---|---|---|---|---|---|---|
| First Cost | $ | 9.55 | 3.56 | 23.59 | 3.58 | 2.13 |
| Future Cost | PV$ | 0.00 | 1.20 | 0.00 | 4.18 | 3.81 |
| Life-Cycle Cost | | 9.55 | 4.76 | 23.59 | 7.76 | 5.94 |

*Discount Rate (%)* 3.0

**Note: Lower values are better**

*Expressed in given impact units per functional unit of product

**Expressed in penalty points per functional unit of product

**Fig. 2** BEES results summary: five selected floor coverings

The Raw Results for potential environmental impacts are expressed in physical units appropriate for the impact.[1] In order to synthesize these results into a single environmental performance score for each floor covering, raw results are weighted (in this example approximately equally) and normalized by reference to each impact's annual per capita performance at the U.S. level. Note that while quantifying the uncertainty surrounding BEES results is an important future research direction, the underlying impact assessment models at present preclude such quantification.

As shown, life-cycle costs range from $4.76 to $23.59 (in present value dollars) per square foot over 50 years. The total environmental performance scores range from 0.0048 to 0.0337 penalty points per square foot over 50 years and are displayed graphically in Fig. 3. These quantitative performance scores permit a customer to evaluate the overall life-cycle impacts of a product and also enable an evaluation of the product on a measure-by-measure basis.

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[1] Following are more complete descriptions of environmental impact units: Acidification: millivolts of hydrogen ion equivalents; Criteria Air Pollutants: micro Disability-Adjusted Life Years; Ecological Toxicity: grams of 2,4-dichlorophenoxyacetic acid equivalents; Eutrophication: grams of nitrogen equivalents; Fossil Fuel Depletion: megajoules of surplus energy; Global Warming: grams of carbon dioxide equivalents; Habitat Alteration: threatened and endangered species count; Indoor Air Quality: grams of Total Volatile Organic Compounds; Ozone Depletion: grams of chlorofluorocarbon-11 equivalents; Smog: grams of nitrogen oxide equivalents; Water Intake: liters of water; and Human Health: grams of toluene equivalents.

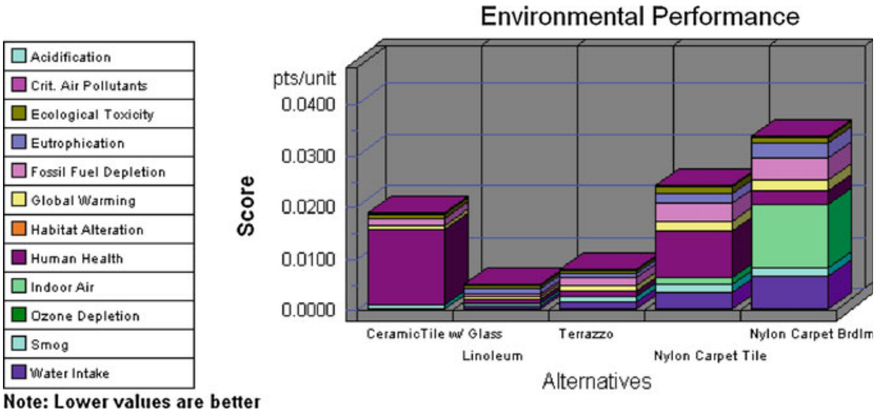

**Fig. 3** BEES environmental performance scores for five selected floor coverings

Use of the BEES approach adds value to consumer purchase decisions for several reasons. First, BEES development and analysis by the National Institute of Standards and Technology, a non-regulatory federal agency known for developing unbiased world-class measurement science, lends integrity to the results. Second, BEES is internally consistent with respect to underlying life cycle costing, scoping, inventory analysis, impact assessment, and interpretation criteria, permitting fair comparisons among products. Finally, BEES' use of consensus standard guidance for life cycle environmental and economic impact assessment facilitates industry acceptance of the approach.

Taken together, BEES' integrity, internal consistency, and results comparability promote technological innovation. Its use of a performance-based approach—one that accounts for inevitable tradeoffs among the many dimensions of life cycle environmental and economic performance, rather than one prescribing arbitrary performance thresholds on an impact-by-impact basis—levels the playing field for industry and promotes competition on a meaningful basis. In the short run, performance-based measures enable meaningful improvement by manufacturers in emerging industries by pinpointing weak links in their products' life cycles (e.g., process efficiencies, transportation distances). In the long run, performance-based measurements are essential for technological innovation. If consumers were to judge environmental performance solely on the basis of a single-attribute prescriptive requirement—say, bio based content—manufacturers would be motivated to find the least-cost means of maximizing bio based content. Some may accomplish this through inferior performance on other important attributes. Prescriptive requirements inhibit innovation by restricting the choices available to manufacturers. The BEES performance-based measures, on the other hand, give manufacturers the freedom to develop products that can compete on the basis of best value, which is critical to a sustainable economy.

BEES must remain flexible to keep pace with advances in measurement science. Life cycle impact assessment is evolving. While BEES incorporates state-of-the-art impact assessment methods today, the science will continue to evolve and methods now in use—particularly those for land use, water intake, and human health—are likely to change and improve over time. Future versions of BEES should incorporate these improved methods as they become available.

As science advances, so will the relative importance society places on environmental impacts. BEES uses such importance weights to synthesize its 12 environmental impact scores into a single decision-enabling score. Similarly, the U.S. Office of Management and Budget issues annual updates to its discount rates to account for changes in the real earning power of the dollar over time. BEES uses these discount rates in its life cycle economic performance scoring to convert future costs to their equivalent present value. As both society's tradeoffs and the dollar's earning power change over time, BEES should incorporate these values in a systematic manner; one that preserves comparability among BEES results while at the same time accommodating inevitable change.

## 6 Conclusions

U.S. consumers are increasingly demanding sustainable products in the marketplace. However, too often the environmental and economic performance of products marketed as "sustainable" have not been well documented on a quantitative life-cycle basis. Considering multiple impacts and life cycle stages is necessary because superior product performance on a single impact or stage may be achieved at the cost of exacerbating others. A multidimensional approach is necessary for a comprehensive, balanced analysis. Increasingly, policymakers and consumers are calling for quantitative, science-based analytical techniques to evaluate the life-cycle sustainability performance of products.

The analytical method discussed in this chapter represents significant progress in efforts to reliably evaluate the environmental and economic impacts of the production, use, and disposal of products. BEES establishes a scientifically supported set of quantitative measures for sustainability assessment. The program does not tell the consumer which product to purchase, but instead provides quantitative information that enables the user to responsibly weigh the relative merits of each product being considered. The analytical technique represents a conceptual breakthrough in evaluating such products on a cradle-to-grave basis, thus providing a much clearer understanding of overall sustainability performance and the underlying tradeoffs among its many dimensions.

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# Key Business Metrics that Drive Sustainability into the Organization

**Beth Beloff and Dicksen Tanzil**

**Abstract** Sustainability can mean different things to different organizations, depending on their distinct business and stakeholder contexts. Thus, in developing a sustainability program, one must understand the sustainability-related aspirations, goals, and challenges both internal and external to the organization. This chapter describes how an organization's approach to sustainability can be developed through understanding the interaction between the organization and the environmental and social systems in which it operates. Furthermore, it presents the GEMI *Metrics Navigator*$^{\text{TM}}$ process, a roadmap for identifying key sustainability issues and business metrics that can help an organization achieve its sustainability goals.

**Keywords** Business measures · Organization · Sustainability goal · GEMI Metrics Navigator

## 1 Introduction

Business organizations are increasingly faced with a plethora of externally driven sustainability codes, standards, and stakeholder requests. Without understanding what sustainability means to the organization, and the values that may be gained through a sustainability effort, one can easily fall into a metrics morass—having too many goals and metrics with no internally driven focus. This can pose a serious challenge in managing sustainability.

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This metrics challenge was recognized by the Global Environmental Management Initiative (GEMI), an organization of more than 20 leading multinational companies. The *Metrics Navigator*™ (GEMI 2007) was developed to help an organization navigate through various sustainability demands and determine the key issues, objectives, and metrics that can generate value to the organization and its stakeholders.

This chapter begins with a discussion on the context and motivation for integrating sustainability into business. Starting by asking the "why" of sustainability, one can identify the drivers and seek a vested interest by key stakeholders in the successful outcome of the sustainability efforts and initiatives. It presents the GEMI *Metrics Navigator*™ process and discusses how it may be used by a business organization (e.g., a company, a manufacturing facility, or a public agency) to achieve the desired business outcomes. Specifically, it provides a roadmap for identifying the critical few issues that are most material (i.e., relevant and substantive) to an organization, develop the critical few objectives to address those issues, and build the critical few indicators and metrics to assess progress and success.

## 2 The Sustainability Context

### 2.1 *Conceptualizing the Context*

An organization operates within economic, social, and environmental systems. These systems are portrayed as a Venn diagram, with three overlapping circles representing environmental, social, and economic dimensions.

Yet, one can also view the concept of sustainability as a whole system represented by three concentric circles (Fig. 1). The largest circle is the environmental

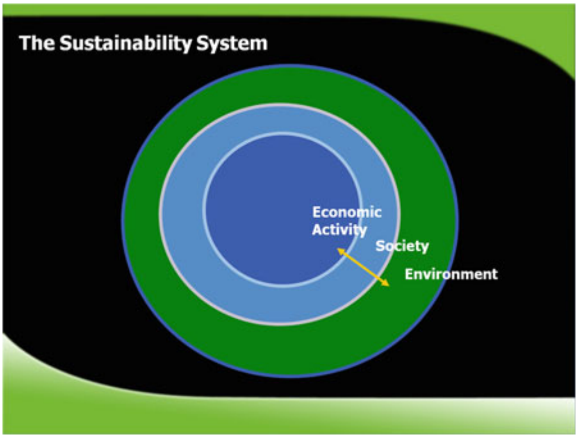


**Fig. 1** The sustainability system

or ecological system on which all life depends. It is the planet Earth and its natural resources and biodiversity. Everything depends on the long-term health of this system. The next circle represents the society, or the human environment. The economic system lies at the center of this conceptual framework, representing economic activity. In this paradigm, societal norms, practices, regulations, rules, and laws mediate between the use of the natural environment and the economic activities represented by industry and commerce. Social systems determine what impacts on ecological systems are acceptable in pursuit of economic development.

These systems are inextricably linked. They are all limited by the constraints of the largest system, the environmental system. The environmental system is increasingly constrained with respect to supply and quality of natural resources, as demand for those resources increases through factors such as population growth, economic development, and increasing global appetite for consumption. This results in the increase in environmental degradation, poverty and challenges regarding social equity, and political instability, which in turn put additional pressure on the environmental system. Hence, ecosystem services such as climate stability, water and air quality, and biodiversity are strained.

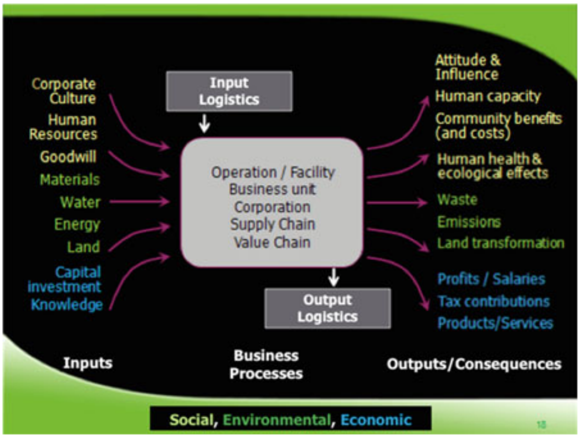
The consequence can be felt as a narrowing funnel (The Natural Step 2010). That is, the opportunity space for business and societal action is increasingly stressed. These stresses result in societal pressure for actions that further regulate what happens in the system. By some measures, we have already exceeded the Earth's capacity to support humanity at our current level of consumption within the ecological system constraints (Wackernagel and Rees 1996; Ewing et al. 2010). How do we reconcile what is happening in the entire sustainability system to what our individual and business actions contribute? We are unable to see the unsustainability of our system; we are like frogs boiling in water, unable to know to get out before it is too late!

## 2.2 Businesses in the Sustainability Context

Pressures in the sustainability system affect businesses as much as they affect individuals and society. Thus, the sustainability context encourages businesses to consider the social, environmental, and economic dimensions of their activities—how it affects and is affected by the broader systems.

The interaction between business and the broader system may be depicted by the input–output model shown in Fig. 2. It includes a set of inputs, business processes, and outcomes. Social, environmental, and economic elements are transformed as they move through the business system. The system uses environmental resources (including materials, water, energy, and land), social resources (including corporate culture and goodwill in the community), and economic resources (including financial and intellectual capital). Those resources are transformed by business processes,

**Fig. 2** Input–output model of economic, social, and environmental resources



with resulting outcomes and consequences. These include the traditional economic outcomes (profits and salaries, tax contributions, products, and services), environmental outcomes (waste, emissions, land transformation), and societal outcomes (attitude and influence, human capacity, community benefits/costs, and effects on human health). This interaction between the business and the economic, environmental, and social systems in which it operates also informs what a business can measure and manage.

## 3 Business Response

Sustainability challenges our current ways of thinking. It requires us to elevate the discussion of business strategy to address implications within the integrated systems.

Currently, optimization often targets short-term solutions at the level of parts, functional units, or discrete activities in the business value chain. For example, a company’s sustainability effort may focus on low-hanging fruit such as water conservation and energy efficiency. Yet how do you know that you are focusing on the right thing? Are you suboptimizing?

Sustainable requires thinking across functions. It necessitates thinking in terms of life cycles and value chains rather than discrete processes or stages. It also requires thinking in terms of long-term scarcity and future costs of natural resources. Short-term business planning mechanisms are not typically supportive of the systems thinking required for sustainability. Analytic mechanisms to identify discrete projects that support sustainability, both of the business operation

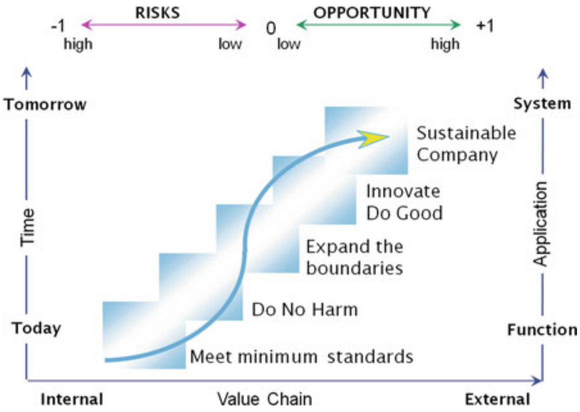


**Fig. 3** Sustainable business learning curve (adapted from Beloff 2005)

and the larger system, on which it depends, require strategic thinking in a long-term context.

In response to those challenges, many leading businesses have undergone the typical "learning curve" depicted in Fig. 3. On the value-chain perspective, these companies have broadened their decision-making from internal focus to incorporating the value chain, i.e., activities of their suppliers, customers, and business partners. The decision time-frame is extended to include not only short-term but also long-term implications. The application of the sustainability efforts is also extended from the domains of discrete business functions (e.g., environmental, research and development) to cross-functional or system-wide across the corporation.

A company's response to sustainability typically begins with meeting minimum standards (e.g., environmental, health and safety, and product safety requirements). In advancing through the learning curve, a company then attempts to "do no harm," i.e., eliminates negative impacts beyond compliance to standards and regulations. These two stages represent the necessary foundation of a sustainability effort. The company can expand the boundaries to involve other entities within the company as well as value-chain partners, and begin to focus on innovation to optimize the environmental, social, and economic benefits of its activities, and strive to become a sustainable company.

Throughout this learning journey, the perspective and business benefits shift from solely risk mitigation to incorporating new opportunities, such as new markets for technologies that address global sustainability challenges. Sustainability can benefit the company's bottom line, e.g., reducing cost through resource efficiency and reducing regulatory and community risk. Risk reduction increases access to capital and, when applied to the supply chain, helps ensure supply chain continuity. The sustainable business value proposition includes top line values such as fostering innovation, creating new products and technologies, building new markets, engaging new stakeholders in successful partnerships, enhancing reputation, recruiting and retaining the best talent, and solidifying customer relationship and brand loyalty.

# 4 Sustainability Measurement and Its Challenges

## *4.1 Why Measure*

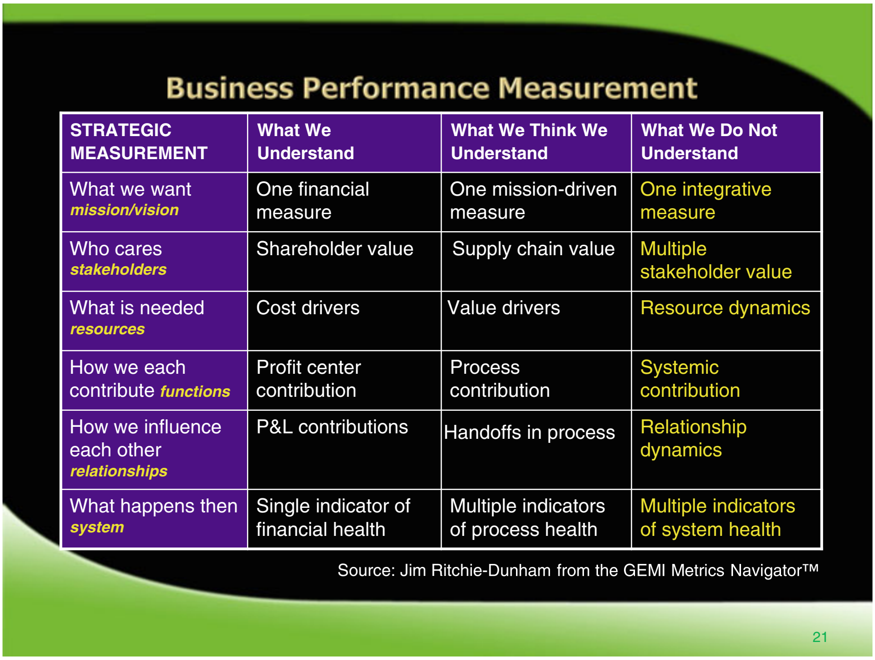
A well-known adage in business is that what is measured is managed. But it is important to understand *why* one wants to measure sustainability in order to make the best decisions about *what* measures to develop and use. Linking traditional financial indicators well understood in business to environmental and social indicators helps build the business case for sustainability and create incentives to apply the concepts of sustainability to business strategy.

An organization's reasons for measuring drive the selection of key sustainability metrics. Metrics for purposes of reporting to stakeholders would be different from the set designed to help improve management decision-making. Metrics can facilitate the understanding of whether organizations are making progress by tracking progress in meeting goals over time. Benchmarking can show comparatively how well business units are performing relative to one another both within the organization or against other organizations and, at scales such as at the level of an operation, facility, business unit, corporation, supply chain, or value chain.

## *4.2 Measuring a Complex System*

Understanding how to measure complex systems does not come easily for business. Companies typically excel at driving toward discrete, financial measures. Yet one financial measure does not necessarily capture how a company's mission aligns with its actions and contributes to achieving its vision. It does not produce insights about being in a global marketplace of limited resources with socially and environmentally conscious stakeholders.

A piece by Jim Ritchie-Dunham in the *Metrics Navigator*™ (GEMI 2007) outlines the challenges in developing measures for complex systems such as sustainability (see Fig. 4). Business organizations are used to a measurement system driven by a single financial measure. Increasingly, businesses believe they understand how to drive toward one mission-driven measure. They look to supply chain value, value drivers, process contributions at the functional level, and handoffs in the process to inform the mission-driven measure. They rely on



Business Performance Measurement

| **STRATEGIC MEASUREMENT** | **What We Understand** | **What We Think We Understand** | **What We Do Not Understand** |
|---|---|---|---|
| What we want ***mission/vision*** | One financial measure | One mission-driven measure | One integrative measure |
| Who cares ***stakeholders*** | Shareholder value | Supply chain value | Multiple stakeholder value |
| What is needed ***resources*** | Cost drivers | Value drivers | Resource dynamics |
| How we each contribute ***functions*** | Profit center contribution | Process contribution | Systemic contribution |
| How we influence each other ***relationships*** | P&L contributions | Handoffs in process | Relationship dynamics |
| What happens then ***system*** | Single indicator of financial health | Multiple indicators of process health | Multiple indicators of system health |

Source: Jim Ritchie-Dunham from the GEMI Metrics Navigator™

**Fig. 4** What businesses understand on performance measurement

multiple indicators of process health, such as through the Balanced Scorecard (Kaplan and Norton 1996).

Measuring sustainability, however, often requires going beyond financial and process indicators. It often requires understanding the health of the environmental, social, and economic systems in which the organization operates. This is an emerging measurement area which companies have not yet understood. It involves dynamic and systemic measures that are new, complex, and in some cases difficult to use. However, difficulty in use should not render them useless.

## *4.3 Navigating the Metrics Landscape*

Various sustainability indicators and Metrics have been defined for various uses (Tanzil and Beloff 2006). They include indicators and metrics for managing sustainability at the global and regional levels (e.g., United Nations 1992) as well as corporate, facility, process, and product levels (e.g., Schwarz et al. 2002; IChemE 2002). For public reporting, the Global Reporting Initiative (GRI 2006) provides the global standards.

However, for internal management, one must identify a meaningful set of metrics that drive sustainability performance in the organization. One must understand the internal and external contexts for the organization's sustainability performance measurement system, and identify the critical few issues, objectives, and metrics to manage. Without focus, one can be easily overwhelmed by the plethora for data and requests for information and fall into a metrics morass.

The GEMI *Metrics Navigator*™ provides a roadmap for avoiding the metrics morass and developing an effective sustainability performance management and metrics regime. It helps organizations decide which metrics are the most meaningful for internal management, and how the metrics can be effectively defined and implemented. This includes the use of lagging metrics that reflect past outcomes, as well as leading metrics that predict future outcomes.

The plethora of standards for sustainability indicators and metrics provide useful resources for selecting and constructing the metrics. However, for internal management, these metrics must be selected based on business and stakeholder contexts that are specific to the organization.

## 5 The GEMI *Metrics Navigator*™ Process

The GEMI *Metrics Navigator*™ is a tool for sustainability assessment, planning, and metrics development. It was developed through a collaborative process between GEMI member companies and the BRIDGES to Sustainability team at Golder Associates[1]. GEMI is a global leader in developing insights and creating environmental sustainability solutions for business. It currently has more than 20 members comprised of leading multinational companies dedicated to fostering global environmental, health and safety (EHS) and sustainability excellence through the sharing of solution tools and information to help business achieve environmental sustainability excellence. GEMI has developed more than 30 self-assessment solution tools in the areas of supply chain, water sustainability, metrics, climate change, management systems, and more. More information about GEMI, including access to its library of solution tools, may be found at www.gemi.org.

The strategic metrics development process in this tool uses a six-step process. The objective of the process is to develop and implement metrics to inform business strategy, enhance decision-making, measure what is right, and communicate effectively with stakeholders. The GEMI *Metrics Navigator*™ workbook and supporting worksheets assist the user in moving through the steps and documenting the discussion at every step, building a logic map regarding the sustainability effort, and recording key business objectives for historical purposes.

The roadmap takes the user through the process of determining the "critical few" issues on which to focus, the "critical few" objectives which produce the

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[1] The BRIDGES to Sustainability team was led by the authors.

greatest value to both the company and society at large, and the "critical few" strategic metrics which are most meaningful and effective in driving sustainability performance, integration into the organization, and the business case.

The process is organized into three questions described below: what is material, what and how to measure, how to assure effectiveness of the sustainability performance measurement system.

## *5.1 What is Material*

The first part of the GEMI *Metrics Navigator*™ process (steps 1–3) helps identify what is material to an organization. Materiality is defined as the relevance and substantiality of an issue to the organization. This early focus on materiality ensures that the organization is measuring that which is right for them.

The GEMI *Metrics Navigator*™ uses the following criteria for assessing an issue's materiality:

- relevance to the business strategy
- significance of the organization's environmental, social, and/or economic impacts
- level of concern to external stakeholders
- ability of the organization to control or influence.

By looking both internally and externally, an organization can identify areas where they can make the most significant difference and emerging issues that may be of higher concern in future.

### 5.1.1 Step 1: Understand the Context for Metrics Development

Sustainability should support business objectives if it is to be accepted within the organization. Thus, the process begins with identifying the business context that serves as the foundation for the organization sustainability programs. This includes the organization's mission, core values, vision, marketplace, business objectives, risks and opportunities, business success factors, and business performance measures in place.

Furthermore, this step articulates the company's definition of sustainability, if there is one, and examines the current and planned future efforts on environmental, social and economic issues along the value chain.

### 5.1.2 Step 2: Assess Issues from Stakeholders' Perspectives

Next, one identifies the key stakeholders internal and external to the organization. Internal stakeholders include key employees and managers across the organization's functional areas that may affect or are concerned about the company's sustainability performance. Issues important to the internal stakeholders are prioritized and ranked based on relevance to the business strategy and the significance of the organization's environmental, social, and/or economic impacts.

After key issues from the internal stakeholders' perspectives are understood and identified, the organization needs to bring in the perspectives of external stakeholders. The key external stakeholders need to be identified, and their perspectives brought to the table either through direct communication or workshop or through proxies (e.g., employees or external experts) who are familiar with the external stakeholders' aspirations and priorities. Then, issues important to the external stakeholders are also prioritized and ranked by level of concern to external stakeholders and the ability of the organization to control or influence the issue.

### 5.1.3 Step 3: Develop Key Objectives

A materiality assessment brings together the priority issues from the internal and external stakeholders' perspectives and identifies the most material issues that need to be managed by the organization. Potential objectives are developed to capture what the organization wants to achieve in managing the material issues. Key objectives are selected by evaluating the business and societal value that could result from meeting the objectives. The key objective should have a clear value proposition for both the company and the society at large.

While only a few material issues and key objectives will be included for proactive management, other issues may require monitoring by the organization.

## *5.2* Step 4: What and How to Measure

The second part of the GEMI *Metrics Navigator*™ process is organized into one step, described below.

### 5.2.1 Step 4: Define Key Performance Indicators and Metrics

This step involves the development of key performance indicators (KPIs, defined here as general statements of what to measure) and metrics (the specific measurements accompanied by clear descriptions of how they are measured).

It helps to sort through the array of possible metrics to measure the success of the key objectives, to select a set of critical few metrics that focus on business success. The possible metrics is identified first by understanding the processes necessary to drive the key objectives, the possible outcomes, and the broader consequences of achieving the outcomes. The possible metric can then be identified to measure the process, outcome, and consequence. The KPIs and metrics are selected based on a set of criteria, such as reliability, relevance to the business, and accuracy.

Different types of metrics may be needed, including:

- outcome metrics—measures of results; e.g., energy consumption, number of community complaints, and salaries and tax benefits flowing to local communities
- process metrics—measures of the actions or processes that drive the results or intended outcomes and are usually tied to the action plans put in place to achieve targets; e.g., percent of facilities that incorporated best practices, and number of executive review meetings on socioeconomic risks and challenges
- consequence metrics—measures that reflect the system view or broader consequences of the intended outcomes; e.g., land area of ecosystem saved due to reduction in raw material use, number of quality-adjusted life years saved by product use, and potential liability cost avoided due to a proactive community engagement program.

The metric may be quantitative or qualitative. Indices that aggregate different metrics into one measure may sometime be useful.

## *5.3* Steps 5–6: How to Assure Effectiveness

The last part (steps 5 and 6) of the GEMI *Metrics Navigator*™ involves implementation and evaluation of the sustainability performance management and measurement regime. While it is the last part of this roadmap, the evaluation feeds back into the beginning of the process in a continuous improvement cycle.

### 5.3.1 Step 5: Evaluate and Communicate Metrics

Step 5 focuses on distilling data into useful and manageable information that is meaningful to the intended users. This implementation step encourages the user to work with existing management and information systems. This section also cautions on the use of metrics developed for one purpose but used for another, metrics that can be misleading or potentially misunderstood.

### 5.3.2 Step 6: Evaluate Improvement and Integration

Step 6 is a critical assessment of the metrics and the effectiveness of the development process itself. This step encourages reflection on the five previous steps and checks if the metrics inform the business strategy. Doing so assures

| WORKSHEET: SUMMARY OF KEY POINTS | |
|---|---|
| What is material | Key business objectives (from Step 1) |
| | Environmental, social and economic elements support business objectives (current and future) (from Step 1) |
| | Key employees and external stakeholders in this effort (from Step 2) |
| | Critical few material issues (from Step 2) |
| | Key objectives which relate to the material issues (from Step 3) |
| What and how to measure | Expected uses of the metrics and by whom (from Step 4) |
| | KPIs and related metrics, what they are and how well they meet the criteria (from Step 4) |
| How to assure effectiveness | Degree of integration of metrics into management systems (from Step 5) |
| | Effectiveness of metrics communication to users (from Step 5) |
| | Expected organizational behavior (from Step 6) |
| | Expected change in personal behavior (from Step 6) |
| | Use of metrics to support the business case and refine business strategy (from Step 6) |
| | Expected business value (from Step 6) |

**Fig. 5** Summary worksheet of the GEMI *Metrics Navigator*$^{\text{TM}}$

that the metric has met its goal and results in business value for the organization.

The summary worksheet (Fig. 5) captures all of the key points developed through the GEMI *Metrics Navigator*$^{\text{TM}}$ process.

## 6 Conclusion

Sustainability encourages a business organization to consider and address the positive and negative, and the intended and unintended consequences of their operations on the social, environmental, and economic systems in which they operate. Metrics enable a company to measure outcomes of their activities as well as create and manage change.

A sustainability strategy assessment should elucidate material, business-critical issues. The GEMI *Metrics Navigator*$^{\text{TM}}$ process provides a roadmap for navigating through the ever-changing landscape of that which is measurable. The process leads to the development of key objectives to address business-critical issues. Also, it identifies the key metrics that help assess how well a company meets those objectives. Additionally, the process assists corporations in refining the metrics for multiple stakeholders and uses. The metrics developed through the GEMI *Metrics Navigator*™ process will reflect the unique metrics critical to operationalizing sustainability for a particular organization in a given place and time.

While the plethora of externally driven sustainability metrics standards and guidelines provide a valuable resource in developing and selecting an internal management metrics, starting with understanding the business objectives and success factors, internal aspirations, and external concerns help assure that the sustainability effort will be successful in generating value for the organization as well as the society at large.

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# Environmental Assessment and Strategic Environmental Map Based on Footprints Assessment

**Jiří Jaromír Klemeš and Luca De Benedetto**

**Abstract** The life cycle assessment (LCA) method is introduced as a powerful tool to assess the environmental impact of product/services. Some important limitations have been evidenced in the past years, including data quality and collection, definition of system and time boundaries, multi-functionality and allocation, occupational health. The environmental performance strategy map (EPSM) is a novel graphical representation reception the strength of ecological footprint and life cycle analyses. The use of EPSM has a potential as an environmental evaluation and strategic environmental map based on the various footprints such as carbon footprint, water footprint, energy footprint, emission footprint, work environment footprint, etc. This graphical method allows the use of these footprints with an additional dimension of cost.

**Keywords** LCA · Strategic environmental maps · Footprints

## 1 Introduction: Life Cycle Assessment

The first step towards environmental assessment is life cycle assessment (LCA). It is a tool for analysing environmental impacts on a wide perspective, with reference to a product system or economic activity. The concept varies depending on the adoption pattern and on the precision that needs to be achieved. Due to the constraints on resource or data availability, industrial companies perform most of the time analyses based on a more simplified approach (Life Cycle Approach), or they

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simply apply the general principles to certain aspects of the production system (Life Cycle Thinking), even though all those aspects are usually referred to as LCA activities.

Despite some limitations and methodological gaps, LCA is still recognised as a very powerful set of tools and ideas in evaluating not only environmental impacts, but, in recent times, also occupational health and safety issues.

## 2 LCA: The History

Life cycle assessment involves the evaluation of specific elements of a product system, in order to determine its environmental impact. It is also called life cycle analysis or cradle to grave approach. LCA comprises a conceptual framework and a set of tools that have been studied and developed in the last 40 years. The core of the concept is the assessment of the impacts at each stage of the product life cycle. The term 'product life cycle' is used here not with reference to a product's sales and profits course over time, but with reference to the notion of production, manufacturing, distribution, use and disposal including all necessary transportation steps. The proposed view is therefore a holistic one that includes the entire lifespan of a product from the extraction of the raw materials to its disposal.

The first studies on LCA date from the late 1960s, early 1970s. In 1969, for example, the Coca Cola Company funded a study to compare resource consumption and environmental releases associated with beverage containers (Udo de Haes and Hejungs 2007). Similar studies were then started in UK, Switzerland and Sweden. In these early studies, LCA was closely linked with energy analysis. Also due to the energy crisis of the early 1970s, waste and outputs were initially not considered and attention was concentrated on calculating the total energy used in production of various household goods. For example (Bousted 1996), in the UK studied various types of beverage containers, including glass, plastic, steel and aluminium. This demonstrated the high embodied energy value of aluminium, in contrast to glass.

After the oil crisis subsided, the energy issues, and the use of LCA in this application, lost prominence. It was only in the late 1980s and early 1990s that a new interest in the tool was found and coupled with efforts to bring standardisation to its use. In 1989 Society of Environmental Toxicology and Chemistry (SETAC) started working on defining a common terminology and a methodology framework.

A first result of this work was the definition of the *functional unit*. This is a quantified description of the product systems to which impacts are attributed. This unit sets the scale for comparison of two or more products and one of its main purposes is to provide a reference to which the input and output data are normalised. Three aspects have to be taken into account when defining the functional unit (Lindfors et al. 1995):

- Efficiency of the product
- Durability of the product
- Performance quality standards.

Finally, when performing an assessment of more complicated systems (e.g. multifunctional systems like waste treatment ones) special attention has to be paid to by-products.

This standardisation work was then picked up by the International Standard Organization (ISO) in 1994 with the first of its 14040 series. The rigid context of the ISO offered coherence to the different methodologies and approaches in LCA without, nevertheless, imposing one. The ISO work has resulted in the definition of specific steps that allow the separation of the subjective and objective phases within the proposed method. The principles and framework for LCA in these documents include: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), life cycle interpretation phase and reporting.

These phases are the codification of the same steps individuated by SETAC in the previous years, with the exception that Life Cycle Improvement has been considered an activity that should permeate all other phases and not one of its own. The Interpretation phase was added instead. The interest on this topic is witnessed also by newer versions of the above-mentioned series, the latest of which was published in 2006 (ISO 14040: 2006 effectively replaces 14041: 1998; 14042: 2000 and 14043: 2000).

During the last years the methodology of the LCA has been consolidated. Generally LCA is accepted as a tool, which allows progress towards full environmental responsibility for all corporate and public stakeholders. Some difficulties in the methodology have been recognised by Frankl et al. (1998):

- Complexity
- High cost and long time scales
- Uncertainty about valuation
- Continuing invisibility of much of LCA work.

Another challenge lies with the communication of the results. Long reports might put off many users. If the results are too simplistic then there is difficulty in validating them.

A survey by the European Environment Agency (Jensen et al. 1997) pointed at the following social impacts of LCA:

- LCA is now seen as necessary by all stakeholders as integral part of environmental management tool kit
- Use of this tool is also seen important in the process of corporate strategy formulation
- Level of knowledge of LCA remains worryingly low in the general public
- Level of progress in LCA adoption varies between countries
- Quality control mechanism remains relatively weak.

Involvement of external stakeholders in defining study boundaries is seeing increasingly important (Fig. 1).

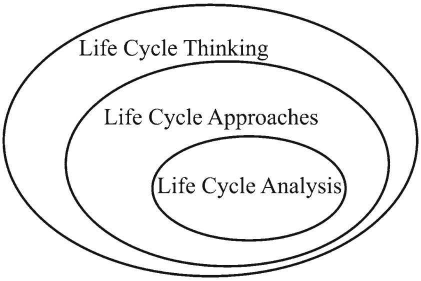

**Fig. 1** Basic levels of LCA (adapted from Frankl et al. 1998)

## 3 LCA: The General Framework

The methodology for life cycle analysis includes the phases described in Fig. 2. It should be noted that ISO 14040 does not describe the technique in detail, nor does it specify which methodology should be used for each phase. It provides mainly a framework in which these elements can be developed.

### *3.1 Goal and Scope Definition*

This is the first subjective phase of the application of LCA. At this stage it is necessary to identify the aim of the analysis and the system boundaries. This is to

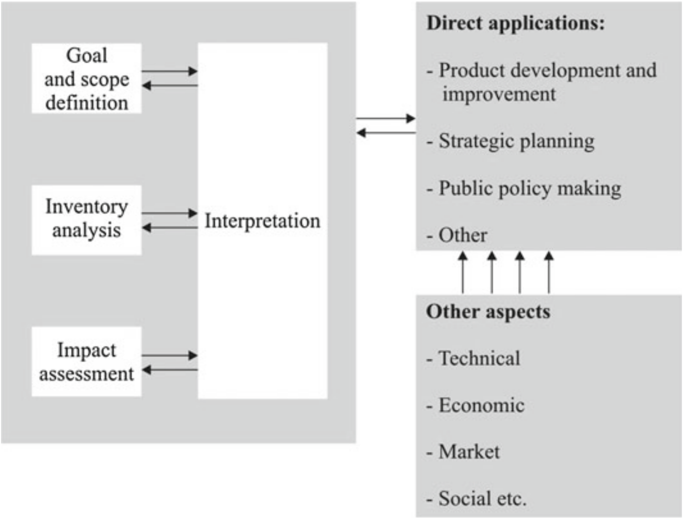

**Fig. 2** Phases and application of LCA (adapted from ISO 14040 2006)

ensure that no relevant part of the system to be investigated is actually left out. The definition of the goal and the scope is critical, since the results will depend greatly on them.

The *goal* needs to state clearly and without ambiguity which is the application, what are the reasons, why the study is carried out and who the recipients of the results of the study are. A goal identified in such a way will allow the practitioner to perform the correct choices throughout the study. The goal could also be adjusted depending on specific and relevant findings of some later steps of the analysis.

The *scope* sets the borders of the assessment. Different elements should be considered in order to specify the scope correctly: product group, functional unit, the system and its boundaries, impact assessment boundaries, the data quality requirements, limitations. The definition of the system boundaries (inputs and outputs) are critical in order to determine the amount of work to be done. This activity is quite subjective and requires decision to be taken on the following areas: geographical boundaries, life cycle boundaries and boundaries between the technology and the biosphere. Given the subjective characteristics of this activity, it is necessary to be very transparent with regard to all decisions and assumptions taken at this stage. The impact categories need to be chosen from a list of standard ones: assessing the boundaries will also limit the categories to be considered during the study. As for the goal, even the scope can be adjusted during the iterative process of the analysis.

## 3.2 Inventory Analysis

Aim of this second phase is to perform mass and energy balances to quantify all the material and energy inputs, waste and emissions from the system causing the environmental burdens. The following main issues (as defined by ISO 14040 1997) should be considered during this phase: data collection, refining system boundaries, calculation, validation of data, relating data to the specific system and allocation.

*Data* can be specific (to the process, the company and the geographical area) or more generic (extracted from trade organisations or governmental institutions). To perform this phase it is possible to rely on quantitative or qualitative data, according to their availability. Data collection can prove to be the most work intensive activity of a LCA. In some cases it is possible to rely on average values from trade organisations or literature.

Generally the results obtainable with LCA are very sensible to the set of data used. It is important to understand the intrinsic criticality of this phase. More generic and qualitative data could be used for a first simplified analysis, to be reiteratively repeated on more specific and system-related data.

The data initially collected can be used to review the *system boundaries*, as defined in the previous phase. If the system is very complex it might be necessary either to review the system boundary or to include more data. Another possibility is the allocation of the relevant environmental burdens to the system, ensuring that the approximation of the input–output relationship and the main characteristics is possible. *Allocation* might be necessary in case of multi-input or multi-output systems.

The inventory should then be interpreted considering as many as possible specified uncertainties and usually the lack of data. In particular *validation* should also be considered and carried out during the whole process of data collection to reduce eventual discrepancies and data quality issues later on.

## 3.3 Impact Assessment

The third phase is based on the aggregation of the environmental impacts quantified in the Inventory Analysis into a limited set of recognisable impact categories (e.g. global warming, ozone depletion, acidification etc.). This phase comprises the following steps: classification, characterisation, normalisation and weighting.

According to (ISO 14042 2000) there are three groups of categories to be considered: Resource use, Human Health consequences and Ecological consequences. These broad groups should include all categories like climate change, stratospheric ozone depletion, photochemical oxidant formation (smog), eutrophication, acidification, water use, noise, etc. These categories should be selected from a list of examples and be relevant to the system under investigation.

The second step in this phase is mainly a quantitative step: *characterisation*. In this step it is necessary to assign the relative contribution of each input and output to the selected impact categories. Pennington et al. (2004) proposed a generic equation to calculate indicators from the inventory data. For each impact category he used generic characterisation factors.

$$\begin{aligned} \mathit{Category.Indicator} = \sum_{S} & \mathit{Characterisation.Factor}(s) \\ & \times \mathit{Emission.Inventory}(s) \end{aligned} \tag{1}$$

where $s$ indicates the inventory data (input). The characterisation factors can be found in the literature as databases or are available in various LCA support tools. The following equation takes into account some of the potential variables of non-generic characterisation factors in the context of human health and natural environment:

$$\mathit{Characterisation.Factor}(s,i,t) = \sum_{j} \frac{\mathit{Effect}(s,j,t)}{\mathit{Emission}(s,j)} \tag{2}$$

subscript *i* is the location of the emission; *j* is the related location of exposure of the receptor and *t* is the time period during which the potential contribution to the impact is taken into account.

The next step in this phase is the *normalisation*. This activity is described by Stranddorf et al. (2003) as a necessity to calculate the magnitude of the category indicator results relative to reference values where the different impact potentials and consumption of resources are expressed on a common scale. The goal of normalisation is to set a common reference enabling comparison of different environmental impacts. There is still rather wide scope for the future research, how to run the normalisation to be really comparable base for the assessment.

Quantitative results of the above-mentioned characterisation of impact categories are not always comparable and an additional step is necessary: *weighting*. This activity aims at comparing the impact categories against each other. This would allow ranking and possibly defining the relative importance of different results. Weighting can be a quantitative or qualitative activity based on social or political considerations. Different weighting methods have been developed (Lindeijer 1996).

### 3.4 Interpretation

This is the last phase as indicated by (ISO 14040 2006). Interpretation is a systematic procedure to evaluate information from the conclusions of the inventory analysis and impact assessment of a product system.

The following tasks should be accomplished in this phase (Jensen et al. 1997):

- Identify the significant environmental issues.
- Evaluate the methodology and results for completeness, sensitivity and consistency.
- Check that conclusions are consistent with the requirements of the goal and scope of the study, including, in particular, data quality requirements, predefined assumptions and values, and application oriented requirements.

If yes report as final conclusions.
If not, return to Task 1 or 2.

## 4 Limitations of LCA Approaches

Even though LCA is a powerful tool to assess the environmental impact of product/services, some important limitations have been evidenced in the past years. The main limitations are all related to the LCA methodological approach, especially data quality and collection, definition of system and time boundaries, multi-functionality and allocation.

LCA is a methodology that is very data dependent. The *quality* and *availability of data* influence the results significantly. Some of the steps of LCA can be reiterated to better tune the analysis to the systems under investigation. It is therefore suggested to start with easily accessible data and eventually to refine the data quality with reference to the results. In some cases it is unavoidable to introduce simplification and limitation of assumptions due to uncertainty of specific data. For instance, toxicological categories as well as some energy production impact categories are deeply affected by lack of data (Lee et al. 2007). There can be different type of data uncertainty (Schmidt et al. 2007), and it must be noted that the methodological uncertainties are sometimes larger than the data ones.

The *time aspect* is often critical in including or excluding some effects of the systems under analysis. LCA should consider environmental impacts on the longest possible timeframe, possibly an infinite one. Most of the studies, nevertheless, use shorter time periods bringing to contestable conclusions (for instance, in MSW treatments, landfills act in a limited period of time as carbon sinks and therefore become a more favourable solution than incineration).

The holistic approach of LCA, one of its main strengths, is also a cause of complexity during the actual execution of the analysis. Having to collect and analyse data from so many different elements can be cumbersome. This is the reason why most of the times some assumptions are taken and the *system boundaries* are modified in order to leave out some elements. In particular the upstream elements of the supply chain are usually not included in the analysis, due to the inherent difficulty in gathering complete information for elements outside the specific product system.

Results of LCA are often used for process optimisation. The applicability of these results depends greatly on the *model of the process* that has been adopted at the beginning of the study. This model is frequently simplified, to be able to take into consideration all possible inputs and outputs, and in most cases does not include *health and safety* elements. This is very reductive because not all kind of results from LCA can be applied directly in process improvements: choices that reduce the environmental impact might not always be applicable for human or industrial constraints, or in some cases can prove to be dangerous. It is therefore necessary to make sure to take into due account the human factor and to integrate work environment in the holistic approach of LCA.

## 5 From Environmental Assessment to Strategic Environmental Maps

The ecological footprint is a way to compare human demand with our planet capacity to regenerate it and it is measure of our burden on the ecosystem. Usually it represents the amount of biologically productive land and sea area needed to regenerate the resources consumed and to absorb the corresponding waste. Different footprints have been developed, to consider the impact of different resources. In a broader view the ecological footprint is related to the method of LCA, which is typically used for products and services, but also applicable for production plants and regions. One of LCA's advantages is that it better covers the whole range of impacts, and it may also provide an accounting of the upstream impacts.

Nevertheless, one of the most important limitations in the application of LCA as an input for strategic decision-making from an environmental perspective is the limited inclusion of cost and investment considerations. A new approach is required in order to integrate financial, environmental, resource and toxicological considerations into a single analysis. The core of the concept is to calculate some specific sustainability indicators, based on LCA. This will help one define the relevant contributions to support strategic decision-making. The cradle to grave approach will assure that all environmental and human consequences taken into account. These must be further balanced against financial and resource consumption considerations.

It is suggested therefore to evaluate all options against the following categories (Čuček et al. 2012):

- Carbon footprint;
- Water footprint;
- Energy footprint (Land, Renewables, Non-Renewables);
- Emission footprint (Emissions in Air, in Water, in Soil, Waste materials);
- Work environment footprint (Work-environment and Toxicological impacts).

Cost should also be considered as an additional category, possibly representing the crucial relation that it has with all other categories.

To represent these relations and to compare options from an environmental and, more generally, business perspective a new graphical representation needs to be introduced: the environmental performance strategy map (EPSM) De Benedetto and Klemeš (2008a, b). The objective of this representation is to build upon the strength of ecological footprint and life cycle analyses to provide a single indicator for each option. The practitioner can make use of this indicator to direct the decision-making process towards the best option from a sustainability and environmental perspective.

The first step in building the EPSM correctly is to calculate the impact of the option under analysis for all the above-mentioned footprints. The combination of these elements and the cost perspective will provide a single indicator to assign to each option. The comparison between different options, with different characteristics and ratio of advantages and disadvantages will be facilitated also by a graphical representation. The best option, from an environmental and financial perspective, will be selected based on this approach.

## 5.1 What Footprints?

Different methods have been developed in the last years to correlate environmental sustainability of specific activities with land and water areas required to supply this activity with resources and to absorb its waste (Hujbregts 1999), later further developed by Monfreda et al. (2004). This is usually referred to as Ecological Footprint.

Some initial objections to the original method on the way energy is accounted for (Ferng 2005), as well as difficulty in using the tool in the decision-making process (Ayres 2000), have been overcome by the development of specific indicators SPI (Krotscheck and Narodoslawsky 1996) and DAI (Eder and Narodoslawsky 1999).

In particular the sustainable process index (SPI) considers the area as a basic measure: the more area a process requires, the more its burden from an ecological point of view. The SPI method is based on the comparison of natural flows with the mass and energy flows generated by a technological process. The calculation of an SPI centres on the computation of the total area required ($A_{\text{tot}}$):

$$A_{\text{tot}} = A_R + A_E + A_I + A_S + A_P \tag{3}$$

where $A_R$ is the area required to produce the raw materials (given as the sum of the areas to provide renewable raw materials, fossil raw materials and non-renewable raw materials), $A_E$ is the area needed to produce process energy, $A_I$ is the area required for the process installations (equipment/plant), $A_S$ is the area required for support staff and $A_P$ is the area required for the accommodation of products and by-products (Krotscheck and Narodoslawsky 1996).

A model that proposes the combination of ecological foot printing with economic considerations is proposed in the ecological value-added system (Kratena 2004). This is based on an input–output system and upon the ecosystem pricing concept, introduced via energy values and the ecological footprint. The balance between carbon sinks and emissions defines the sustainability target for this model.

To provide a more comprehensive analysis of the interaction of the environmental burdens and financial costs, the EPSM is based on the combination of the following five footprints (De Benedetto and Klemeš 2009).

## 5.2 Carbon Footprint

With environmental issues high on the business and political agenda, different definitions of the individual contribution to carbon dioxide emissions have been proposed in the last years (Wiedmann and Lenzen 2007). Usually they are referred to as carbon footprint. In response to this public attention, different tools have been proposed to calculate the value of the carbon footprint, in relation to a product or process (Padgett et al. 2008) and introducing a new Total Site Process Integration methodology (Perry et al. 2008). Even though these tools are useful in increasing public awareness, they often lack transparency and might provide conflicting results.

For the purpose of building the EPSM this chapter refers to a land-based definition, where the carbon footprint estimates the land area required to sequester atmospheric fossil $CO_2$ emissions through afforestation (Monfreda et al. 2004). This area is calculated as (Hujbregts et al. 2008):

$$CF = M_{CO_2} \times \frac{1 - F_{CO_2}}{S_{CO_2}} \times EF \tag{4}$$

There *CF* is the footprint of indirect land occupation by fossil fuel and cement-related $CO_2$ emissions ($m^2$). $M_{CO_2}$ is the product-specific emission of $CO_2$ (kg $CO_2$), $F_{CO_2}$ is the fraction of $CO_2$ absorbed by the oceans and $S_{CO_2}$ is the sequestration rate of $CO_2$ by biomass (kg $CO_2$ $m^{-2}$ $y^{-1}$). *EF* is the equivalence factor for forests.

This footprint unit of measure is expressed in $m^2$.

## 5.3 Water Footprint

The concept of water footprint is a relatively new one; it is related to the concept of virtual water (Hoekstra and Hung 2002; Hoekstra 2007). Virtual water is the amount of water required to produce a service or a product. In analogy with ecological and carbon footprints, this indicator is designed to summarise the contribution of a product or activity to the deterioration of the environment. The focus is on the consumption of the limited resource, water.

While the ecological footprint is designed to calculate the area needed to sustain specific human activities, the water footprint looks at the volume of water. With two different methods (top-down or bottom-up) the water footprint measures the amount of water related to human consumption and takes into consideration blue and green water, as well as the production of polluted grey water (Hoekstra and Chapagain 2007).

For instance, in the case of crops, we can define the green virtual water content as a ratio between the effective rainfall and the crop yield. Analogously, the blue virtual water content is the ratio between the effective amount of irrigated water and the crop yield. The total virtual water content is given by the sum of these two elements (Klemeš et al. 2010a, b).

The authors of this chapter use the EPSM to represent an overall indication of the comparative sustainability of different options from a strategic decision-making point of view (De Benedetto and Klemeš 2010). The water footprint of an activity consists therefore of two components:

- The direct water used (for producing/manufacturing or for supporting activities) and
- The indirect water use (that propagates throughout the supply chain).
- This footprint unit of measure is $1/m^2$.

## 5.4 Energy Footprint

The energy supply footprint (Stoeglehner 2003) takes into account different energy supplies as related to different demand categories, such as heating and hot water production, process energy, electricity and traffic. The footprint is calculated by multiplying the final energy use of different energy carriers with their land need indices and adding these results to the footprint of the whole energy supply. This footprint unit of measure is $m^2$. It is important to notice that the Energy footprint, as defined in Stoeglehner (2003), includes some $CO_2$ contributions from burning processes. However, it does not include all other $CO_2$ contributions and that is why it is important to make use of the Carbon footprint as defined by Perry et al. (2008).

## 5.5 Emissions Footprint

For identifying the real environmental burden we define as Emission's footprint the quantity of emissions of the process under investigation in water, soil and air converted to area requirements. The conversion of emissions is calculated according to the principle that anthropogenic mass flows must not alter the quality of local compartments (Sandholzer and Narodoslawsky 2007). Maximum flows are defined based on the natural existing quality of the compartment and their replenishment rate per unit area. For emissions to soil, the replenishment rate is given by the decomposition of biomass to humus (measured by the production of compost by biomass). For ground water this is the seepage rate (given by local precipitations). A growing attention has been paid to the emissions footprint of electricity grids. Weber et al. (2010) stated that the generation and distribution of electricity comprises nearly 40 % of US $CO_2$ emissions, as well as large shares of $SO_2$, $NO_x$, small particulates and other toxins.

Emissions to the compartment air are treated slightly different, as there is no natural replenishment rate for this compartment. Here the natural exchange of substances between forests and air per unit area, which is known for most airborne substances, is taken as a base of comparison between natural and anthropogenic flows (Hillman and Ramaswami 2010). Different emissions to air are not weighted, as only the largest dissipation areas are to be considered. Lower area consumptions emissions may be dissipated without violating the principle that anthropogenic mass flows must not alter the quality of local compartments.

This footprint unit of measure is $m^2$.

### 5.6 Work Environment Footprint

For the purpose of building the EPSM, the work environment footprint is the work environment LCA as proposed by Schmidt et al. (2004). This method, based on the collection of goods statistics, is designed to calculate the number of reported lost days of work per produced weight unit on the sector level. The following impact categories are included in the assessment (Schmidt et al. 2004):

- Fatal accidents;
- Total number of accidents;
- CNS-function disorder;
- Hearing damages;
- Cancer;
- Musculoskeletal disorders;
- Airway diseases (allergic and non-allergic);
- Skin diseases;
- Psycho-social diseases.

This footprint unit of measure is the number lost days of work/person.

## 6 Safety, Cost and Environmental Issues

Optimisation of processes and plant layouts is an important and debated issue. This is particularly critical in the process industry, where safety is paramount. Different techniques have been developed to take into consideration safety and cost issues. These techniques are usually based on multi-objective optimisation (Dongwoon and Jiyong 2006) or mixed integer linear programming models (Guirardello and Swaney 2005). The efficiency of this approach is further confirmed by a three-year study on Plant Optimisation (Pierucci et al. 2006). The conclusions drawn by the paper indicate that Plant Optimisation can be considered the main advisory tool to reduce costs and increase Plant profit while operating the plant in safe conditions. A very important issue is to have powerful and reliable optimisation methods. Varbanov and Friedler (2008) have proven P-Graphs optimisation methods on carbon minimisation of combined energy cycles involving fuel cells.

Generally these approaches take into consideration mainly safety and cost issues. The strategic decision-making process could be further strengthened by a life cycle approach to account for the main environmental burdens. However there is still a tendency for companies to treat safety, health, environment (SHE) and cost as separate issues (Crawley and Ashton 2002). This adds complexity to environmental management systems (EMS), and makes the companies lose out on possible synergies between environmental and safety issues. From an economical point of view, this practice is not optimal; since design could be taken too far before it is found too dangerous from a work environment perspective.

As noted previously, one of the main limitations of the LCA methodology, as described by ISO 14040, is the lack of inclusion of work environment issues. This does not mean that safety and health analysis of processes is not carried out by the company. Most frequently these issues are addressed ex-post, to analyse the suggestions indicated by the application of an environmental oriented LCA.

Historically the first efforts in including the human factor in LCA have been made in Scandinavia. The Nordic countries have therefore produced different approaches for work environment-LCA (WE-LCA).

Antonsson and Carlsson (1995) proposed a method based on five quantitative and two qualitative impact categories. The WE-LCA is carried out in a similar way as for the external environment, with the four steps of goal and scope definition, inventory analysis, impact assessment and interpretation. The method requires the use of an inventory of effects, instead of emissions, followed by the impact assessment.

The quantitative impact categories are:

- Deaths due to work-related accidents
- Workdays lost due to work-related accidents
- Workdays lost due to illness
- Allergies
- Hearing loss.

The qualitative impact categories are:

- Carcinogenic impact
- Impact on reproduction.

Data for the quantitative categories can be collected from single companies or trade statistics organisations. It must be noted that the final result will depend greatly on the quality and precision of this set of data. Moreover, the level of detail must be balanced against the goals of the analysis. Another source of uncertainty in the method is the fact that not all impact categories can be estimated quantitatively.

Work environment issues have been left out not only from LCA methodology, but also from environmental technology databases and reports of Best Available Technologies (BAT). In a project conducted for the European Commission on a selection of cases of the International Cleaner Production Information Clearinghouse (ICPIC) system (Ashford 1997), evidenced the following:

- Lack of information regarding the interactions of human beings with the production processes, materials or products.
- No information is given regarding the physical or economic context for the processes.
- Limited information is given regarding the physical form of the substances at certain stages in the process so that, should a worker be exposed, the physiologic route of entry cannot be adequately anticipated.

The role of personal risk perception and involvement in occupation health and safety issues in EMS has been interestingly analysed by Honkasalo (2000). In particular, in industrial environments risks seem to be perceived differently depending on the level of involvement of the perceiver. Risks caused by others (for instance global environmental issues) are not tolerated easily, because the perceiver feels that they cannot be affected.

Risks taken voluntarily (for instance safety risks) are more accepted. This is probably one of the main reasons for the overestimation of environmental issues compared with the health and safety ones. Employee participation is another difference between EMS and work environment related approaches. EMS does not usually require employee participation. In safety and health issues it is absolutely necessary to make sure that workers are involved and can actually influence the process.

The first step is the inventory procedure, where material flows are calculated for the product (with reference to a set of data obtained from the governmental statistical office). The material flows are then aggregated on relevant processes in the provided database and for each process the weight is multiplied with the impacts per weight unit for each of the affected categories. It has to be noted how the method introduces a great source if uncertainty. One of the main challenges is to match the actual activities with data sets in the database (many thousand product groups must be related to a small number of sectors, less than 300).

Aim of the normalisation activity in the impact assessment step is to relate the total number of accidents and work-related diseases with the Danish population (the same could be applied to other countries, if similar databases are available). A list of impact categories and normalisation factors are illustrated in Table 1.

Interpretation can be done following the inventory or after the normalisation. In the first case it is possible to establish an overview of how much each of the activities contributes to the single effect categories. Following the normalisation, it is possible to depict which are the most important impact categories in the life cycle of a product. The method described is without doubt the most comprehensive approach to determine the impact of work environment issues with an LCA approach. The established

**Table 1** Impact categories and normalisation factors (Schmidt et al. 2004)

| Basic for normalisation (effect category) | Person equivalents, PE (Danish population) | Worker equivalents (Danish work force) |
|---|---|---|
| Fatal accidents | $1.54 \times 10^{-5}$ | $3.06 \times 10^{-5}$ |
| Accidents | $9.69 \times 10^{-3}$ | $1.92 \times 10^{-2}$ |
| Cancer | $3.54 \times 10^{-5}$ | $7.02 \times 10^{-5}$ |
| Psycho-social damages | $1.40 \times 10^{-4}$ | $2.77 \times 10^{-4}$ |
| CNS-function disorders | $6.37 \times 10^{-5}$ | $1.26 \times 10^{-4}$ |
| Hearing damages | $4.56 \times 10^{-4}$ | $9.06 \times 10^{-4}$ |
| Airway diseases, non-allergic | $1.00 \times 10^{-4}$ | $1.99 \times 10^{-4}$ |
| Airway diseases, allergic | $7.93 \times 10^{-5}$ | $1.57 \times 10^{-4}$ |
| Skin diseases | $3.12 \times 10^{-4}$ | $6.19 \times 10^{-4}$ |
| Musculoskeletal disorders | $1.44 \times 10^{-3}$ | $2.85 \times 10^{-3}$ |

database associated to it covers about 80 economic sectors and provides an important tool for this kind of analysis in Denmark. It would be most useful if other countries collected the same kind of information, so that similar analyses could be done with increased reliability in other countries as well.

## 7 Conclusions

The history and the main concepts at the basis of the LCA methodology have been reviewed. The main limitations of the method (namely methodological approach, especially data quality and collection, definition of system and time boundaries, multi-functionality and allocation, occupational health) have also been discussed. Potential of the environmental impact assessment using combination of various footprints has been analysed. Examples of inclusion of work environment issues in Life Cycle approaches as well as models that balance health, safety and environmental impact have been presented. This has been further developed to include validation of the proposed model and possible applications, for an overview, see e.g. Čuček et al. (2010) and the implementation to the biomass, see e.g. Lam et al. (2010) and further devolved by Lam et al. (2011). An extended graphical targeting technique for direct reuse/recycle in concentration and property based resource conservation networks has been presented by Saw et al. (2011).

Particular attention has been given to the efforts of the Nordic countries, with reference to identifying a technique that allows a quantitative approach to the inclusion of work environment in the LCA methodology. As a potential solution a process simulation approach has been proposed. More detailed information about simulation and optimisation approach has been published recently (Klemeš et al. 2010a, b).

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# Part III
# Sustainable Energy

# Exploring How Technology Growth Limits Impact Optimal Carbon dioxide Mitigation Pathways

**Dan Loughlin**

**Abstract** Energy system optimization models prescribe the optimal mix of technologies and fuels for meeting energy demands over a time horizon, subject to energy supplies, demands, and other constraints. There may be realistic reasons why solely relying on the least cost technological pathway is not practical, however. For example, difficult-to-quantify factors may complicate the rapid expansion of specific technologies. Modelers may choose to limit technology penetration with growth bounds. Whether growth bounds have been used and how these bounds impact the model outputs are not always transparent, however. In this work, alternative growth bounds on wind and solar power, nuclear power, and carbon dioxide ($CO_2$) sequestration are examined for a hypothetical greenhouse gas (GHG) mitigation scenario. A nested parametric sensitivity analysis is used to examine the response to individual and combinations of bounds. From a modeling perspective, the results illustrate that growth bounds can have a large impact on shaping the least cost results. From a planning perspective, the results suggest that natural gas technologies may play a critical role in meeting GHG mitigation targets if optimistic goals for the expansion of nuclear, renewables, or sequestration are not met.

**Keywords** Energy system modeling · Greenhouse gas mitigation · Least cost optimization · Nested parametric sensitivity analysis · Technology growth assumptions

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## 1 Introduction

The MARKet ALlocation (MARKAL) model is an energy system optimization model that was originally developed in the 1970s in response to that decade's oil crises (Fishbone and Abilock 1981; Loulou and Lavigne 1995). While MARKAL has continued to evolve for more than 30 years, its overall objective remains the same: to select the least cost mix of fuels and energy technologies over a modeling time horizon, while simultaneously meeting energy demands and various energy and emissions constraints. As an optimization model, MARKAL's strength lies in its ability to support long-term energy and environmental planning by *prescribing* a cost-effective course of action. Through sensitivity and scenario analysis, MARKAL can also be used to explore how the least cost pathway changes in response to various stimuli, such as changes in fuel costs, energy demands, and the introduction of new policy measures. For optimized or user-specified scenarios, MARKAL can be used to track associated metrics related to sustainability, including emissions of air pollutants, energy-related demands for water, and the use and depletion of energy resources. Constraints can be placed on any of these metrics, allowing the resulting impacts on optimal energy system choices to be examined.

A Reference Energy System (RES) lies at the core of MARKAL. The RES represents energy sources, sinks, and flows that comprise an energy system. Coverage of the energy system can vary by application, but typically ranges from the import or extraction of energy resources, through the conversion of these resources into fuels and electricity, to the use of these energy carriers to meet end-use energy demands. The RES is sufficiently flexible that MARKAL can be applied at the global, national, regional, or local levels.

MARKAL's optimization process considers the capital and operations and maintenance costs of competing technologies, supply curves for fuels, the competition for fuel among uses and sectors, and other factors such as pollutant emission limits. Fuel prices are calculated endogenously as a function of the quantity of each fuel that is used.

To apply MARKAL to a particular energy system, a database must be developed that characterizes the system's current and projected energy supplies, demands, and technologies. The U.S. EPA's Office of Research and Development (ORD) has developed two MARKAL energy system databases (U.S. EPA 2008). These databases represent the U.S. energy system at the national and nine census division resolutions, over a modeling horizon that extends from 2000 through 2050. The national and nine-region databases are referred to below as EPANM and EPA9r, respectively. Both databases cover the power generation, residential, commercial, transportation, and industrial sectors. Multi-sector coverage allows simultaneous consideration of both supply- and demand-side measures in meeting emissions or other performance goals.

The EPANM database has the advantage of a runtime of only approximately 1 min on a desktop computer. This compares to a runtime of 20–45 min for EPA9r.

Regionalization, however, allows consideration of inter-region fuel transportation costs, as well as regional differences in energy demands, resource supplies, technology performance, and policies.

The primary source of data for the databases is the Department of Energy's Annual Energy Outlook (AEO) and the economic and technology assumptions it incorporates (U.S. DOE 2008b). For the research presented here, the 2008 version of the AEO is used, although an effort to update input assumptions to AEO 2010 has since been completed. Data from the AEO is supplemented with technology and emissions data from other sources, such as the technical literature and reports produced by the EPA's Office of Transportation and Air Quality and Office of Air Quality Planning and Standards. The databases are periodically updated and are calibrated to produce fuel use estimates in line with the AEO.

One feature that differentiates EPA's MARKAL databases from many other energy system modeling efforts is the detail with which air pollutants are represented. The energy system is a major source of many air pollutants, being responsible for nearly 95 % of anthropogenic nitrogen oxides ($NO_x$) emission, 92 % of anthropogenic sulfur dioxide ($SO_2$) emissions, and 10 % of anthropogenic coarse particulate matter ($PM_{10}$) emissions (U.S. EPA 2009a). The MARKAL databases currently include system-wide coverage of emission factors for $NO_x$, $SO_2$, and $PM_{10}$. Factors for fine particulate matter ($PM_{2.5}$), mercury, methane, and black and organic carbon are being added.

ORD is applying these databases in a number of analyses. Within ORD's Global Change Research Program, MARKAL is being used to characterize technologies, fuel use, and the resulting emissions for a range of scenarios of future states of the world. These scenarios differ in their assumptions about U.S. population growth and migration, economic growth and transformation, land use, technologies, and climate change. ORD also is using MARKAL to examine the potential impacts of climate change mitigation policies on criteria pollutants, the impacts of criteria pollutant policies on greenhouse gases, and whether coordinated air quality and climate efforts can yield more efficient solutions by exploiting synergies.

## 2 Background

There are several approaches for modeling GHG mitigation using MARKAL. If the objective is to examine a particular policy proposal, many of the energy-related provisions of the proposal can be represented explicitly within MARKAL. These include renewable portfolio standards, carbon dioxide ($CO_2$) intensity targets for electricity production, energy efficiency requirements for end-use demands, and sectoral- or system-wide caps on emissions. Alternatively, MARKAL can be applied more generally, identifying a least cost technology pathway for achieving a $CO_2$ reduction target, represented either as a $CO_2$ emissions trajectory or as a cumulative limit on emissions. The latter approach provides MARKAL with more flexibility in the timing of reductions and results in smoother technology and fuel transitions.

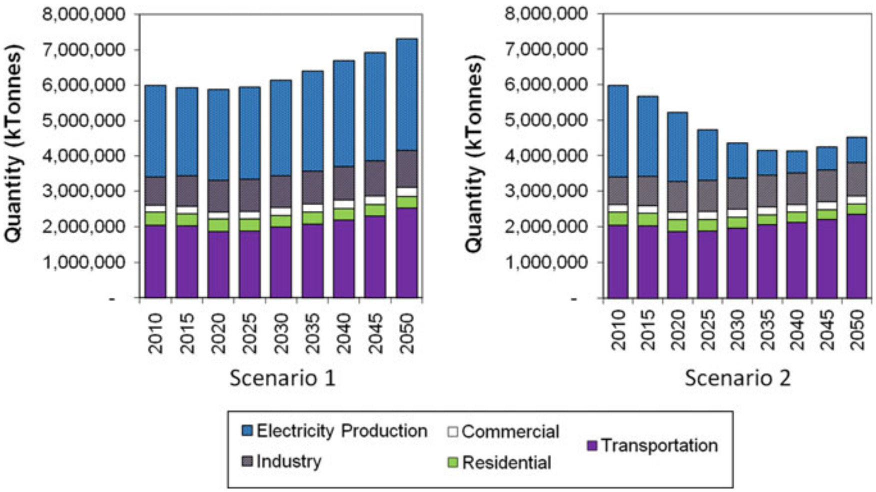

**Fig. 1** Comparison of sectoral and system-wide $CO_2$ emissions for two scenarios

To illustrate the application of MARKAL, two scenarios are modeled using the EPANM database. Scenario 1 represents a least cost solution through 2050, assuming that no national, regional, or state GHG policies are in place. Scenario 2 involves similar assumptions, although a cumulative $CO_2$ constraint has been applied. The constraint yields approximately 30 % cumulative reduction in $CO_2$ emissions between 2010 and 2050 when compared to Scenario 1.[1] This reduction target can be met by a combination of supply-side actions (e.g., increased production of lower- or zero-carbon energy) and demand-side actions (e.g., adoption of higher efficiency technologies). While MARKAL has the ability to incorporate elasticities in energy service demands (e.g., reduced driving when gasoline prices are high), this feature increases computational requirements and complicates the interpretation of the results. Thus, it is not used in this analysis.

Figure 1 shows the sectoral $CO_2$ emissions associated with each scenario. For Scenario 2, mitigation efforts occurred to a much greater extent in the electric sector than in other sectors.

Underlying these aggregated results are the model-selected technology and fuel penetrations within each sector. Figure 2, for example, shows electricity production by technology for each scenario. In Scenario 1, a relatively inexpensive coal supply leads to the expansion of coal-fired electricity production. Nuclear power also expands over the time horizon. Hydropower capacity is constant, while natural gas use increases. Under a GHG policy in Scenario 2, MARKAL selects a very different least cost path for producing electricity. Conventional coal

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[1] This target was not selected to represent any particular policy. Considering the potential role of domestic and international offsets, however, the magnitude of cumulative energy system $CO_2$ reductions is similar to that of several policy options that have been discussed by Congress.

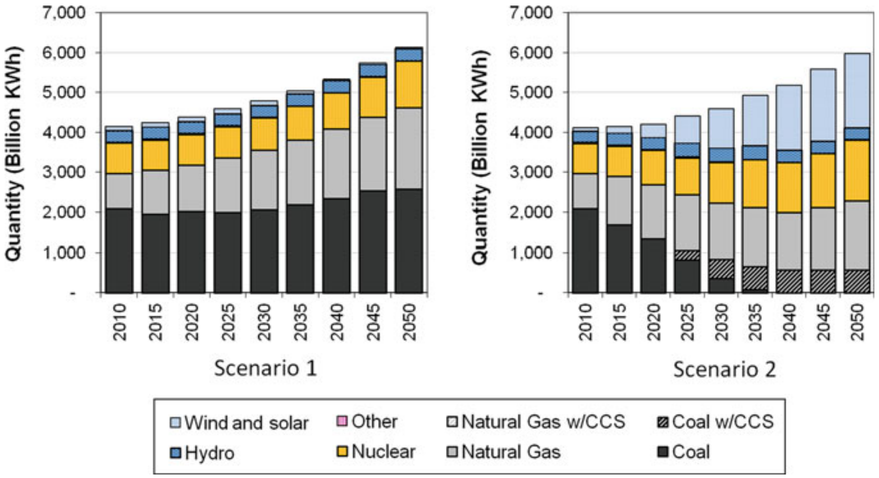

**Fig. 2** Comparison of electricity production by technology for two scenarios

technologies are phased out, being replaced by natural gas, wind, biomass, and carbon capture and storage (CCS) on coal.

Accompanying the technology changes are changes in emissions. System-wide $CO_2$, $NO_x$, and $SO_2$, relative to 2010, are shown in Fig. 3. In both scenarios, criteria pollutant emissions decrease from their initial values. The primary drivers for these decreases are pollutant regulations, such as the Clean Air Interstate Rule (U.S. EPA 2010c), the emission standards that govern light and heavy duty vehicles and fuels (U.S. EPA 2010b), and New Source Performance Standards (NSPS) (U.S. EPA 2010a).

Emissions for each pollutant species are reduced further under the GHG policy scenario. This response is largely driven by changes within the electric sector, where low- and zero-$CO_2$ technologies also tend to have low pollutant emissions. Changes in light and heavy duty vehicle emissions are very limited since most vehicles are assumed to emit at the applicable emissions standards, regardless of engine technology. Electric and plug-in hybrid vehicles are an exception; their fuel combustion-related emissions are reduced by the fraction of their operation under electric power. These vehicles did not achieve market penetration in either scenario.

## 3 Objectives

The two scenarios above represent only two of a large number of potential realizations of the future U.S. energy system. As MARKAL optimizes, a variety of assumptions influence the results. These assumptions include, for example, the shape of the projected resource supply curves, the costs and efficiencies of current and future technologies, many of which are not yet commercially available, and

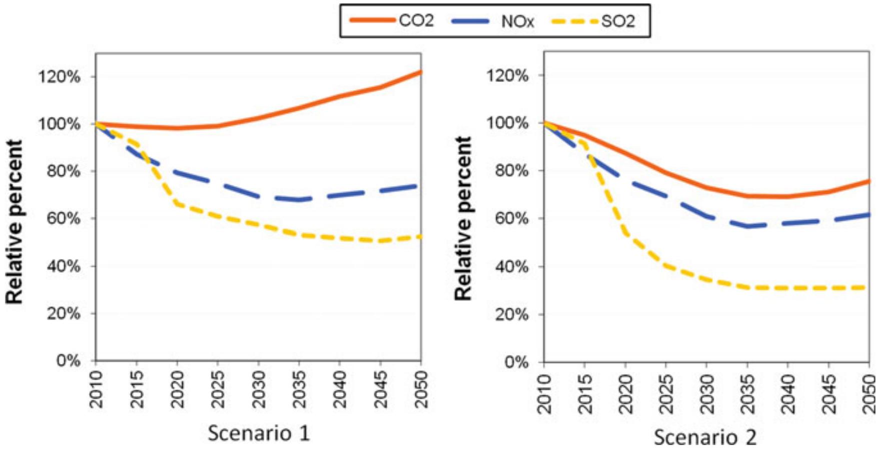

**Fig. 3** Changes in system-wide $CO_2$ and pollutant emissions relative to emissions in 2000

the maximum rates at which certain technologies are allowed to grow. Exploring the role and impact of growth limits is the goal of this paper.

Without any limits on technology growth, MARKAL may opt to increase the capacity of a technology at an impractical rate. For example, if wind turbines were the least cost electricity production option, MARKAL potentially would meet *all* new electricity demands solely by increasing wind capacity. In reality, however, this expansion would be limited by unmodeled factors. These include the availability of capital to fund capacity expansion, the number of turbines that could be manufactured, the rate at which installation expertise could be expanded, the availability and access rights of suitable land, the construction of new transmission lines to reach remote wind sites, and the simultaneous growth of enabling technologies, such as stationary storage, that would be necessary to integrate large-scale intermittent resources into the electric grid.

A number of approaches are used by modelers to capture the dynamics of technology penetration. For example, learning curves are used to represent both the high initial cost of new technologies and how this cost decreases with experience (Silverberg 1991). Learning curves can be represented endogenously, allowing energy models with perfect foresight to build capacity in technologies before it is cost-effective if the net inter-temporal result is more cost-effective (Barreto 2001).

Technology adoption has also been generalized and modeled as a diffusion process (Rogers 1962). Diffusion models often result in S-shaped penetration curves. These models account for the differentiated preferences of consumers, who are often grouped into classes such as technology innovators, early adopters, early and late majority, and laggards. Diffusion models have been used to examine energy technologies by a number of researchers (Häfele 1981; Lund 2006).

An alternative to these generalized approaches is the explicit assessment of the drivers and barriers for a particular technology. For example, the U.S. Department of Energy (DOE) "20 % wind energy by 2030" report provides an optimistic growth trajectory for wind that assumes advances in turbine technologies, transmission, and energy storage (U.S. DOE 2008a). The resulting trajectory can then be added to a model like MARKAL as a maximum growth limit from one time period to another or as an annual upper bound on penetration. The latter approach is used here.

Even with studies such as the DOE "20 % wind by 2030" available, there still is considerable uncertainty regarding achievable growth rates. An advantage of MARKAL's efficient operation and fast runtime is that it can be used in an iterative manner to explore the implications of a large number of alternative assumptions. In the next sections of this paper, alternative growth limits for two classes of electricity production technologies and for $CO_2$ sequestration are modeled. The resulting least cost technology and fuel use selections within the electric sector are tracked, as are the impacts on criteria pollutant emissions. Parametric techniques are employed that allow examination of both individual and combined changes in growth limit assumptions. While this paper focuses on growth rates, the approach can also be used to examine other input assumptions, including resource supplies and technology costs and efficiencies.

# 4 Approach

## 4.1 Overview

In a typical parametric sensitivity analysis, an initial step is to specify baseline values for model inputs of interest. Then, the value of each of these inputs is perturbed individually, holding all other inputs at their baseline values. The responses of the model's outputs are recorded, allowing sensitivities to be quantified and compared.

In many instances, it may also be useful to explore the responses to simultaneous changes in multiple inputs. In a nested parametric analysis, discrete values are identified along the range of each input of interest. Then, *combinations* of these values are enumerated and evaluated with the model (Saltelli et al. 2000). The result is a matrix of solutions. Any solution within the matrix can be selected as a baseline from which parametric changes, individually or in combination, can be evaluated. The set of solutions can also be examined to identify trends and conditions that lead to outcomes of interest.

The application of both parametric and nested parametric analyses is described below. Visualization, correlation analysis, and pivot tables were used to deduce important relationships.

## 4.2 Characterizing Input Levels

Inputs that were examined include growth limits for: (i) wind and solar power generation, (ii) nuclear power generation, and (iii) $CO_2$ sequestration. These inputs were selected because each is highly uncertain, yet has the potential to influence the least cost $CO_2$ mitigation pathway. Four discrete levels of both nuclear power and wind and solar power growth limits were identified, as well as 10 different growth limits for $CO_2$ sequestration.

Wind and solar technologies are lumped together because of their similarities: both are zero-carbon renewables with relatively low current production capacity. Also, because of intermittency, both would benefit from improvements in energy storage and long distance transmission. To identify an optimistic growth limit for wind and solar generation, published studies were examined in which high penetration scenarios had been developed. The Electric Power Research Institute (EPRI) "Power to reduce $CO_2$ emissions" is one such study (EPRI 2009). Our optimistic growth limit for wind and solar power was derived from EPRI's Limited Portfolio scenario, in which the growth of nuclear and CCS was highly limited, but wind and solar were allowed to grow rapidly. Through 2030, EPRI's projection tracks well with DOE's "20 % wind energy by 2030" study.

For nuclear power, an optimistic limit was deduced from the EPA's analyses of the American Clean Energy and Security Act of 2009, also known as the Waxman-Markey bill (U.S. Congress 2009; U.S. EPA 2009b, 2010e). The Waxman-Markey analysis was conducted by EPA's Office of Atmospheric Programs (OAP) using an array of economic and detailed technology models, including the Inter-temporal General Equilibrium Model (IGEM) (Goettle et al. 2007), the Applied Dynamic Analysis of the Global Economy (ADAGE) model (Ross 2008), and the Integrated Planning Model (IPM) (U.S. EPA 2006). OAP developed a set of scenarios representing alternative assumptions about factors such as the prospects of nuclear power and CCS and the availability and cost of international GHG offsets. Our optimistic nuclear growth limit represents the maximum nuclear power output for each 5-year time period over the set of OAP's scenarios.

The EPA's Waxman-Markey analysis was also used to develop an optimistic growth limit on $CO_2$ sequestration. Again, the set of Waxman-Markey scenarios was examined, and the maximum $CO_2$ sequestration for each time period across the scenarios was selected to be the optimistic $CO_2$ sequestration growth limit.

Next, three alternative growth limits were developed for each input, including: 50 % more growth than the optimistic bound relative to the 2010 levels, 50 % less growth than the optimistic bound relative to 2010 levels, and, no growth from 2010 levels. The 50 % growth increase is intended to represent a breakthrough that enables higher capacity and quicker deployment. In contrast, the 50 % less than optimistic growth rate represents conditions in which the assumptions that enable the optimistic bound are not fully realized. These growth trajectories are referred to below as "breakthrough" and "pessimistic", respectively.

For the $CO_2$ sequestration growth limit, additional alternatives were generated in which carbon capture and sequestration (CCS) technology availability was delayed from 2020 to 2025 and to 2030. Including the option with no CCS, 10 sequestration scenarios were examined.

The alternative growth bounds for each of the three growth limit assumptions are shown in Figs. 4, 5 and 6.

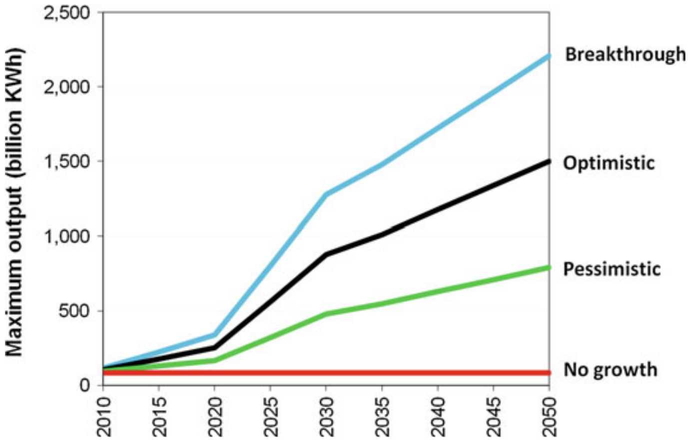

**Fig. 4** Alternative upper bounds for wind and solar generation used in the parametric analysis

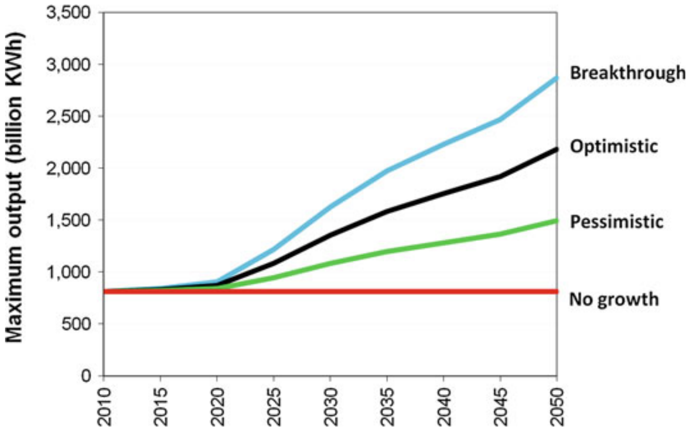

**Fig. 5** Alternative upper bounds on nuclear power generation used in the parametric analysis

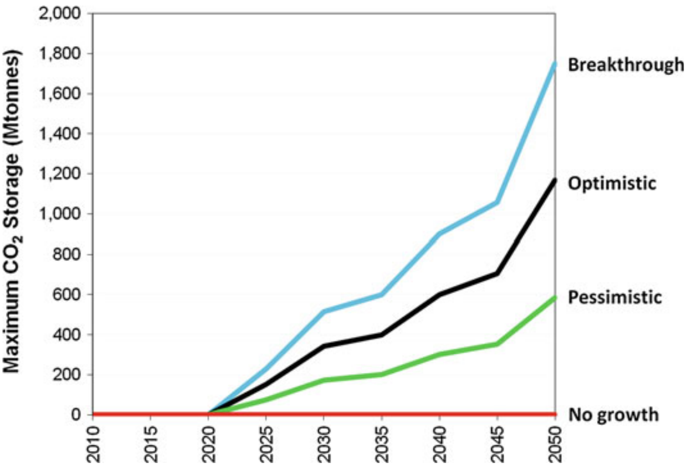

**Fig. 6** Alternative upper bounds on $CO_2$ sequestration growth used in the parametric analysis

## 4.3 Modeling and Analysis

There are 160 combinations of the growth limits characterized above. Each combination was modeled with MARKAL using the EPANM database, holding all other inputs to the model held constant. Among the model outputs recorded for each run were electricity generation by technology and fuel, marginal prices for electricity and natural gas, marginal $CO_2$ abatement price, and electric sector $NO_x$ and $SO_2$ emissions.[2]

As an initial step in analyzing the results, sensitivities around a baseline run were examined. The baseline run was defined as having optimistic growth bounds on nuclear, solar, and wind, and sequestration, with sequestration availability starting in 2025. Thus, the baseline is referred to as the "optimistic baseline."

The breakthrough sequestration case involves CCS introduction in 2020 and allows a faster growth rate. The pessimistic case, the "2030-Pessimistic" trajectory, involves both delayed introduction and slower growth.

Figure 7 illustrates how the electricity production mix responds to individual changes in each of the growth limit assumptions. These results are referred to as "individual sensitivities" later in the chapter.

A critical observation from these results is that MARKAL was successfully able to identify a least cost solution for each sensitivity model run. This means that there was sufficient slack in the set of growth bounds to absorb pessimistic or no-growth assumptions in any one of three inputs.

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[2] The marginal price is the cost the model sees for one additional unit of a commodity. This is different than an average cost for the commodity, which effectively would be the average of the marginal prices of each unit X.

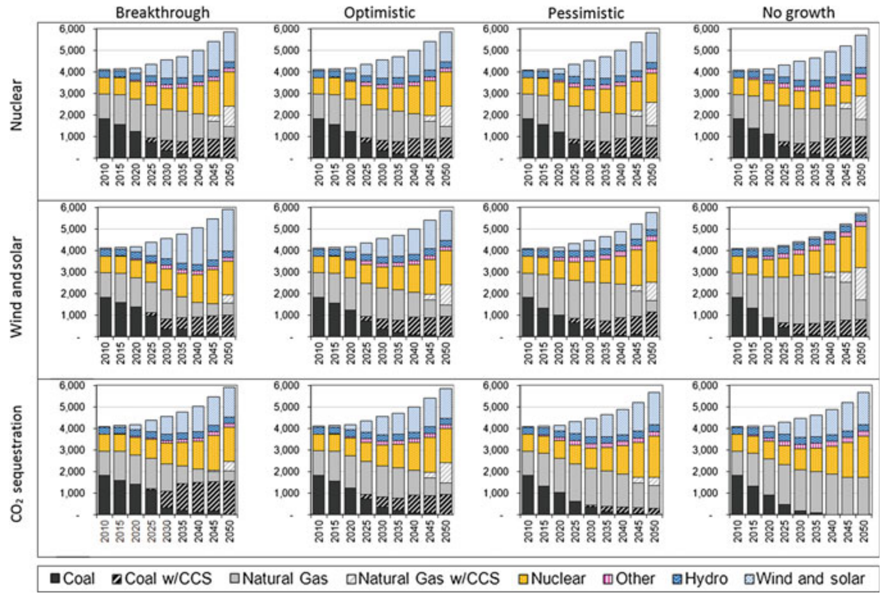


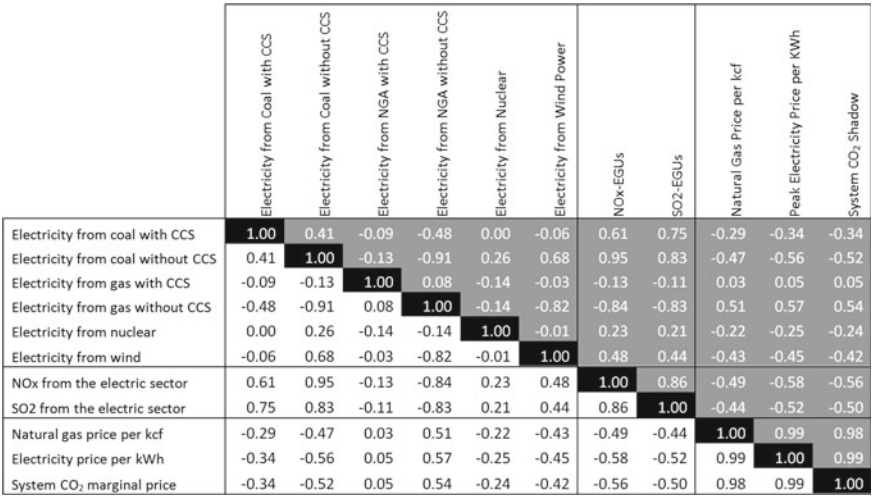
**Fig. 7** Electricity production (billion kWh) by technology class for each parametric run

The high relative cost of nuclear meant that the allowable nuclear capacity was not completely used in either the optimistic or breakthrough nuclear cases. Natural gas appears to be playing a key role in mitigation. Natural gas use grows in most scenarios between 2010 and 2030, indicating that it is providing a low-$CO_2$ bridge before renewables, nuclear, and sequestration are allowed to grow. In runs with pessimistic or no-growth assumptions about one or more of the three bounds, natural gas use grows from the optimistic baseline to fill much of the gap.

While CCS is not required to meet the mitigation target, as evidenced in the sequestration no-growth scenario, it plays a major role in all of the other parametric sensitivity runs. Further, although CCS is typically thought of as a technology that is applied to coal, the model elects to install CCS on natural gas combined cycle facilities after 2040.

The full set of nested parametric results potentially provides additional insights, but the amount of data can pose analytical challenges. Examining correlation coefficients among model outputs is a simple but powerful analytical approach. Figure 8 shows correlation coefficients between selected model outputs for the year 2030.

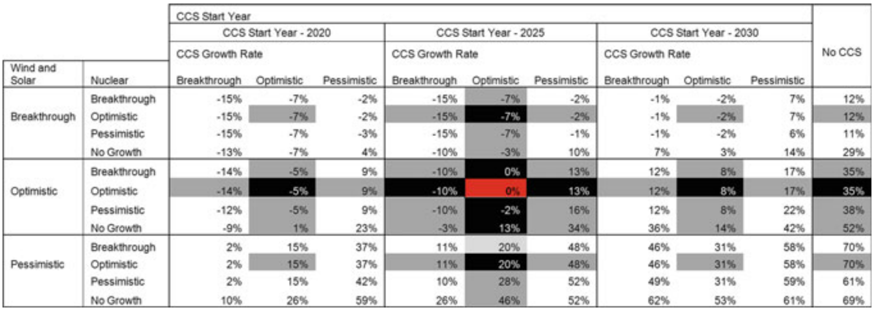
The most striking relationships are the near-perfect correlations in 2030 between natural gas price and electricity price (0.99) and between natural gas price and the marginal $CO_2$ price (0.98). Correlation coefficients for 2050 were developed and demonstrated this high degree of correlation. This result illustrates the importance of natural gas, both on the cost and feasibility of meeting GHG mitigation targets under technological uncertainty.



| | Electricity from Coal with CCS | Electricity from Coal without CCS | Electricity from NGA with CCS | Electricity from NGA without CCS | Electricity from Nuclear | Electricity from Wind Power | NOx-EGUs | SO2-EGUs | Natural Gas Price per kcf | Peak Electricity Price per KWh | System $CO_2$ Shadow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Electricity from coal with CCS | 1.00 | 0.41 | -0.09 | -0.48 | 0.00 | -0.06 | 0.61 | 0.75 | -0.29 | -0.34 | -0.34 |
| Electricity from coal without CCS | 0.41 | 1.00 | -0.13 | -0.91 | 0.26 | 0.68 | 0.95 | 0.83 | -0.47 | -0.56 | -0.52 |
| Electricity from gas with CCS | -0.09 | -0.13 | 1.00 | 0.08 | -0.14 | -0.03 | -0.13 | -0.11 | 0.03 | 0.05 | 0.05 |
| Electricity from gas without CCS | -0.48 | -0.91 | 0.08 | 1.00 | -0.14 | -0.82 | -0.84 | -0.83 | 0.51 | 0.57 | 0.54 |
| Electricity from nuclear | 0.00 | 0.26 | -0.14 | -0.14 | 1.00 | -0.01 | 0.23 | 0.21 | -0.22 | -0.25 | -0.24 |
| Electricity from wind | -0.06 | 0.68 | -0.03 | -0.82 | -0.01 | 1.00 | 0.48 | 0.44 | -0.43 | -0.45 | -0.42 |
| NOx from the electric sector | 0.61 | 0.95 | -0.13 | -0.84 | 0.23 | 0.48 | 1.00 | 0.86 | -0.49 | -0.58 | -0.56 |
| SO2 from the electric sector | 0.75 | 0.83 | -0.11 | -0.83 | 0.21 | 0.44 | 0.86 | 1.00 | -0.44 | -0.52 | -0.50 |
| Natural gas price per kcf | -0.29 | -0.47 | 0.03 | 0.51 | -0.22 | -0.43 | -0.49 | -0.44 | 1.00 | 0.99 | 0.98 |
| Electricity price per kWh | -0.34 | -0.56 | 0.05 | 0.57 | -0.25 | -0.45 | -0.58 | -0.52 | 0.99 | 1.00 | 0.99 |
| System $CO_2$ marginal price | -0.34 | -0.52 | 0.05 | 0.54 | -0.24 | -0.42 | -0.56 | -0.50 | 0.98 | 0.99 | 1.00 |

**Fig. 8** A matrix of correlation coefficients for select model outputs across the nested parametric sensitivity runs. Values for 2030 are shown. The *white*- and *grey-shaded* areas are mirror images

The response of natural gas use to the various growth limits was examined in more detail using a pivot table. Figure 9 shows the percent change in electricity produced from natural gas in 2030 for each combination of growth limits. Scenarios with no growth in wind and solar are omitted to simplify the table and because current growth trends in these technologies suggest that a no-growth assumption is unrealistic. The cells in Fig. 9 that correspond to the individual sensitivities shown in Fig. 7 are shaded black. The red cell represents the optimistic baseline scenario. Cells that represent changes to two growth limits are shaded gray. Unshaded cells involve changes to all three growth bounds from their optimistic baseline levels.



| | | CCS Start Year | | | | | | | | | No CCS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CCS Start Year - 2020 | | | CCS Start Year - 2025 | | | CCS Start Year - 2030 | | | |
| | | CCS Growth Rate | | | CCS Growth Rate | | | CCS Growth Rate | | | |
| Wind and Solar | Nuclear | Breakthrough | Optimistic | Pessimistic | Breakthrough | Optimistic | Pessimistic | Breakthrough | Optimistic | Pessimistic | |
| Breakthrough | Breakthrough | -15% | -7% | -2% | -15% | -7% | -2% | -1% | -2% | 7% | 12% |
| | Optimistic | -15% | -7% | -2% | -15% | -7% | -2% | -1% | -2% | 7% | 12% |
| | Pessimistic | -15% | -7% | -3% | -15% | -7% | -1% | -1% | -2% | 6% | 11% |
| | No Growth | -13% | -7% | 4% | -10% | -3% | 10% | 7% | 3% | 14% | 29% |
| Optimistic | Breakthrough | -14% | -5% | 9% | -10% | 0% | 13% | 12% | 8% | 17% | 35% |
| | Optimistic | -14% | -5% | 9% | -10% | 0% | 13% | 12% | 8% | 17% | 35% |
| | Pessimistic | -12% | -5% | 9% | -10% | -2% | 16% | 12% | 8% | 22% | 38% |
| | No Growth | -9% | 1% | 23% | -3% | 13% | 34% | 36% | 14% | 42% | 52% |
| Pessimistic | Breakthrough | 2% | 15% | 37% | 11% | 20% | 48% | 46% | 31% | 58% | 70% |
| | Optimistic | 2% | 15% | 37% | 11% | 20% | 48% | 46% | 31% | 58% | 70% |
| | Pessimistic | 2% | 15% | 42% | 10% | 28% | 52% | 49% | 31% | 59% | 61% |
| | No Growth | 10% | 26% | 59% | 26% | 46% | 52% | 62% | 53% | 61% | 69% |

**Fig. 9** Percent change in electricity produced by natural gas in 2030, relative to the optimistic baseline scenario

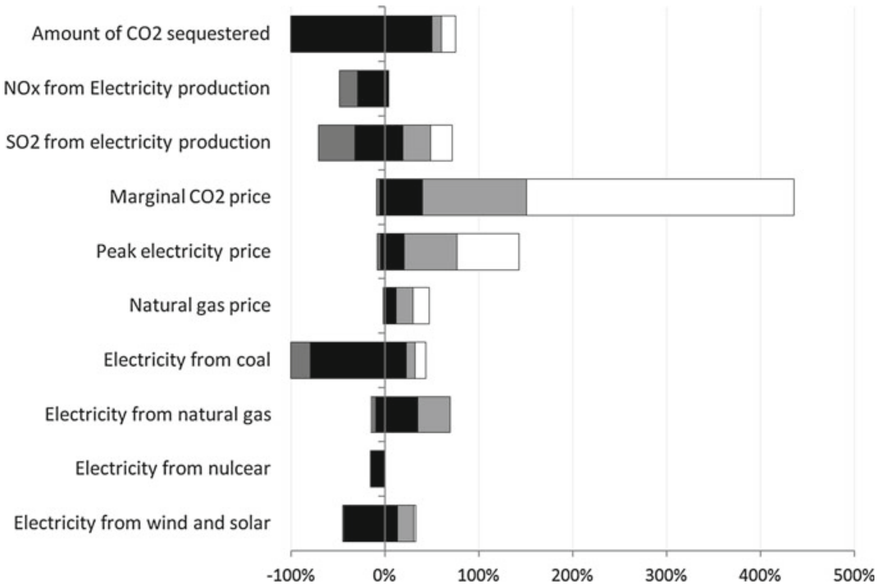


**Fig. 10** Percent changes in selected MARKAL outputs from their optimistic baseline levels. Black bars the maximum and minimum sensitivities to changes in any one input over the ranges shown in Fig. 9. White bars represent additional changes when multiple inputs are modified simultaneously

Across the individual sensitivities that are shown in Fig. 9 (e.g., the black shaded cells), electricity production from natural gas in 2030 decreases by no more than 7 %, but increases by 35 % when CCS is eliminated as an option. Combinations of growth assumptions yield a much greater response, driving electric sector natural gas use to as much as 70 % above its value in the optimistic baseline.

Pivot tables were developed for each of the MARKAL outputs that were tracked, although article length limitations restrict the display of additional tables. Instead, the responses to individual and combined sensitivities for each tracked output are summarized in Fig. 10. The black bars represent the maximum and minimum sensitivities to a change in any one of the growth bounds. The gray and white bars represent the range of additional sensitivity to changes in two and three growth bound assumptions, respectively. These shading patterns correspond to the shading in Fig. 9.

The results suggest that changes to the growth bounds can yield large changes in a number of model outputs, particularly when pessimistic or no-growth assumptions are realized for multiple inputs simultaneously. The $CO_2$ marginal had the greatest sensitivity, growing as high as 400 % above the optimistic baseline. While technically feasible within the model, an increase in the $CO_2$ marginal prices of 400 % is likely to be impractical from an implementation standpoint. The price response was much lower if only one or two of the pessimistic growth bounds are realized.

## 5 Summary and Conclusions

Only limited in-depth research has been conducted that analyzes the various factors that may constrain the penetration of low- and zero-carbon electricity production technologies under a greenhouse gas mitigation scenario. In this study, the influence of technology-specific growth constraints is explored. Explicit growth bounds are applied to wind and solar power, nuclear power, and $CO_2$ sequestration, and these bounds are varied both individually and in combination. The results suggest that assumed growth bounds may have considerable influence on the selection, cost, and emissions impacts of a least cost technology pathway for GHG mitigation. Thus, it is recommended that additional research attention be directed toward both characterizing realistic technology growth bounds and exploring how those bounds can be represented most appropriately within energy and economic models.

In addition, the results provide insights regarding the roles that different technologies may play in a least cost prescription for mitigating $CO_2$. Nuclear power, renewables, and sequestration all proved to have important roles, sharing market share unless explicitly bound out. Nuclear power achieved a foothold, but its high relative costs meant that its optimistic and breakthrough growth bounds were not met. Pessimistic growth bounds led to much greater reliance on natural gas for electricity production.

Perhaps the most interesting results were related to the use of natural gas within the electric sector. The results corroborate recent analyses by the Energy Information Administration (EIA) and others that argue that natural gas can provide a short-to-mid-term bridge before while zero-carbon technologies are under development (Newell 2009; Brown et al. 2009). The results presented here further suggest that natural gas may become even more critical if optimistic growth targets for solar and wind power, nuclear power, or sequestration are not realized. If pessimistic assumptions are made about more than one of these growth limits, modeling suggests the potential for substantial impacts on energy and $CO_2$ mitigation costs.

The cost and availability of natural gas in the future is thus an important consideration in the context of GHG mitigation. Recent advances in identifying and extracting unconventional natural gas have led to increases in EIA's estimates of the United States' natural gas reserves (U.S. DOE 2010). Considerable uncertainty remains, however, regarding the overall quantities of these resources and the extent to which they can be cost-effectively extracted. There are also potentially environmental consequences associated with new extraction techniques. For example, hydraulic fracturing is both water intensive and has the potential to generate large quantities of wastewater. EPA is currently conducting a hydraulic fracturing study to identify potential risks (U.S. EPA 2010d).

In this context, policy making will benefit if uncertainties in natural gas supplies can be reduced and if the environmental implications of greatly expanded natural gas extraction are understood more fully. Models such as MARKAL could play an important role in supporting decision makers by allowing different assumptions about natural gas supplies to be examined. By quantifying natural gas demands for various alternative scenarios, energy system models may also prove useful as an upstream component in environmental assessments of natural gas extraction.

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**Disclaimer** The views expressed in this presentation are those of the author and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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# Nanoscale Engineering Approach for Enhancing the Performance of Photovoltaic Cell Technologies for Non-Fossil Energy Sources

**Piao Liu, Glenn Gibson, Carlos A. Jarro, Suresh Rajaputra and Vijay Singh**

**Abstract** Energy consumption in the world is increasing rapidly and the supply of fossil fuels will not be able to keep up with the demand for too long. Fortunately, two emerging technologies, photovoltaic (PV) cells and concentrated solar power (CSP), can deliver a large portion of United States' energy needs in the next 40 years if they are properly developed. In this chapter, first, fundamental mechanisms of how electricity is generated by these two technologies are described. Next, recent developments in the application of nanotechnology for enhancing PV cell performance are presented. Among inexpensive solar cell technologies, copper indium diselenide ($CuInSe_2$ or CIS) based thin film solar cells have achieved solar to electrical conversion efficiency of 19.5 %. However, further improvement of efficiency is needed for them to become competitive with traditional energy sources. Two major efficiency limiting factors are, less than optimal energy band gap and short carrier diffusion length. In our group, we have used nanoscale engineering to develop device designs that would counter these two limiting factors. Specifically, vertically aligned nanowire arrays of $CuInSe_2$ of controllable diameter and length were produced by simultaneously electrodepositing Cu, In, and Se from an acid bath into the pores of anodized aluminum oxide (AAO) formed on top of an aluminum sheet. Ohmic contact to CIS was formed by depositing a 100 nm thick gold layer on top and thus a Schottky diode device of the *Au/CIS nanowires/Al* configuration was obtained. Analysis of the current–voltage characteristics of these devices yielded higher resistivity than those reported for CIS thin films, as expected from the size-dependent effects.

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Capacitance–voltage measurements were performed on the diodes to get the estimates of space charge density and the junction potential. Based on these experimental results, a nanowire-based solar cell configuration is proposed and illustrated.

**Keywords** Nanowires · Solar cells · Copper indium diselenide · Quantum confinement · Schottky diodes

# 1 Introduction

## *1.1 Importance of Developing Renewable Energy Sources*

The importance of developing renewable energy sources is a topic that has been discussed for decades. However, the choice of energy source is largely dependent on its availability. According to the EIA (http://www.eia.doe.gov), the United States and China have vast coal reserves, while Iceland gets virtually all of its electricity from either hydroelectric or geothermal power plants and 98.5 % of Norway's electricity is generated from hydropower. France, because of its shortage of fossil fuels and limited suitable hydroelectric sites, depends on nuclear power for almost 80 % of its electricity. Due to the environmental damage and $CO_2$ emissions associated with burning of coal, both China and the United States are in the process of substantially expanding their nuclear power capabilities within the next decade. Denmark gets much of its electrical power from wind turbines and Germany, which also has limited fossil fuel resources, is currently investing heavily in its solar power capability.

Figure 1 gives the percentages of various sources used to generate the world's electrical energy in 2007. Also, given in parentheses are the amounts of electricity generated by these sources in giga-kilowatt-hours (GkWh). The worldwide total amount of consumed electricity in 2007 was 16,990 GkWh, which is the energy equivalent of a little over ten billion barrels of oil or 2.57 billion tons (Gt) of coal. It is seen from Fig. 1 that fossil fuels are used to generate about two-thirds of the world's electricity (http://www.eia.doe.gov).

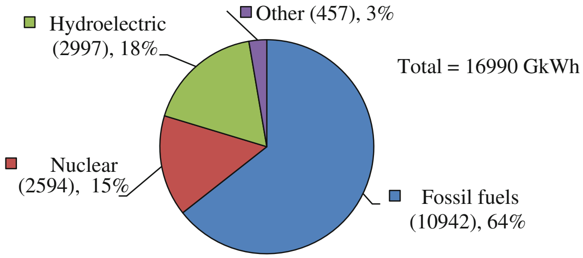
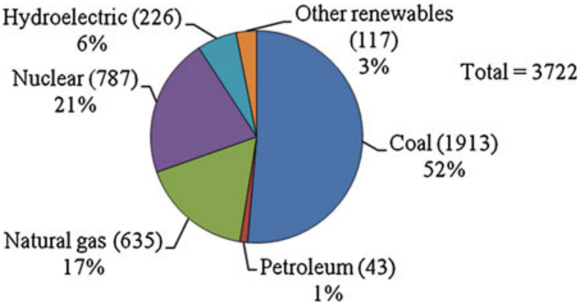


**Fig. 1** 2007 world consumption of electricity by energy source

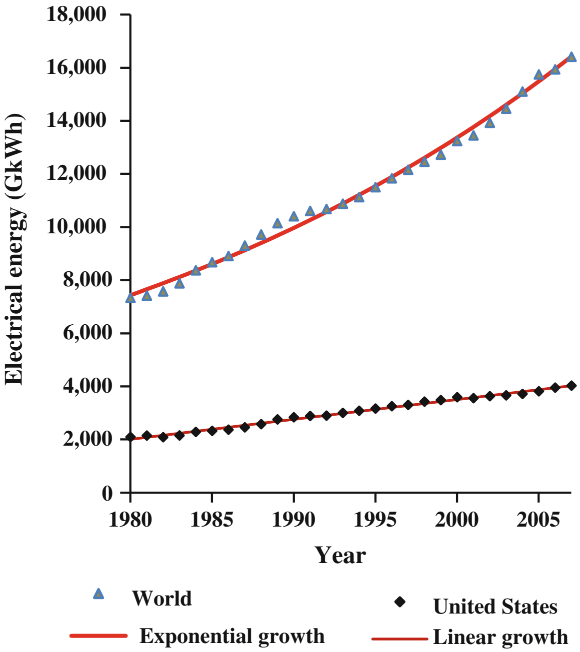
**Fig. 2** 2008 United States consumption of electricity by energy source



The 2008 amounts and percentages of the sources used to generate electricity within the United States are given in Fig. 2 (Energy Information Administration). As in the United States, about half of the world's electricity is generated by coal. Neither the amounts in Fig. 1 nor 2 include the generation and distribution losses.

Figure 3 shows the electricity consumption, excluding generation and distribution losses, in both the world and United States during the period 1980 through 2007 (http://www.eia.doe.gov). Superimposed on the actual data curves are the exponential approximation of the world data and the linear approximation of the United States data. The exponential approximation of the world data shows a compounded 3 % increase per year. By including the necessary excess capacity, this growth implies that in the succeeding years the worldwide generating capacity would need to be increased by 122.9, 126.3, and 130.1 GW and so on just to keep

**Fig. 3** Electricity consumption in GkWh



pace with demand. If the recent trend continues, by 2040 the worldwide demand would be 43,230 GkWh, more than two and a half times its 2007 demand. The United States has increased consumption at a linear rate of 74.68 GKWh per year and would need to add 18.7 GW to its generating capacity each year to meet its future demands. Its demand in 2040 would be 6,490 GkWh. To add 18.7 GW of capacity would require the construction of over eighteen 1,000 MW generating plants.

Not only has consumption increased in the United States, but the consumption per capita has also increased. However, on a per capita basis, the industrial sector's usage has not grown while the residential sector has increased its usage by 65 % and the commercial sector has more than doubled its per capita consumption. The average Canadian or American, including commercial and industrial usage, consumes four to six times as much electricity as the average person in the world as a whole. In 2006, the average person in the United States used 12,936 kWh, while the average person in the world used only 2,480 kWh and the average chinese person used only 1,682 kWh. However, China is increasing its consumption at an astonishing rate. From 1980 to 2006, China's consumption went from 261 to 2,529 GWkh and more than doubled in the 6 years between 2000 and 2006. Not only is China's consumption increasing, but its consumption growth rate is increasing.

Although oil and gas fields and coal mines are still being discovered by exploration companies, the supply of fossil fuels does not have an exponential growth as the demand of energy does. Likewise as the non-renewable energy sources become scarce the price of generating electricity from them increases, this underdevelopment of fossil fuels supply added to the exponential growth of the demand could bring important economic and political problems.

## 1.2 Two Technologies, Photovoltaic Cells and Concentrated Solar Power, Can Deliver a Large Portion of U.S. Needs by 2050

A big part of the renewable energy sources available in the world is the energy delivered directly by the sun. There are two fundamental means of collecting energy from the Sun directly: photovoltaic (PV) cells and concentrated solar power (CSP). These two generating technologies could deliver a large portion of United States' needs in the next 40 years (Zweibel et al. 2007). In the southwestern deserts of the United States, 2,940 GW could be generated by PV panels covering a land area of 30,000 square miles, and an additional 558 GW could be generated by CSP plants, covering a land area of 16,000 square miles. The development of these energy sources would require a change in the power distribution grid. The United States will have to build a direct current (DC), high-voltage transmission line infrastructure to transmit electricity from Southwestern U.S. to cities and regions across the nation.

The not-immediately consumed energy generated by PV and CSP plants will have to be stored in order that it may be used during the night when there is no electricity generated by these types of plants. This can be made by using the electrical energy at the destination region to produce compressed air, which can be stored in underground caverns and other storage facilities used at present for storing natural gas. At night time the compressed air will be released as needed, to turn turbines that generate electricity for regional needs, aided by burning small amounts of natural gas.

This electrical energy development model predicts that by 2050 solar power would be able to provide 69 % of the electrical energy and 35 % of the total energy needs of United States. This will significantly reduce the greenhouse gas emissions and the dependence on foreign oil. Also, the upgrades to the power grid system would lead to creation of new jobs in the green energy sector.

The solar power development could even decrease the energy demand. Assuming the United States had a 1 % annual electric energy demand growth, by 2050, the total energy consumption will actually become lower than today. In 2006, 100 quadrillion Btu were consumed. This will fall to 93 quadrillion Btu by 2050 because, today, a lot of energy is consumed just to extract and process fossil fuels and later, even more energy is wasted in burning the fuels and controlling their emissions.

# 2 Background

## 2.1 *Basic Operation of the Concentrated Solar Power Generators*

The concentrated solar power generation method uses a large array of mirrors to direct the energy to a focal point where the concentrated energy heats a special fluid, called a heat transfer fluid (HTF), which is sent to a heat exchanger where the heat is used to turn water into steam. In some arrays the mirrors are like halves of long parabolic tubes and reflect the energy toward pipes that contain the HTF, and in other designs the energy is collected at one central point that is located at the top of a tower. A third method uses an array of parabolic dishes. Regardless of the design, the mirrors move so that they are, within the limits of their design, optimally directed toward the Sun and, along with the heat exchanger.

A representative but simplified diagram of a solar thermal power plant is shown in Fig. 4 (Agar 2005). To this design there may be added a thermal storage tank, an HTF heater, a steam preheater, and other equipment for making the system more efficient. Also not shown is the control equipment for tracking the Sun. Another possibility is to heat water directly from the Sun's radiation. But an HTF with a high specific heat capacity is used because it can hold more heat at a lower pressure. The solar array would need to be designed to withstand much greater

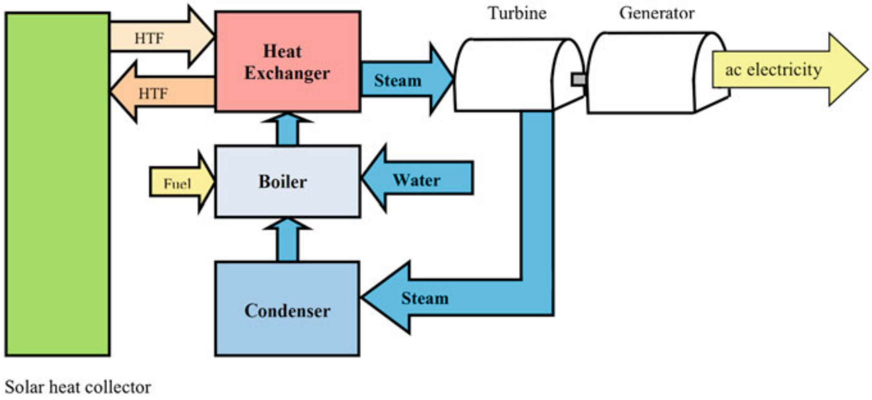


**Fig. 4** Simplified solar thermal power plant

pressures if the water were heated directly. These CPS power plants may be quite large. A plant to be located in the Mojave Desert is to have a capacity of 553 MW and cover 24 km$^2$ (6,000 acres).

## 2.2 Basic Operation of the Photovoltaic Cell Generators

A photovoltaic cell generation plant consists of several panels containing large photovoltaic sheets or arrays of solar cells connected in such a way that they produce a suitable voltage and current. This energy has to be stored in the day so it can also be used in the night. A very popular medium used to store electrical energy generated by small photovoltaic arrays is a battery array. However, the battery technology is not able to store large quantities and their life time is not high enough to be an affordable solution for a photovoltaic generation plant. A proposed method to store the energy generated by the PV plant is the use of air compressors and underground gas storage facilities. Figure 5 shows a diagram of a generic photovoltaic generation plant and storage facilities.

To date, most solar cells are used for generating the electricity requirements for a single home or business. A diagram of such a system is given in Fig. 6. Because solar cells produce DC electricity, a DC to AC inverter must be included to obtain the AC electricity required by the appliances and equipment in the home or business and to match the electricity on the power grid. The system may be connected to the power grid, as shown in Fig. 6, or have a bank of batteries for storage that could provide electricity when the sun light is not available during night time or cloudy days. If it is connected to the power grid, then a meter is included that allows the home or business to receive credits when the solar cell system is producing excess power and debits when power must be drawn from the power grid. How the credits and debits are translated into money depends on the current state and national laws. While steam-powered plants tend to be large, centralized systems that take advantage of the economy of scale, solar cell systems

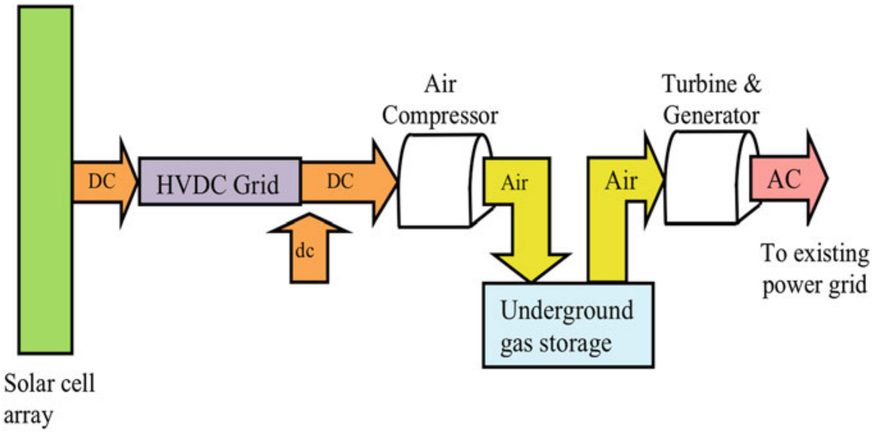


**Fig. 5** Diagram of a photovoltaic generation plant

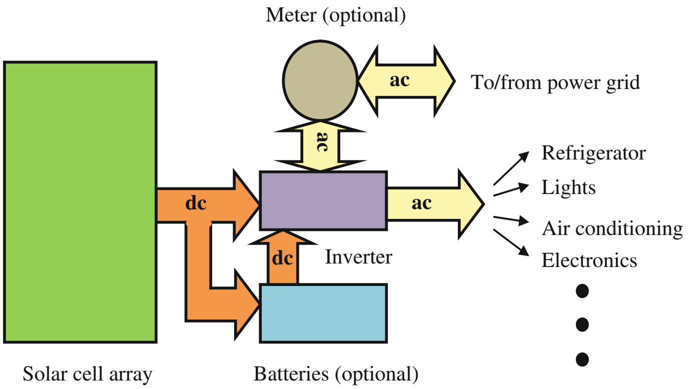


**Fig. 6** Diagram of a solar cell system for a home or business

are relatively small and distributed, but reduce the transmission costs. Large solar cell systems for the sole purpose of supplying power to the grid will become more common as they become economically competitive.

In order to make solar cells more competitive it is necessary to make them more efficient while reducing their price. It is important then to understand the definition of efficiency and the basic operation of the cell. Figure 7 shows the basic operation of a solar cell. The sun’s light contains particles called photons, these photons have to be absorbed by the material the solar cell is made of. When a semiconducting material absorbs a photon, an electron of lower initial energy (valance band) gains energy and jumps to the conduction band. In this way the electron can move more easily. The gain in energy of this electron leaves a hole in the valance band. This means that a single photon is capable of generating two types of current: the movement of the electron, and the “movement” of the hole. The movement of a

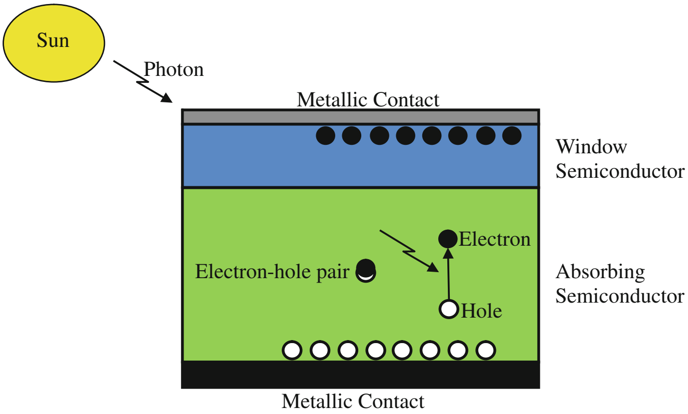


**Fig. 7** Basic operation of a solar cell

hole really means that electrons are moving in the valance band from one vacancy (hole) to the next vacancy, making it seem as if the vacancies (holes) were moving in the opposite direction. In the following, we consider the electron and the hole as two particles with the same amount of energy but different sign. The movement of these electrons and holes is the electrical current. In order to collect these electrons and holes a different type of semiconductor called a “window” is used. This semiconductor has two functions: allow the transit of the photon (high energy band gap) and generate an electric field capable of separating the electron from the hole. In this way a metal connected to the window can collect the electrons and a metal connected to the absorber can collect the holes, generating DC voltage ($V_{oc}$) and, when a load is applied, a DC current. This is how the energy from the sun is converted. The efficiency of a given solar cell will depend on how transparent is the window semiconductor, how effective is the absorber (carrier generation and separation) semiconductor, and how many electrons and holes are collected (carrier extraction). Our approach to improve these characteristics and electrical properties of a solar cell is the use of nanostructured solar cells, and it is explained in the following sections.

## 3 Objectives

Among all types of solar cells, silicon-based solar cells (both single crystal silicon and poly-silicon) (McClure et al. 1998) cadmium sulfide (CdS)/cadmium telluride (CdTe) heterojunction-based (Singh et al. 2000; Xuanzhi 2004; Dhere et al. 2006), and cadmium sulfide (CdS)/copper indium diselenide ($CuInSe_2$ or CIS) heterojunction-based (Dhere et al. 2006; Beach 2007; Ramanathan 2003) thin film solar cells are of great interest due to their special characteristics and applications for certain demands. CdS/CdTe-based solar cells have reached a solar to electrical conversion efficiency of 16.5 % (Xuanzhi 2004) while copper indium diselenide

($CuInSe_2$ or CIS) and its related compounds like copper indium gallium selenide (CIGS) have achieved efficiency of as high as 19.5 % (7).

However, further improvement of efficiency is needed for solar cells to become competitive to traditional energy sources. Nanostructured semiconductor materials have recently received a great deal of attention due to their interesting size-dependent electro-optical properties (Chu et al. 2002; Xu et al. 2006; Liu et al. 2010b). The use of semiconductor nanowires for photovoltaic applications can be advantageous for many reasons. Briefly, it permits interpenetrating networks of materials for semiconductor heterojunctions at the nanoscale, allowing efficient carrier extraction and separation following light absorption. Also, long absorption paths are possible while maintaining short distances for carrier collection, even in imperfect materials. In terms of reducing cost, single crystal materials can be grown in relatively thin films with little material. In addition, strong light diffraction and trapping are possible due to the geometry of the nanowires. Last but not least, manipulation of materials properties is possible by varying the size of the nanostructures.

For example, to further increase the efficiency of CdS/CIS solar cells and reduce its cost, special properties of nanostructured materials are used in combination with the highly efficient heterojunction structure. At this point, the major factor limiting the efficiency is the relatively low open circuit voltage ($V_{oc}$) caused by the lower than optimal energy band gap of 1.04 eV in CIS. For enhanced performance, the effective energy band gap of CIS needs to be increased from 1.04 eV to 1.5 eV. This can be done by adopting a nanowire device structure where the small diameter of CIS wire would lead to quantum confinement and hence an increased effective band gap, tunable to the optimal value of 1.5 eV. Also the band gap of the CdS window layer (2.5 eV in bulk condition) can be increased to 3.5 eV in nanoscale design. Since we want the light to pass through CdS layer and be absorbed in the CIS layer near the junction, we could take advantage of this quantum effect, making wider band gap CdS layers to pass the light. To be more detailed, blue light has the wavelength of 0.45 μm which results in a 2.8 eV energy packet for its photons according to $E = \frac{\hbar c}{\lambda}$. That is to say, nanostructure of CdS passes the blue light which normal structure of CdS cannot pass. Therefore, transparency is greatly improved and major absorption occurs near the junction, resulting in higher light-generated current as well as in higher efficiency. Here we propose a nanowire-based solar cell configuration (Singh et al. 2008), as shown in Fig. 8.

This device structure is fabricated starting with a glass slide which works as substrate to provide mechanical support as well as to pass the sun light. On top of that, a thin layer (usually about 200 nm) of transparent conductor ITO is deposited by sputtering as the contact to the n-type CdS. On top of that, 1 μm aluminum layer is deposited by E-beam evaporation and then anodized to form the AAO template. CdS and CIS layers are then consequently electrodeposited into the nanopores to form heterojunction inside the template. CIS nanowires need to be deposited all the way to the top surface of the template. A final layer of molybdenum or gold is then sputtered to form the top ohmic contact to CIS.

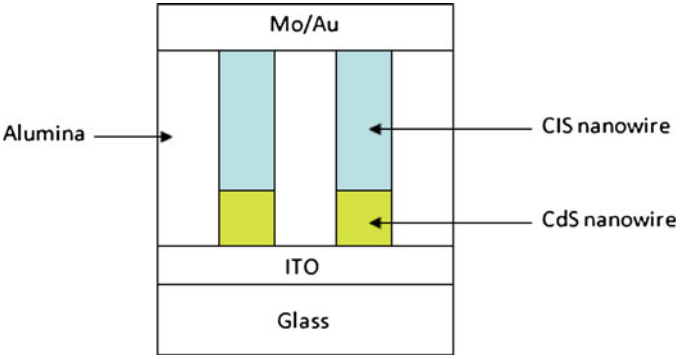


**Fig. 8** Structure of CdS-CIS nanowire-based solar cells on glass/ITO substrate

This structure provides flat and insulating substrate which keeps the sample away from potential mechanical damages and chemical etching as well as unnecessary electrodeposition on the backside. Besides the advantages mentioned in the Introduction, other advantages of this device structure include: (a) ITO-coated glass already available on market, which simplifies the whole fabrication process. (b) Many kinds of metals can be tested as the top contact, thus the mechanism at the boundary of metal and CIS nanowires can be further studied. We are currently fabricating and investigating this structure.

## 4 Nanowire Device Fabrication and Characterization Procedures

Fabricating and characterizing the nanowires of both absorption layer and window layer are essential and pre-required before constructing the heterojunction inside nanoporous templates. For the absorption layer of copper indium diselenide (Phok et al. 2007), we have successfully fabricated CIS nanowires by preparing a short length ( ~ 1,000 nm) anodized aluminum oxide template and simultaneously filing it with copper, indium, and selenium by electrodeposition. Two-step anodization process was used to prepare the AAO templates. A 60 micrometer thick aluminum sheet with backside protected by glue and paper served as the anode, and a platinum foil served as the counter electrode. The electrolyte contains 0.3 M oxalic acid powder dissolved in de-ionized water. The first step anodization was performed at 20 V constant voltage for 10 min. The formed aluminum oxide layer was then etched off in a hot mixture of phosphoric acid and chromic acid. The second step anodization was performed under a constant potential of 25 V at room temperature for 10 min, resulting in a layer of approximately 1 μm thick porous alumina. To thin the aluminum oxide barrier layer at the aluminum/porous alumina interface, we ramped down the anodization voltage at the rate of about 10 % per min till it reached a value of 1 V. Then the sample was immersed in 50 %

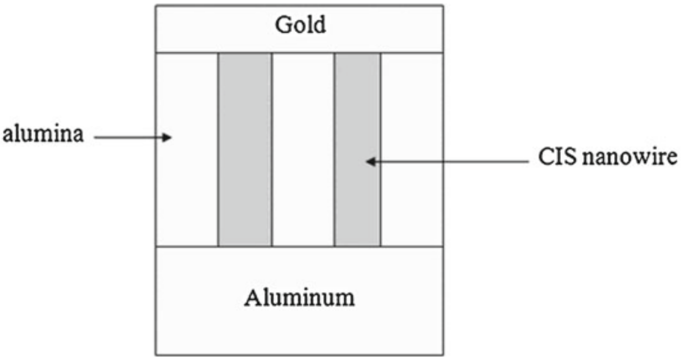


**Fig. 9** Configuration of the device for CIS nanowire/Al Schottky diode measurement

phosphoric acid for 3 min at room temperature to widen the pores and further thin the barrier layer. Then it was subjected to a heat treatment in air at 200 °C for several hours to remove any unwanted residuals like hydroxides resulting from the anodization and etching process. AAO templates with a typical pore diameter of about 25 nm and pore length of around 1,000 nm were prepared by this two-step anodization process.

Next, CIS nanowires were electrodeposited in the pores. The bath for CIS nanowire electrodeposition contained 1.5 mM copper sulfate hydrate, 2 mM indium sulfate hydrate, and 3.5 mM selenious acid. The pH was then adjusted to a value of 3 by adding potassium hydrogen phthalate and hydrochloric acid to the mix. The electrodeposition was conducted under a dc pulse voltage of $-1$ V for 20 min at room temperature. A Pt plate was used as the counter electrode. Typical current density during the ED process was 0.25 mA/cm$^2$. For recrystallization, the deposited CIS nanowires were annealed in Argon gas at 350 °C for 1 h.

These CIS nanowires embedded in the AAO matrix were first characterized by scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDX), and X-ray diffraction (XRD) (Phok et al. 2007). Next, a thin layer of gold was deposited on top of the nanowires by electron beam evaporation to form ohmic contact with CIS nanowires as the configuration shown in Fig. 9 (Liu et al. 2010a). Current–voltage and capacitance–voltage characteristics of the Al-CIS nanowire Schottky diode were measured with a computer-controlled setup of a programmable semiconductor parameter analyzer.

## 5 Results and Discussion

Cross-sectional view of a typical annealed sample of CIS nanowires inside porous alumina template is shown in Fig. 10 (Liu et al. 2010b). Here, we can see that nanowires grow continuously from the bottom of the pore, which lies at the aluminum substrate/porous alumina interface, all the way to the top surface. It is estimated that more than 90 % of the pores are filled with CIS nanowires and

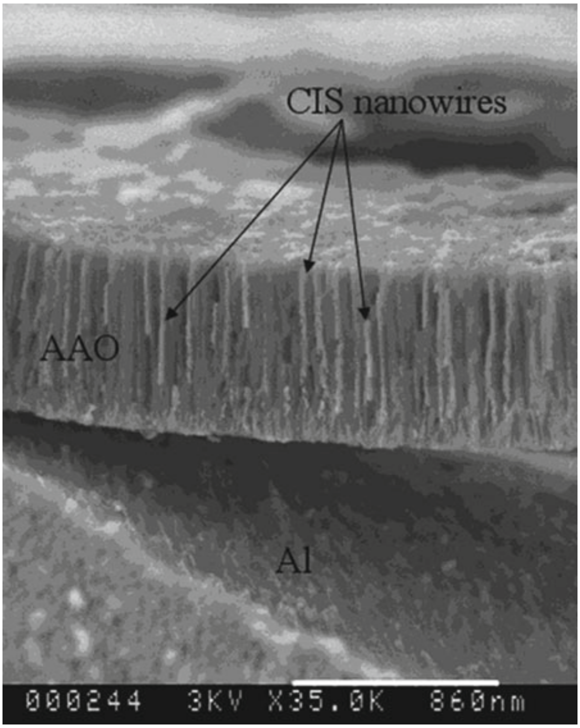


**Fig. 10** The corresponding cross-sectional view of the CIS nanowires inside AAO. *Bright vertical lines* are CIS nanowires, surrounded by darker AAO lines. Aluminum is the substrate on which CIS nanowires and AAO pores are standing

around 80 % nanowires are grown all the way through the pores. Note that in the cross-sectional view, the AAO template detached from the aluminum substrate, which is considered to be caused by the stress produced during the process of breaking the device and mounting it on the stub for electron microscopy.

By evaporating a thin layer ( ~ 100 nm) of gold on top of the nanowires to form an ohmic contact to CIS, the Al/CIS (nanowire)/Au Schottky diode device of Fig. 11 was obtained. It was used to investigate the electric characteristics of the electrodeposited CIS nanowires. The current density versus voltage (J-V) characteristic of an Al/CIS nanowire Schottky diode is shown in Fig. 11 (Liu et al. 2010a) for this measurement, gold electrode was biased positive with respect to the aluminum electrode.

In Fig. 11, the current–voltage relationship is more linear than exponential at high current values (deep forward bias) because the resistance-induced voltage drop is dominant in that regime. From the slope in this linear regime, a value of 44.3 Ω was calculated for the series resistance of the device. Attributing this resistance mainly to the bulk resistance of nanowires and knowing that the porosity of the AAO template is 25 %, the fill factor is 90 %, and 80 % of the filled nanowires are grown all the way from bottom to the top surface, we calculated the resistivity of the CIS nanowires to be $5.6 \times 10^3$ Ω cm. For these calculations, 0.07 $\text{cm}^2$ was the device area of the 1/8 inch diameter gold dots, and the junction area was 0.07*25 %*90 %*80 % = 0.0126 $\text{cm}^2$. The resistivity of CIS film is

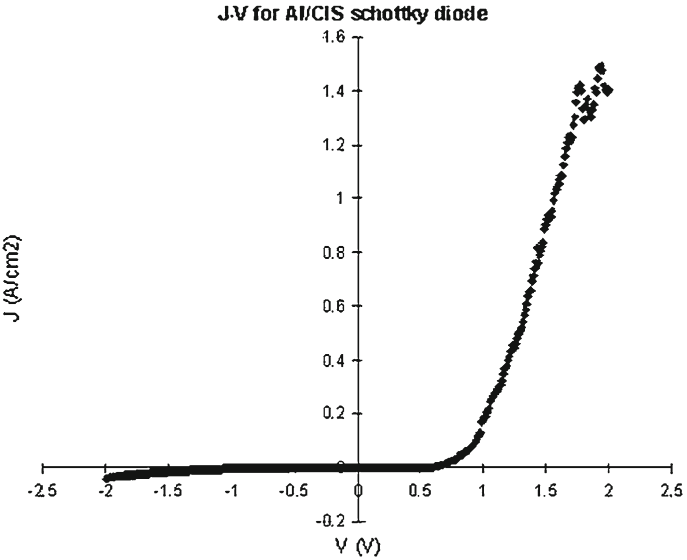


**Fig. 11** A typical J-V curve of Al/CIS nanowire Schottky diode

known to depend strongly on its grain size (Yong et al. 2007). In results reported by Yong et al. (2007), the resistivity of polycrystalline CIS ranged from 0.58 to 516 Ω cm as the grain size decreased from 400 to 100 nm for the same CIS thin film annealed at different temperatures. Resistivity data for CIS of smaller than 100 nm grain size are not available in the literature because the as-deposited planar polycrystalline CIS films have grain sizes of around 100 nm and the grain sizes tend to become even larger as these planar films are subjected to traditional annealing treatments. The only exception is in our case, where the particle size is limited by the template pore size and does not increase with annealing temperature. In our nanowires, a resistivity value of $5.6 \times 10^3$ Ω cm for a particle size of 25 nm is in conformity with their results.

Zero bias capacitance measurements on these Schottky diodes revealed that the capacitance first decreased with frequency (f), at low test frequencies, but became less and less sensitive as f was increased, becoming invariant for $f = 1$ MHz and higher. This effect was attributed to a part of the junction space charge being stored in "slow" mid-gap traps in the CIS nanowires. Charge in these traps is able to respond to the applied test voltage of "low" frequency, but is unable to respond to the test voltage of "high" frequency. To minimize the effects of such traps and defects, the capacitance–voltage (C–V) measurement was conducted at the "high" frequency of 1 MHz. The resulting plot of $1/(C^*)^2$ versus reverse bias voltage $V_R$ is shown in Fig. 12 (Liu et al. 2010a).

Even when the $1/C^2$ versus V characteristic is nonlinear (as in Fig. 12), and defects and traps are present, equations from reference (Sze 1981) can be used to calculate the variation in local space charge density, qN(x) as a function of x, where x

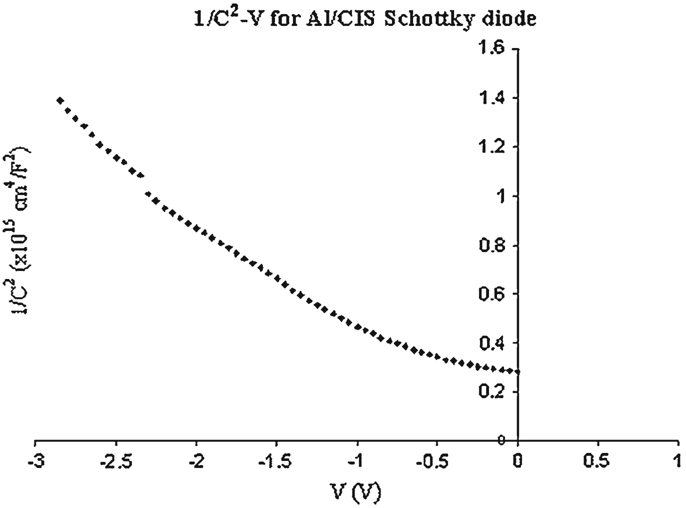


**Fig. 12** 1/C$^2$-V curve of Al/CIS nanowire Schottky diode

is the depth inside CIS, from the Al–CIS interface. N(x) can be thought of as local "effective carrier concentration." N(x) is approximately equal to the local concentration of ionized acceptors, Na(x) in CIS, when the charge stored in local defects and traps is much smaller than qNa(x). Note that at room temperature, Na(x) is approximately equal to the local carrier (hole) concentration in CIS. On the other hand, when charge stored in defects and traps is not much smaller than qNa(x), then N(x) and Na(x) can differ substantially. N(x) was calculated by using the equations from reference (Sze 1981) and the capacitance–voltage data of Fig. 12. In this calculation, junction area of 0.0126 cm$^2$, rather than the device area of 0.07 cm$^2$ was used. Thus, at zero bias, the junction capacitance per unit area is 59.5 nF/cm$^2$, which corresponds to a depletion layer width of 120 nm where a value of 8.1 is used for the relative dielectric constant of CIS (Bhattacharya 2002). The slope of the plot in Fig. 12 at zero bias is $1.46 \times 10^{14}$ cm$^4$/(F$^2$.V), which corresponds to a value of $N = 1.2 \times 10^{17}$ cm$^3$. In other words, the value of $N$ at the edge of depletion region, which is 120 nm from the junction with aluminum, is $1.2 \times 10^{17}$ cm$^3$. Similarly, the slope of the plot in Fig. 12 at a bias of $-3$ V is $7.1 \times 10^{14}$ cm$^4$/(F$^2$.V), which corresponds to a value of $N = 2.45 \times 10^{16}$ cm$^3$. At this bias, the junction capacitance value is 26.8 nF/cm$^2$, which corresponds to a depletion layer width of 267 nm.

For our device, the Schottky junction model calculation yielded effective carrier concentration in the CIS nanowires varying from $1.2 \times 10^{17}$ cm$^3$ to $2.45 \times 10^{16}$ cm$^3$ as the distance from the aluminum interface varied from 120 to 267 nm. This variation along the length of nanowire is thought to be related to the differences in the velocity of ion transport for copper, indium, and selenium, down the narrow nanotubes of porous alumina during electrodeposition. This would lead to changes in the stoichiometry of CIS as the relative concentration of copper, indium, and selenium changes during the growth of wires in the nanopores, by the electrochemical deposition process (Sudo et al. 1993). Such concentration gradients have been reported earlier in the electrodeposition of bulk CIS films (Chien-Jung et al. 2005). The composition of the nanowires is more Cu rich at the initial stage of deposition. In other words, the Cu/In ratio is higher at the interface between aluminum and CIS nanowires, which results in a higher carrier concentration near the CIS/Al junction. As the deposition goes on, the Cu component gradually decreases and In composition gradually increases, and the nanowire composition gradually becomes close to stoichiometric. It should be noted that the composition of bulk electrodeposited CIS films can be adjusted by post-deposition annealing and recrystallization, making these films eventually stoichiometric. However, in the case of nanowire, post-deposition annealing seemed to be not as effective. This might be because of the confinement of nanostructure, which results in less mobility of the atoms during high-temperature processes.

## 6 Conclusions

Two technologies, namely photovoltaic cells and concentrated solar power, can deliver 69 % of U.S. electricity needs and 35 % of the total energy needs by 2050. However, in order to make solar cells more competitive it is necessary to make them more efficient while reducing their fabrication cost. Nanostructured semiconductor materials with their special characteristics and advantages make them interesting in solar cell applications. A semiconductor material that is commonly used in thin film heterojunction solar cells, namely $CuInSe_2$ as the absorption layer, was successfully fabricated inside porous aluminum oxide templates. Schottky diodes between p-type semiconductor CIS nanowires and aluminum metal were fabricated by electrodepositing CIS into the pores of an alumina template formed on top of an aluminum sheet. Scanning electron microscopy revealed well-formed, compact nanowires inside the pores. J-V curve was measured for the Schottky diode and a resistivity value of $5.6 \times 10^3\ \Omega$ cm was calculated for these embedded CIS nanowires, with particle size of about 25 nm. Effective carrier concentration in the CIS nanowires varied from $1.2 \times 10^{17}$ $cm^3$ to $2.45 \times 10^{16}$ $cm^3$ as the distance from the aluminum interface varied from 120 to 267 nm. Electrical characteristics of the junction between the CIS nanowire and aluminum were similar to those of the junction between thin film CIS layer and aluminum, except in that case, the C–V measurement yielded constant carrier concentrations. Groundwork has been laid for nanowire solar cell designs, which would yield thin film solar cells that are inexpensive to manufacture and have power conversion efficiency in excess of 25 %.

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# Sustainable Mobility: Insights from a Global Energy Model

**Timothy J. Wallington, James E. Anderson, Sandra L. Winkler and Maria Grahn**

**Abstract** A global energy model that includes a detailed description of light-duty vehicle and fuel technologies was used to investigate cost-effective light-duty vehicle/fuel technologies in a carbon-constrained world. Total $CO_2$ emissions were constrained to achieve stabilization at 450–550 ppm by 2100 at the lowest total system cost. Three conclusions emerge. First, there is no “silver bullet” vehicle or fuel technology. Given the current uncertainties in future costs/efficiencies for light-duty vehicle and fuel technologies, there is no clear fuel/vehicle technology winner that can be discerned. Second, a multi-sector perspective is needed when addressing greenhouse gas emissions. Connections between transportation and other energy sectors are likely to become important in the future. Third, alternative fuels are needed in response to the expected dwindling oil and natural gas supply potential by the end of the century, which were used almost completely in all scenarios (even for a 450 ppm $CO_2$ target).

**Keywords** Global energy model · Carbon emission · Sustainable transportation

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## 1 Introduction

Global climate change, caused by increasing levels of greenhouse gases (GHG) in the Earth's atmosphere resulting from human activities (IPCC 2007), is a major issue of current concern. $CO_2$ released during fossil fuel combustion and deforestation is the largest contributor to radiative forcing of climate change (IPCC 2007). The United Nations Framework Convention on Climate Change has been ratified by 192 countries and calls for stabilization of greenhouse gas concentrations in the atmosphere at a level that would "prevent dangerous anthropogenic interference with the climate system" (UNFCCC 2008). While there is no consensus on a precise level of $CO_2$ in the atmosphere that would prevent such interference, levels in the range 450–550 ppm have been discussed. In the present work, we consider scenarios where $CO_2$ levels are stabilized at 450–550 ppm. The current (2010) global average atmospheric $CO_2$ concentration is 389 ppm, is increasing by approximately 2 ppm per year, and the rate of increase is itself increasing (it has approximately doubled since the 1960s) (Tans 2010).

Efforts to stabilize atmospheric $CO_2$ levels are complicated by many considerations, not least of which being the fact that $CO_2$ emissions are spread across different geographic regions and economic sectors (e.g., industrial, residential, commercial, transportation). Figure 1 shows the regional distribution of fossil fuel $CO_2$ emissions in 2007 obtained from an online resource provided by the Energy Information Agency (EIA) of the U.S. Department of Energy (EIA 2010). In 2007 the total global emission of $CO_2$ from fossil fuel consumption was 30 Gt (Gt $= 10^9$ tonnes $=$ 1Pg). The pie charts on the top of Fig. 1 show (from left to right) a breakdown of U.S. emissions into end-use sectors and a breakdown of emissions from the U.S. transportation sector into different transportation modes. Data for these charts were obtained from Tables 2-1 and 2-15 of the 2009 Inventory of U.S. Greenhouse Gas Emissions and Sinks from the U.S. Environmental Protection Agency (USEPA 2009). The pie charts on the bottom of Fig. 1 show comparable data for the EU-15 countries. Data for the use sectors were obtained from the annual greenhouse gas inventory published by the European Environment Agency (EEA 2009). The EEA GHG inventory divides the transport sector into five modes. However, it does not provide emissions for sub-modes of road transport. The road transport sub-mode shares can be estimated using the TREMOVE model (TREMOVE 2009). The TREMOVE shares were applied to the EEA GHG inventory of road transport emissions to construct the bottom right pie chart in Fig. 1.

As evident from Fig. 1, passenger vehicles (cars and light-duty trucks) in the USA and EU-15 are responsible for approximately $60\ \% \times 33\ \% \times 20\ \% = 4\ \%$ and $69\ \% \times 27\ \% \times 16\ \% = 3\ \%$ of global fossil fuel $CO_2$ emissions, respectively. On a global basis, in 2007 light-duty vehicles were responsible for approximately 3.1 Gt [estimated from the World Business Council for Sustainable Development's Sustainable Mobility Project (SMP) model (WBCSD 2004)] which represents about 10 % of the approximately 30 Gt of global fossil fuel $CO_2$ emissions.

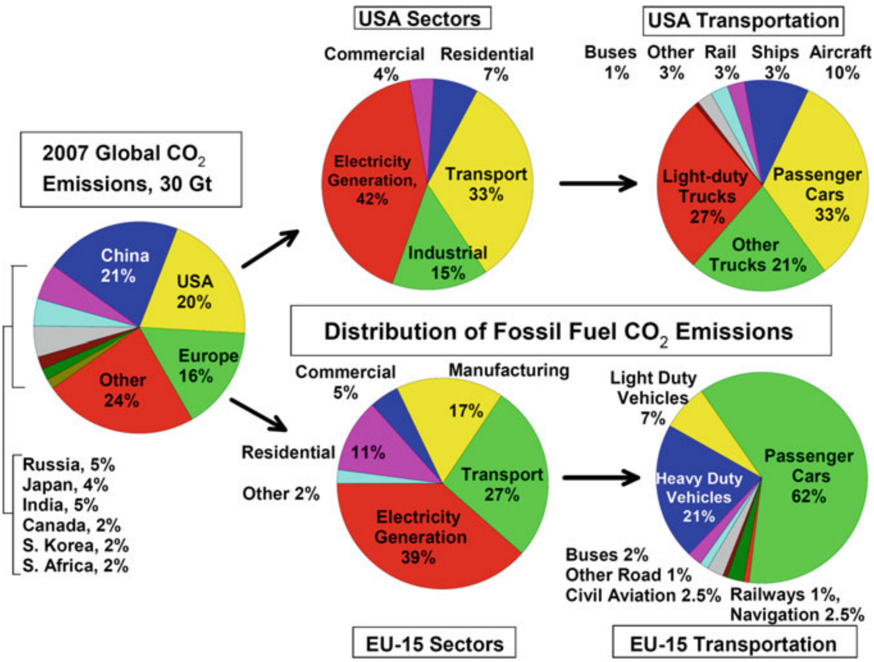
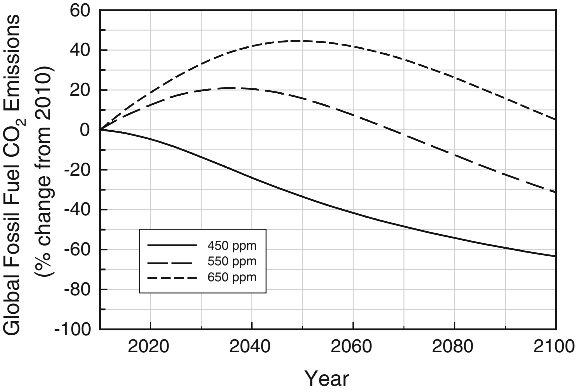


**Fig. 1** Distribution of $CO_2$ emissions from fossil fuel combustion

Wigley and co-workers have developed $CO_2$ emission profiles consistent with stabilization of $CO_2$ concentration in the Earth's atmosphere at various levels (Wigley 2010). Figure 2 shows plots of such $CO_2$ emission profiles consistent with stabilization at 450, 550, or 650 ppm. The emissions are expressed as a change from that in 2010. As seen from Fig. 2, large reductions in global emissions are required to stabilize at 450 pm; for example, emissions in 2050 and 2100 would need to be approximately 30–40 % and 60–70 %, respectively, lower than those today. Comparison of the magnitude of the emissions reductions shown in Fig. 2 to the widely distributed emissions from the various regions and sectors in Fig. 1 indicates that stabilization at 450 ppm requires actions in all geographic regions and economic sectors. For example, the complete elimination of all emissions from light-duty vehicles would only result in an approximately 10 % reduction in global emissions; less than one-third of the reduction needed to follow an emissions pathway consistent with stabilization at 450 ppm.

Given the magnitude of the $CO_2$ reduction task to achieve stabilization at 450 ppm, a multi-sector approach is needed in which efforts will be taken to reduce, or limit, $CO_2$ emissions from all regions and economic sectors. Having established that all sectors will need to participate, the question arises as to how to distribute the task among the sectors. There are in principle two approaches, either

**Fig. 2** Global fossil fuel $CO_2$ emissions pathways (expressed as % change from emissions in 2010) consistent with stabilization at 450, 550, or 650 ppm (Wigley 2010)



all sectors face the same percentage reduction, or different percentage reductions could be allocated to different sectors. The first approach is conceptually the simplest, but is potentially more expensive as it ignores differences in carbon mitigation costs in different sectors. The second is more complex, but can be economically more efficient. The task for light-duty vehicles using the first approach is *relatively* straightforward to assess. One version of this approach can be illustrated using the following logic. We will consider the reduction needed from 2005 to 2050. Following a 450 ppm stabilization path from the Wigley et al. MAGICC model (Wigley 2010) requires a 32 % reduction in global $CO_2$ emissions from 2005 to 2050. The $CO_2$ emissions from light-duty vehicles in 2005 in the SMP model are 3.02 Gt and, absent any fuel economy improvements, the emissions in 2050 are projected to be 7.16 Gt due to projected increases in vehicles numbers and distance traveled (WBCSD 2004). The "allowed" emissions in 2050 would be $3.02 \times (1.00-0.32) = 2.05$ Gt. Hence, the task for the light-duty vehicle sub-sector would be to reduce the projected emissions of 7.16 Gt to the allowed emissions of 2.05 Gt (i.e., a 71 % decrease). Assuming that the same mobility is delivered this would require a 71 % decrease in the $CO_2$ emissions per passenger km, or 3 % decrease per year on a compounding basis. This dramatic decrease in $CO_2$ emissions, if achieved solely by vehicle technology for conventional internal-combustion engine vehicles, would correspond to a fuel economy of the order of 100 miles per US gallon [a similar conclusion was reached by Grimes-Casey et al. (2009)].

One possible objective of allocating different percentage reductions to sectors (i.e., the second approach to task distribution) is to minimize total cost. It is much more difficult to estimate the task for light-duty vehicles for such an approach. To facilitate discussions of possible strategies along these lines, we have developed a global energy model (GET-RC 6.1) that includes a detailed description of passenger vehicle technology options (Azar et al. 2000, 2003, 2006; Grahn et al. 2009a, b; Wallington et al. 2010). It is important to understand the fuel and vehicle technology choices available for passenger vehicles and how actions in other energy sectors are likely to impact these choices. Surprisingly, there have been few

**Table 1** Vehicle and fuel technology combinations included in GET-RC 6.1

| Vehicle technology[a] | Fuel technology | | | | | | |
|---|---|---|---|---|---|---|---|
| | Petro | BTL | GTL | CTL | NG | Hydrogen[b] | Electricity[c] |
| ICEV | Yes | Yes | Yes | Yes | Yes | Yes | – |
| HEV | Yes | Yes | Yes | Yes | No | No | – |
| PHEV | Yes | Yes | Yes | Yes | No | No | Yes |
| BEV | – | – | – | – | – | – | Yes |
| FCV | Yes | Yes | Yes | Yes | No | Yes | – |

[a] *ICEV* Internal-combustion engine vehicle, *HEV* Hybrid-electric vehicle, *PHEV* Plug-in hybrid-electric vehicle, *BEV* Battery-electric vehicle, *FCV* Fuel cell vehicle

[b] Nine hydrogen production options from coal, natural gas, oil, or biomass with, or without CCS, and solar were included, see Table 3. Hydrogen can also be produced from electricity from nuclear, hydro, wind, or CSP

[c] Thirteen different electricity production options were included, see Table 4

global long-term energy systems studies that have analyzed the competition of electricity, hydrogen, and biofuels in the transportation sector (Endo 2007; Turton and Barreto 2007; Gül et al. 2007) (Table 1).

Given the scale of the emission reduction challenge, the fact that the environmental impacts of fossil carbon emissions are independent of emission source and location, and the connections between energy sectors (e.g., biomass can be used to provide heat, electricity, or liquid transportation biofuels), a systems perspective is required when assessing potential options for the mitigation of greenhouse gas emissions. We believe that results from global energy models provide the necessary global systems perspective required to think through the complex questions related to supplying sustainable mobility. To facilitate future discussions regarding technology and policy options for providing sustainable mobility, the GET-RC 6.1 model was used to investigate the impact of $CO_2$ target, vehicle technology costs, and the availability of carbon capture and storage (CCS) and concentrating solar power (CSP) on the cost-effective vehicle and fuel technologies choices for sustainable mobility. CCS is included as an option to decarbonize fuels derived from fossil sources and biomass. In the present work, CSP is both an energy technology and a proxy for other inexpensive low-$CO_2$ electricity-generating technologies that may be developed in the future.

## 2 Model Description

The linear programming GET model constructed by Azar, Lindgren, and co-workers (Azar et al. 2000, 2003, 2006) covers the global energy system and is designed to meet exogenously given energy demand levels, subject to a $CO_2$ constraint, at the lowest system cost (all costs are in US$). A graphic depicting the main features in the model is shown in Fig. 3.

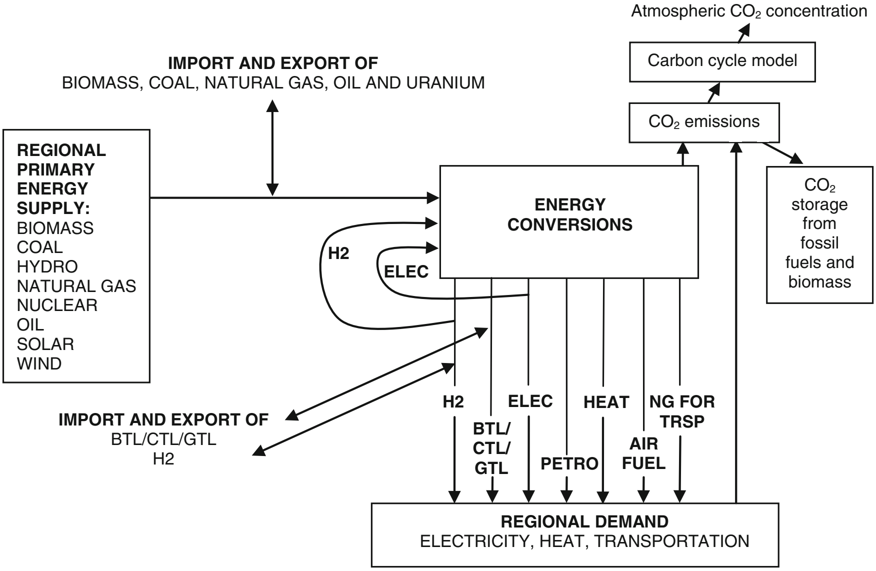


**Fig. 3** The basic flowchart of supply and fuel choices in GET-RC 6.1. Labels used: hydrogen ($H_2$), electricity (ELEC), low and high temperature heat for the residential, service, agricultural, and industrial sectors (HEAT), natural gas as transportation fuel (NG FOR TRSP), diesel and gasoline (PETRO), and synthetic fuels for aviation (AIR FUEL). Note that electricity and hydrogen can loop back to the energy conversions module allowing electricity to generate heat and allowing hydrogen to generate both electricity and/or heat

## *2.1 Model Structure*

The world is treated as 10 distinct regions with unimpeded movement of energy resources between regions (with the exception of electricity) with costs ascribed to such movement. Regional solutions were aggregated to give global results. The pattern of allowed global $CO_2$ emissions was constrained according to the emission profile leading to an atmospheric $CO_2$ concentration of 450 or 550 ppm, developed by Wigley and co-workers (Wigley 2010) (see Fig. 2). The model does not consider greenhouse gases other than $CO_2$. The model is run for the period 2000–2130 with 10-year time steps. We present and discuss the results for time period 2010–2100.

The description of the energy system in the model is a simplification of reality in at least five important respects: (i) consideration of limited number of technologies, (ii) assumption of price-inelastic demand, (iii) selections made only on the basis of cost, (iv) "perfect foresight" with no uncertainty of future costs, climate targets, or energy demand, and (v) no consideration of the importance of energy security, local air quality, or other benefits of new technologies. The model does not predict the future and is not designed to forecast the future development of the energy system. Nevertheless, the model is a useful tool to understand the system behavior and the interactions and connections between energy technology options in different sectors in a future carbon-constrained world.

### 2.2 Energy Demand

Energy demand is divided into three sectors: (i) electricity, (ii) transportation, and (iii) "heat" which comprises all stationary uses of energy except for those associated with generating electricity or transportation fuels. Emphasis was given to personal transportation in the present study. Regional energy demand in the model is derived by combining World Energy Council projections of global population (increasing to 10 billion in 2050 and 11.7 billion in 2100), and estimates of the development of per capita income (IIASA/WEC scenario C1), as well as assumptions regarding the activity demand (e.g., person-km, pkm, for personal transportation) associated with a given per capita income. For more details regarding the derivation of regional energy demand, see Azar et al. (2000).

### 2.3 Primary Energy Sources and Emission Factors

Biomass raw material cost was assumed to be $4/GJ in Europe and the Former Soviet Union, $3/GJ in North America, Australia, and Japan, and $2/GJ in all other areas (all costs in US$). We have chosen to follow the regional biomass supply potentials described in Johansson et al. (1993) adding up to a global potential of 205 EJ. This potential is similar to a recent OECD estimation of 245 EJ. Hoogwijk (2004) also presents a similar biomass supply potential. For four different scenarios and two biomass production cost levels (lower than $2/GJ and lower than $4/GJ), Hoogwijk (2004) estimates the global supply potential to lie in the range of 130–439 EJ/yr (with a mean value of 253 EJ/yr) by the year 2050.

The model includes global supply potentials of oil, gas, and coal of approximately 12000 EJ (2 trillion barrels), 11000 EJ (300 trillion $m^3$), and 265000 EJ (10 trillion tonnes hard coal), respectively. To account for reserve growth, the supply potentials for oil and natural gas are approximately twice the current estimates of economically recoverable, conventional reserves (BP 2008). The model assumes a regional distribution following Johansson et al. (1993). The $CO_2$ emission factors used are as follows: natural gas: 15.4, oil: 20.5, coal: 24.7 and biomass: 32 kgC/GJ of delivered fuel (Swedish EPA 2008). Future use of nuclear, hydro, wind, biomass, and solar energy is assumed to contribute negligible $CO_2$ emissions.

## 2.4 Cost Data

Data for vehicle technology as well as conversion plants and infrastructure (e.g., investment costs, conversion efficiencies, lifetimes, and capacity factors) are held constant at their “mature levels”, see Tables 2, 3 and 4. Technological change is exogenous in the GET model, i.e., the cost and performance of the technologies are independent of how much they are used. We assume mature technology costs throughout the time period considered. The model was tested to confirm that this assumption did not lead to an unduly rapid adoption of technologies. We further assume that all technologies are available in all regions. Global dissemination of technology is not seen as a limiting factor and thus is not included. All prices and costs are in real terms as future inflation is not considered. A global discount rate of 5 % per year was used for the net present value calculations. There are significant uncertainties inherent in estimating future technology costs and the cost assumptions will need to be revised as further information becomes available. Nevertheless, the model is a useful tool to understand the system behavior and the interactions and connections between energy technology options in different sectors in a future carbon-constrained world.

## 2.5 Constraints

Constraints on how rapidly changes can be made in the energy system have been added to the model to avoid solutions that are obviously unrealistic. This includes constraints on the maximum expansion rates of new technologies (in general, set so that it takes 50 years to change the entire energy system) as well as annual or total extraction limits on the different available energy sources.

The contribution of intermittent electricity sources (wind and solar photovoltaic) is limited to a maximum of 30 % of the electricity use. CSP is considered non-intermittent (Grahn et al. 2009a, b). To simulate the actual situation in developing countries, a minimum of 30 EJ per year of the heat demand is required from biomass during the first decades. For CCS, we assumed a storage capacity of 600 GtC (IPCC 2005), a maximum rate of increase of CCS of 100 MtC/year, and negligible leakage of stored $CO_2$. The future role of nuclear energy is primarily a political decision and will depend on several issues such as safety, waste disposal, questions of nuclear weapons proliferation, and public acceptance. We assume that the contribution of nuclear power does not exceed current levels.

## 2.6 Personal Transportation

Electricity and hydrogen are energy carriers; for simplicity we include these as "fuels". Gasoline and diesel fuels are not differentiated and are collectively described as petroleum (petro). Five fuel options: petro, natural gas (NG), synthetic fuels (coal to liquid, CTL; gas to liquid, GTL; biomass to liquid, BTL), electricity, and hydrogen ($H_2$) and five vehicle technologies: internal-combustion engine vehicles (ICEVs), hybrid-electric vehicles (HEVs), plug-in hybrid-electric vehicles (PHEVs), battery-electric vehicles (BEVs), and fuel cell vehicles (FCVs) were considered.

The relative efficiency values used in the model are given in Table 2 and were derived from published studies as discussed elsewhere (Grahn et al. 2009b; Wallington et al. 2010). For consistency and simplicity we assume the relative efficiency of PHEVs when powered by electricity is the same as BEVs. An all-electric battery range of 65 km was adopted for PHEVs which enables approximately two-thirds of their daily driving distance to be powered by electricity from the grid on a single overnight charge. HEVs have a relatively short all-electric range (we assume 2 km). The all-electric range was set to 200 km for BEVs. Results from cases in which a range of 100 km was assumed for BEVs are presented elsewhere (Grahn et al. 2010). Powertrain types and efficiencies for freight trucks were updated to be consistent with those assumed in the car sector.

Table 2 provides the incremental cost data relative to internal-combustion engine vehicles powered by petroleum (Petro ICEV) for vehicle technologies used in the model (Grahn et al. 2009b; Wallington et al. 2010). These incremental costs are estimated for the technologies in their "mature" state. Fuel storage is a significant component of vehicle cost for vehicles running on natural gas, hydrogen, and batteries. As vehicle-fuel consumption is assumed to steadily decline over the study period for all vehicle types, energy storage requirements for the assumed 500-km range would also decline proportionally. To estimate vehicle costs in GET-RC 6.1, we assume energy storage costs consistent with fuel consumption for each vehicle type in the year 2050, assuming a globally averaged vehicle size.

The data in Table 2 are based on literature estimates of potential mature technology costs which we equate to costs in 2030–2050 (Grahn et al. 2009b; Wallington et al. 2010). It is unclear whether these costs will be realized in the future. The technology costs were assumed to remain constant during the entire time period modeled. While it is clearly not appropriate to use mature costs for advanced technology during the beginning of the time period, this assumption did not compromise the study because advanced technologies are not initially required to meet the $CO_2$ constraints, and so were not selected by the model in the beginning of the time period. The base passenger vehicle with a conventional, internal-combustion engine powered by petroleum is set to $20,000. The incremental cost for a comparable vehicle powered instead by synthetic fuel (e.g., biofuel) is set to $100 for component modifications required to make the vehicle compatible with such fuels. For consistency the incremental costs for other

**Table 2** Passenger vehicle energy use and cost data in the model

| Fuel-engine technology[a] | Vehicle energy efficiency ratio (HHV)[b] | | Vehicle cost ($) | |
|---|---|---|---|---|
| | Year 2000 | Year 2100 | Base | Increment |
| Petro ICEV | 1.0[c] | 1.0[c] | 20,000 | – |
| Synth ICEV | 1.0 | 1.0 | | 100 |
| NG ICEV | 1.0 | 1.0 | | 1600 |
| $H_2$ ICEV | 1.15 | 1.15 | | 1500–3600 |
| HEV | 1.3 | 1.3 | | 1300–1900[e] |
| BEV | 3.75 | 2.85 | | 7900–23300[e,f] |
| PHEV[d] | 2.46 | 2.17 | | 3000–8000[e] |
| Petro FCV | 1.2 | 1.2 | | 4200–4800[e] |
| Synth FCV | 1.3 | 1.3 | | 4200–4800[e] |
| $H_2$ FCV | 1.8 | 1.8 | | 3900–5500[e] |

[a] Petro ICEV, Synth ICEV, NG ICEV, $H_2$ ICEV Internal-combustion engine vehicle fueled either by petroleum, synthetic fuel (CTL, GTL, or BTL), natural gas, or gaseous hydrogen, HEV Hybrid-electric vehicle, BEV Battery-electric vehicle, PHEV Plug-in hybrid-electric vehicle, Petro FCV, Synth FCV, $H_2$ FCV Fuel-cell vehicle fueled either by petroleum, synthetic fuel, or gaseous hydrogen

[b] Tank-to-wheels energy (higher heating value [HHV] basis) used by Petro ICEV divided by that for alternative technology (Grahn et al. 2009b; Wallington et al. 2010)

[c] By definition. Note that the absolute value of energy consumption (MJ/km) by Petro-ICEVs in 2100 is a factor of 2 less than that in 2000

[d] Efficiency shown assumes two-thirds of total distance traveled is powered via grid electricity. Synth HEV and Synth PHEV also included in the model with efficiencies same as petroleum HEV and PHEV and with $100 additional incremental cost

[e] Battery cost of $150–450/kWh, fuel cell stack cost of $65/kW, hydrogen storage cost of $1500–3500/GJ, natural gas storage cost of $1300/GJ assumed, (Grahn et al. 2009b; Wallington et al. 2010)

[f] BEV cost based on 200-km driving range compared to 500-km range for the other technologies

synthetic-fuel vehicles were increased by $100 relative to the comparable petroleum-powered vehicle (TIAX 2007). Uyterlinde et al. (2007) have recently provided incremental cost estimates of 2000 Euros for NG-ICEVs and 1800 Euros for Petro-HEVs in 2040, comparable to our estimates. Costs for alternative powertrain and alternative fuel technology in freight trucks were updated to be consistent with those assumed in the car sector.

## 3 Results

The GET-RC 6.1 model has been used to investigate cost-effective fuel and vehicle technology options for passenger vehicles consistent with stabilization of atmospheric $CO_2$ levels at 450 or 550 ppm, with and without CCS and CSP, with vehicle costs varied over the ranges given in Table 2 (Grahn et al. 2009b; Wallington et al. 2010). Results from runs using five cases for vehicle technology costs are presented here illustrating the impact of battery and hydrogen storage costs. The impacts of natural gas storage and fuel cell stack cost have been described by Grahn et al. (2009b). (All cases here assume a NG–ICEV storage cost of $1300/GJ and a fuel cell stack cost of $65/kW)

The cost values for the five cases are given in Table 5. Case #1 assumes a battery cost of $300/kWh and a hydrogen storage cost of $3500/GJ. Cases #2, #3 and #4 have the same hydrogen storage cost ($1500/GJ) but different battery costs ($450, $300, and $150/kWh for cases #2, #3, and #4, respectively). Comparison of the results from cases #2, #3, and #4 sheds light on the impact of battery cost. Cases #1, #5, and #3 have the same battery cost ($300/kWh) but different hydrogen storage costs ($3500, $2500, and $1500/GJ for cases #1, #5, and #3, respectively). Comparison of the results from cases #1, #5, and #3 sheds light on the impact of hydrogen storage cost. The incremental costs are estimated for the technologies in their "mature" state. Fuel storage is a significant component of vehicle cost for vehicles running on natural gas, hydrogen, and batteries. As vehicle-fuel consumption is assumed to steadily decline over the study period for all vehicle types, energy storage requirements for the assumed 500-km range also decline proportionally. Energy storage costs are based on fuel consumption for each vehicle type in the year 2050, assuming a globally averaged vehicle size (consistent with 2.45 MJ/km for Petro ICEVs). It should be stressed that the data in Table 5 are based on literature estimates of potential mature technology costs which are equated to costs in the year 2050. It is unclear whether these costs will be realized in the future. The technology costs were assumed constant during the entire time period. While it is clearly not appropriate to use mature costs for advanced technology during the beginning of the time period, this assumption did not compromise the study because advanced technologies are not required to meet the $CO_2$ constraints, and so were not selected by the model.

As described in Sect. 2, the GET-RC 6.1 model includes energy use in all sectors and in all regions. It is impractical to present the results for energy use in all sectors from the different cases. Our focus is on understanding the system dynamics which may influence the choice of light-duty vehicle and fuel technologies in a future carbon-constrained world. Hence, we will present the light-duty vehicle choices and the global primary energy supply results. However, we note that in addition to the results that we will present below, the model is optimizing (for lowest global system cost) the choice of technologies used in all other transportation modes (air, land, rail, sea) for both passengers and freight (selecting from the fuel options listed in Table 3), in electricity production (selecting from the primary energy sources listed in Table 4), and heat generation (again selecting from the different available primary energy sources).

The results from the different model runs are presented in Figs. 4, 5, 6 and 7. The results shown are the lowest-cost solution to satisfy a given $CO_2$ stabilization target given certain technology costs and availabilities as outlined in Table 5 and in the text below. The left-hand panels in Figs. 4, 5, 6 and 7 show the global light-duty vehicle fleet over the time period 2010–2100. As discussed above the demand for transportation by light-duty vehicles is assumed to be inelastic and hence the

**Table 3** Cost and $CO_2$ data for transportation fuels (see Table S3 in Grahn et al. (2009b) for details)

| Primary energy | Secondary energy | $CO_2$ emission kgC/GJ$_{fuel}$ | Total fuel cost \$/GJ$_{fuel}$ |
|---|---|---|---|
| Oil | Petro | 22.78 | 9.73 |
| NG | NG | 15.40 | 8.90 |
| Biomass | BTL | 0.00 | 11.69 |
| NG | GTL | 22.00 | 9.97 |
| Coal | CTL | 41.17 | 10.02 |
| Biomass | $H_2$ | 0.00 | 15.92 |
| NG | $H_2$ | 19.25 | 12.76 |
| Coal | $H_2$ | 38.00 | 13.53 |
| Oil | $H_2$ | 27.33 | 14.22 |
| Solar | $H_2$ | 0.00 | 31.04 |
| Bio-CCS | $H_2$ | −52.36 | 21.73 |
| NG-CCS | $H_2$ | 2.05 | 14.83 |
| Coal-CCS | $H_2$ | 4.12 | 16.21 |
| Oil-CCS | $H_2$ | 2.93 | 16.71 |

**Table 4** Cost and $CO_2$ data for electricity options (see Table S4 in Grahn et al. (2009b) for details)

| Primary energy | $CO_2$-emissionkgC/GJe | Total electricity prod cost \$/GJe |
|---|---|---|
| Biomass | 0.00 | 10.39 |
| Natural gas | 28.00 | 7.21 |
| Coal | 49.40 | 7.86 |
| Oil | 41.00 | 9.19 |
| Solar | 0.00 | 13.91 |
| Hydro | 0.00 | 4.92 |
| Wind | 0.00 | 6.95 |
| Nuclear | 0.00 | 13.68 |
| CSP | 0.00 | 14.42 |
| Bio-CCS | −96.00 | 23.23 |
| NG-CCS | 3.42 | 11.49 |
| Coal-CCS | 7.06 | 13.19 |
| Oil-CCS | 5.13 | 14.53 |

total vehicle fleet is the same in each of the cases investigated. The different colored segments of the light-duty vehicle fleet show the global contribution from the different vehicle-fuel technologies. The right-hand panels in Figs. 4, 5, 6 and 7 show the total global primary energy used over the time period 2010–2100. While the demand for transportation, electricity, and heat is inelastic, the energy conversion pathways (with their differing associated energy efficiencies) to provide these services vary from case to case. Hence, the total global primary energy used varies from case to case. As an example, consider the top four panels (a–d) in Fig. 4. The top panels (Fig. 4a, b) show the lowest-cost solution to providing the global demands for transportation, electricity, and heat without a $CO_2$ constraint.

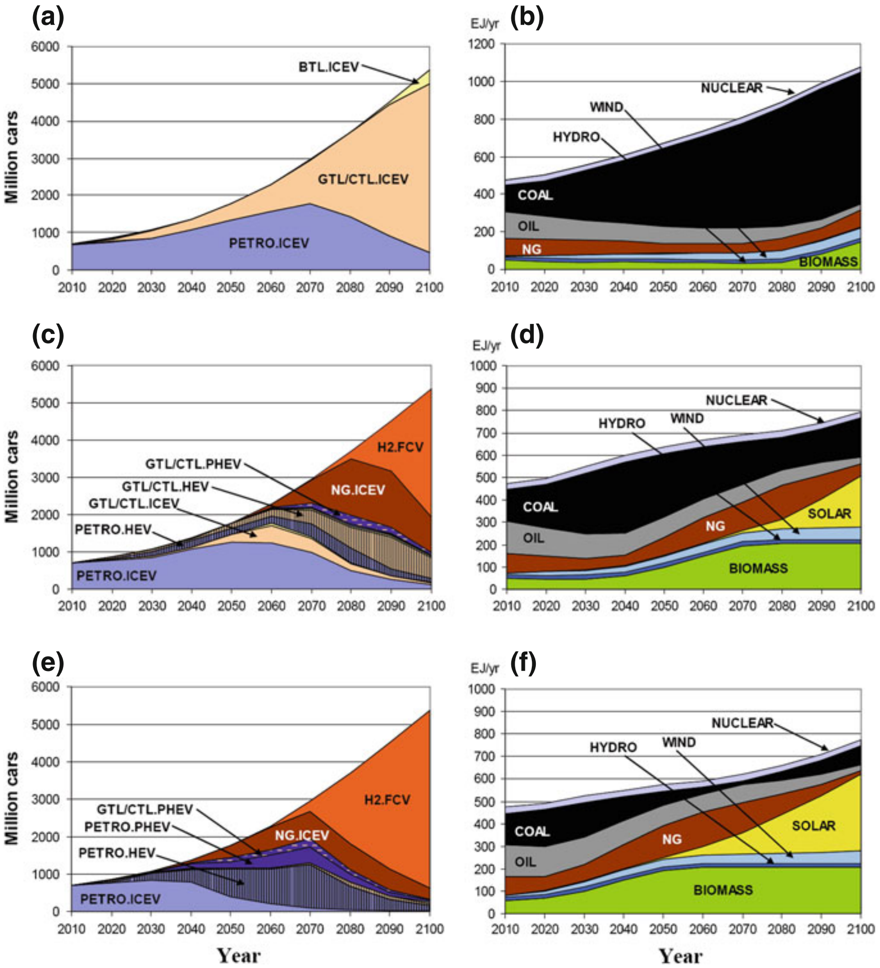


**Fig. 4** Global light-duty passenger vehicle fleet (millions) and primary energy supply for vehicle technology cost case #1 and consistent for scenarios without a $CO_2$ constraint (*top panels*), with $CO_2$ stabilization at 550 ppm (*middle panels*) and with $CO_2$ stabilization at 450 ppm (*bottom panels*). See text for further details. Neither CCS or CSP were available in these scenarios. **a** Passenger vehicle fleet, No $CO_2$ constraint. **b** Primary energy supply, No $CO_2$ constraint. **c** Passenger vehicle fleet, 550 ppm. **d** Primary energy supply, 550 ppm. **e** Passenger vehicle fleet, 450 ppm. **f** Primary energy supply, 450 ppm

The middle two panels (Fig. 4c, d) show the lowest-cost solution with a 550 ppm $CO_2$ constraint. In the absence of any $CO_2$ constraint the model selects to use large amounts of coal because it is inexpensive, even after considering its comparatively low energy efficiency compared to other energy sources. Hence, the total primary energy used is higher in the case without a $CO_2$ constraint (Fig. 4b) than in the case with a $CO_2$ constraint (Fig. 4d).

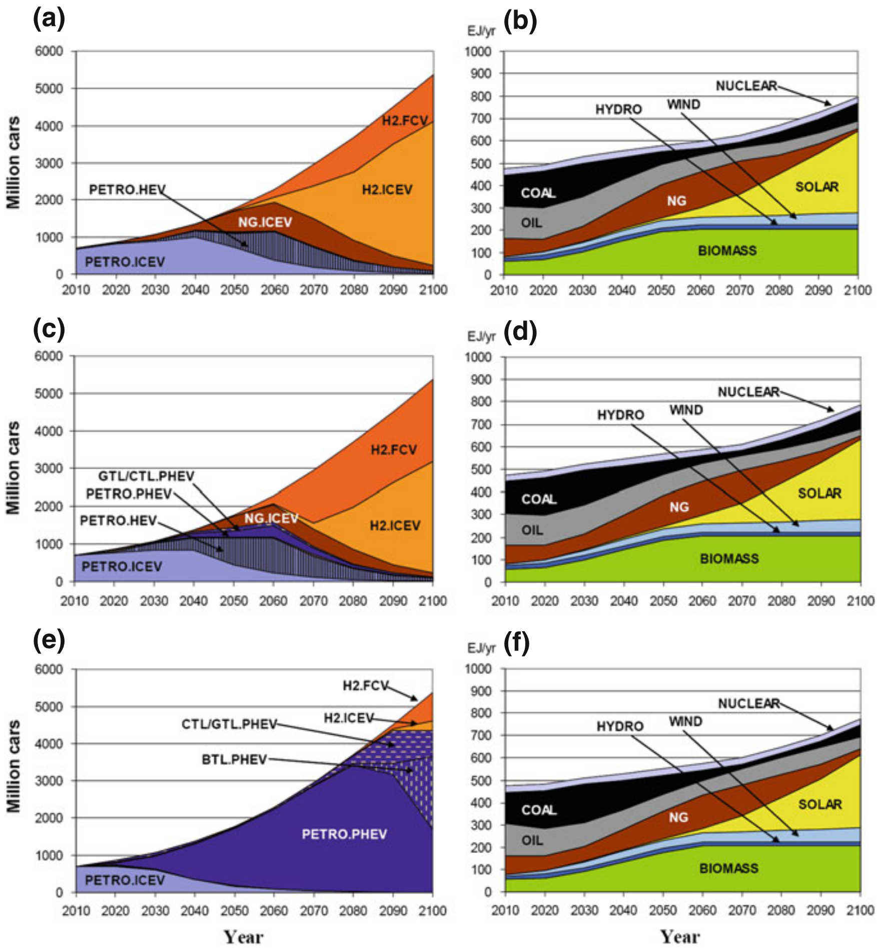


**Fig. 5** Global light-duty passenger vehicle fleet (millions) and primary energy supply for vehicle technology cost cases #2, #3, and #4 consistent with $CO_2$ stabilization at 450 ppm for cases in which the battery cost was assumed to be either \$450/kWh (*top two panels*), \$300/kWh (*middle two panels*), or \$150/kWh (*bottom panels*), respectively. See text for further details. Neither CCS or CSP were available in these scenarios. **a** Passenger vehicle fleet, battery cost: \$450/kWh. **b** Primary energy supply, battery cost: \$450/kWh. **c** Passenger vehicle fleet, battery cost: \$300/kWh. **d** Primary energy supply, battery cost: \$300/kWh. **e** Passenger vehicle fleet, battery cost: \$150/kWh. **f** Primary energy supply, battery cost: \$150/kWh

Finally, we reiterate the caveats listed in Sect. 2.1. The model is not designed to forecast the future development of the global energy system. The results are not predictions of the future light-duty vehicle fleet. However, we believe that the results described below provide useful insights into the system dynamics which are likely to be present in a future carbon-constrained world and which need to be considered in planning for sustainable mobility.

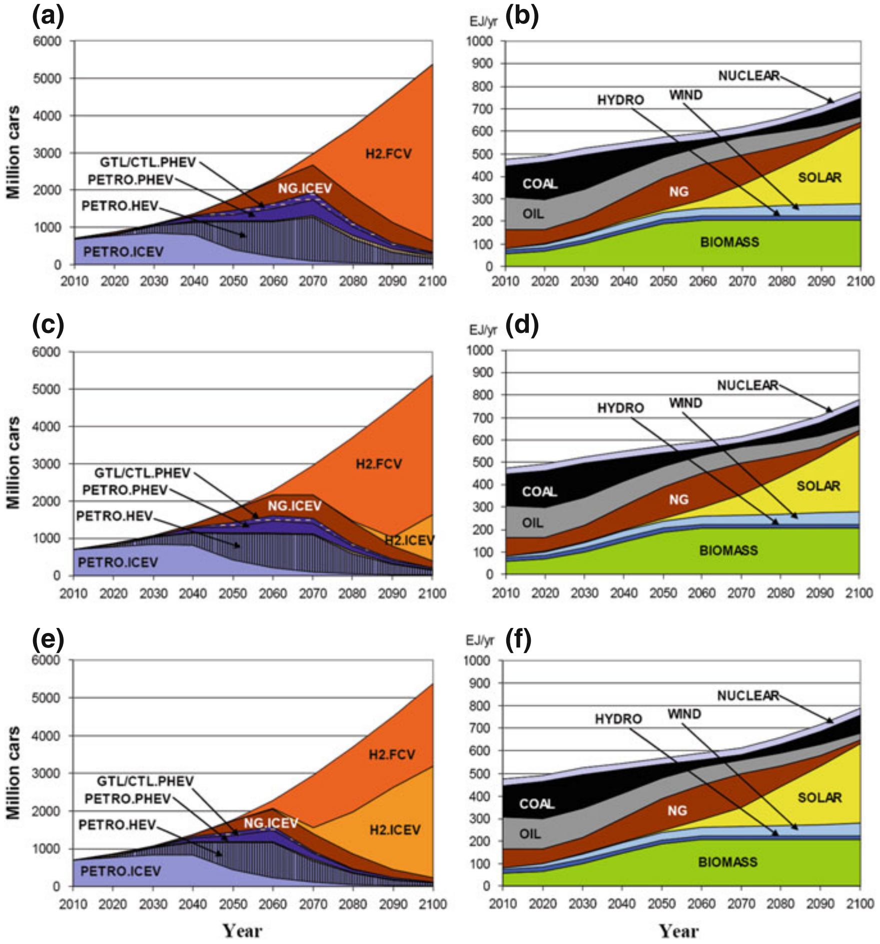


**Fig. 6** Global light-duty passenger vehicle fleet (millions) and primary energy supply for vehicle technology cost cases #1, #5, and #3, consistent with $CO_2$ stabilization at 450 ppm for cases in which the hydrogen storage cost was assumed to be either \$3500/GJ (*top two panels*), \$2500/GJ (*middle two panels*), or \$1500/GJ (*bottom panels*), respectively. See text for further details. Neither CCS or CSP were available in these scenarios. **a** Passenger vehicle fleet, $H_2$ storage cost: \$3500/GJ. **b** Primary energy supply, $H_2$ storage cost: \$3500/GJ. **c** Passenger vehicle fleet, $H_2$ storage cost: \$2500/GJ. **d** Primary energy supply, $H_2$ storage cost: \$2500/GJ. **e** Passenger vehicle fleet, $H_2$ storage cost: \$1500/GJ. **f** Primary energy supply, $H_2$ storage cost: \$1500/GJ

## *3.1 $CO_2$ Targets*

Figure 4 illustrates the impact of $CO_2$ constraints on the lowest-cost light-duty vehicle and fuel technologies and primary energy sources. CCS and CSP are not available in these runs. The top two panels show the lowest-cost solution when no $CO_2$ constraint is applied. As seen from the top left-hand panel in Fig. 4, light-duty

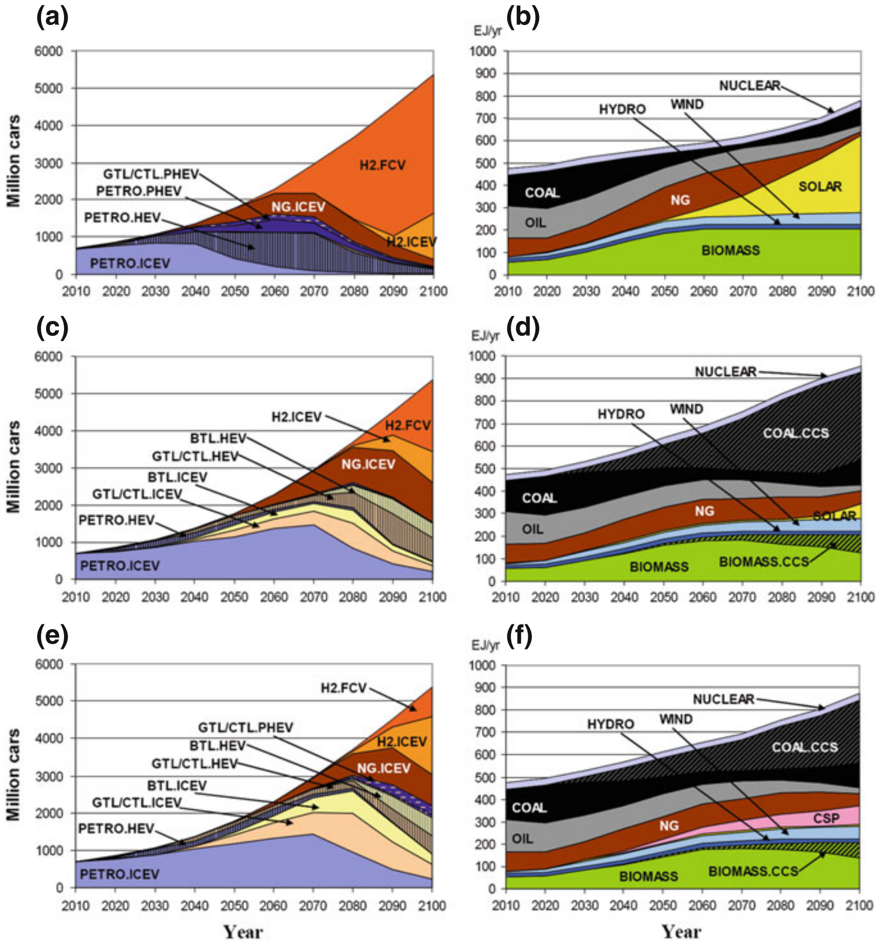


**Fig. 7** Global light-duty passenger vehicle fleet (millions) and primary energy supply for case #1 vehicle technology costs and consistent with $CO_2$ stabilization at 450 ppm for cases in which neither carbon capture and storage nor concentrating solar power is available (*top panels*), where carbon capture and storage is available (*middle panels*), and where both carbon capture and storage and concentrating solar power are available (*bottom two panels*). **a** Passenger vehicle fleet, CCS not available, CSP not available. **b** Primary energy supply, CCS not available, CSP not available. **c** Passenger vehicle fleet, CCS available, CSP not available. **d** Primary energy supply, CCS available, CSP not available. **e** Passenger vehicle fleet, CCS available, CSP available. **f** Primary energy supply, CCS available, CSP available

vehicles are run largely on petroleum until about 2070 when the use of petroleum declines giving way to CTL fuel. In the absence of a $CO_2$ constraint the lowest-cost solution to providing the demanded mobility is to use conventional ICEVs powered by petroleum then CTL. Interestingly, the small yellow sliver in Fig. 4 which appears at 2080–2100 reflects the use of biofuel which, following the

**Table 5** Cases for incremental costs of different passenger vehicle technology and fuel options relative to conventional petroleum internal-combustion engine technology explored in current work

| | Case #1 | Case #2 | Case #3 | Case #4 | Case #5 |
|---|---|---|---|---|---|
| $H_2$ storage ($/GJ) | **3500** | 1500 | 1500 | 1500 | **2500** |
| Battery ($/kWh) | 300 | **450** | **300** | **150** | 300 |
| *Vehicle Technology* | | | | | |
| Petro ICEV | 0 | 0 | 0 | 0 | 0 |
| Synth ICEV | 100 | 100 | 100 | 100 | 100 |
| NG ICEV | 1600 | 1600 | 1600 | 1600 | 1600 |
| $H_2$ ICEV | 3600 | 1500 | 1500 | 1500 | 2600 |
| Petro HEV | 1600 | 1900 | 1600 | 1300 | 1600 |
| Synth HEV | 1700 | 2000 | 1700 | 1400 | 1700 |
| BEV | 15600 | 23300 | 15600 | 7900 | 15600 |
| Petro PHEV | 5500 | 8000 | 5500 | 3000 | 5500 |
| Synth PHEV | 5600 | 8100 | 5600 | 3100 | 5600 |
| Petro FCV | 4500 | 4800 | 4500 | 4200 | 4500 |
| Synth FCV | 4500 | 4800 | 4500 | 4200 | 4500 |
| $H_2$ FCV | 5500 | 4500 | 4200 | 3900 | 4900 |

depletion of oil and natural gas, becomes the most cost-effective option in parts of the world where coal availability is limited (e.g., Latin America).

The middle two panels in Fig. 4 show the result when a 550 ppm $CO_2$ constraint is imposed. The bottom two panels show the result for a 450 ppm constraint. As the severity of the $CO_2$ constraint is increased, actions to replace conventional petroleum ICEVs are required earlier. For example, moving from a $CO_2$ stabilization target of 550 ppm to 450 ppm brings forward by approximately 20–30 years the time when advanced vehicles and alternative fuels are introduced in large scale.

Our finding that petroleum-fueled ICEV technology dominates for at least the 2010–2050 period for a 550 ppm stabilization target (see middle panels in Fig. 4) is in agreement with results from Turton and Barreto (2007). Takeshita and Yamaji (2008) ran a linear cost-minimizing energy model with a $CO_2$ stabilization target of 550 ppm by the year 2100 and with a business as usual scenario. For the 550 ppm scenario, they reported substantial (approximately 25 % in 2100) use of BTL technology, while CTL/GTL was dominant for business as usual in 2100. These results are consistent with our findings. Gül et al. (2007) used a MARKAL-based energy systems model to analyze competing energy carriers for Western Europe’s transportation sector. In their $CO_2$ reduction scenario (reduction from 1990 of 50 % by 2050 and 75 % by 2100), the car sector is dominated by gasoline/diesel (first in ICEVs, then HEVs, and to a small extent also PHEVs) with hydrogen-fueled FCVs becoming dominant by 2100. These are consistent with our findings (see Fig. 4) in which petroleum-fueled ICEVs dominate initially and are replaced first by HEVs/PHEVs and then by hydrogen-fueled vehicles (ICEVs or FCVs). Finally, reflecting the efficiency of hydrogen-fueled ICEVs, the results showing hydrogen use at the end of the century in almost all scenarios and gasoline/diesel dominating the passenger vehicle sector for the first half of the century are consistent with previous results from our group (Azar et al. 2000, 2003; Grahn et al. 2009a).

### 3.2 Vehicle Technology Costs

The impact of assumptions regarding future vehicle technology costs is illustrated in Fig. 5 and 6. The sensitivity to variation of battery costs is shown in Fig. 5. The top panels in Fig. 5 show the results obtained using vehicle technology case #2 with a battery cost assumption of $450/kWh. The middle and bottom two panels show results obtained with battery cost assumptions of $300 and $150/kWh (cases #3 and #4, see Table 5). With decreased battery price, and hence decreased vehicle cost, PHEVs become more attractive. With a battery cost of $450/kWh, PHEVs do not contribute to the lowest-cost result. The bottom panels in Fig. 5 show that PHEVs become a cost-effective solution for battery costs at the low end of the range investigated ($150/kWh). Even at the lowest battery cost, BEVs were not found to be a cost-competitive, large-scale technology, even though BEVs were allowed to compete with reduced functionality (200 km driving range instead of 500 km for all other vehicles). However, BEVs do become part of the lowest-cost solution when a 100 km driving range is assumed (Grahn et al. 2010). Finally, in contrast to the impact of $CO_2$ constraint on primary energy use illustrated in Fig. 4, the vehicle battery cost has a very modest impact on the global primary energy supply (discernable if one examines the magnitude of total energy supply used in the three cases in Fig. 5 for the year 2100). This reflects two factors. First, vehicles are only part of the total energy demand. Second, the battery cost impacts the competition between electric- and hydrogen-powered vehicles, and these vehicles have comparable energy efficiency (see Table 2). The slight advantage of PHEVs is reflected in the slightly decreased global energy demand in Fig. 5.

The sensitivity to hydrogen storage costs is shown in Fig. 6. The top, middle, and bottom panels in Fig. 6 show results from runs with hydrogen storage costs of $3500, $2500, and $1500/GJ, respectively. The corresponding vehicle costs are given in Table 5 (cases #1, #5, and #3). Decreasing the hydrogen storage cost favors hydrogen-powered vehicles. $H_2$ ICEVs are less efficient than $H_2$ FCVs (see Table 2) and hence $H_2$ ICEVs need to carry more hydrogen fuel on board than do $H_2$ FCVs to meet the 500-km range requirement (see Sect. 3.2). As the costs for hydrogen storage are decreased the $H_2$ ICEVs become more competitive relative to $H_2$ FCVs. Lower hydrogen storage costs favor $H_2$ ICEVs more than $H_2$ FCVs and so $H_2$ ICEVs become a larger fraction of the hydrogen-powered vehicles (in fact, as seen from the top panels in Fig. 6, $H_2$ ICEVs do not contribute in the $3500/GJ hydrogen storage case).

## *3.3 Impact of CCS and CSP Availability*

The availability of CCS and CSP can have a profound influence on the lowest-cost passenger vehicle fuel and technology choice in a carbon-constrained world. For example, for the vehicle cost case #5 without CCS or CSP (top two panels in Fig. 7), personal transportation changes from petroleum-fueled ICEVs to a combination of mostly HEVs and PHEVs fueled by petroleum and some ICEVs fueled by natural gas. Approaching 2100, these vehicles are replaced by FCVs and ICEVs fueled by hydrogen (produced via solar energy).

The availability of CCS (compare middle two panels with top panels in Fig. 7) extends the use of conventional petroleum-fueled ICEVs by a few decades, results in the use of more ICEVs and HEVs fueled by biofuels and CTL/GTL, and delays the introduction of hydrogen (produced from coal with CCS). The system dynamic at work is that CCS provides relatively inexpensive low-$CO_2$ electricity and heat from coal which prolongs the use of traditional ICEVs. The availability of CCS leads to coal displacing biomass (biomass is a limited resource with a higher demand than supply in the model) in the heat sector which allows increased production of transportation fuel from biomass (when CCS is not available, biomass is used mostly to provide heat). While CCS enables the production of much cheaper hydrogen (from coal instead of solar), the overall importance of hydrogen decreases reflecting the fact that CCS enables non-transport sectors to realize more emission reductions at a lower cost than in the transport sector.

When CSP is also made available (see bottom two panels in Fig. 7), a substantial amount of CSP-generated electricity (see bottom right-hand panel in Fig. 7) is used in the global energy system (although not in transportation) which displaces the small amount of solar-hydrogen in the middle right-hand panel in Fig. 7. This makes biomass, which would otherwise go to the stationary sectors, available for conversion into biofuel for vehicles which ultimately displaces hydrogen (see increased light yellow biofuel [BTL] and decreased orange hydrogen sections in bottom left hand compared to middle left-hand panel in Fig. 7).

## *3.4 Fossil Fuel Reserve Depletion*

It is assumed in the model that in the year 2000 there are global supply potentials of approximately 2 trillion barrels of oil, 300 trillion $m^3$ of natural gas, and 10 trillion tonnes of hard coal. The maximum global biomass supply potential was 200 EJ/year and is reached at 2050–2060. The supply potentials for oil and natural gas are approximately twice the current estimates of economically recoverable, conventional reserves (BP 2008). Interestingly, in all of the cases considered here, the supply potentials of oil and natural gas are more than 90 % depleted by 2100, whereas coal is only 5–10 % depleted. Figure 8 shows the accumulated use

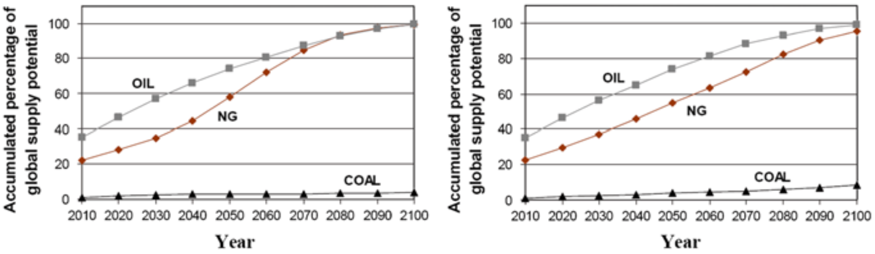


**Fig. 8** Cumulative % use of supply potentials for oil, NG, and coal in scenarios with 450 ppm $CO_2$ stabilization constraint, case #1 vehicle technology costs, without CCS or CSP available (*left panel*) or with CCS and CSP available (*right panel*)

(expressed as percentage of initial supply potential) for scenarios run with a 450 ppm $CO_2$ stabilization target with vehicle technology costs from case #1 (see Table 5). The left panel shows the results obtained when both CCS and CSP are unavailable. The right panel shows the results obtained when CCS and CSP are both available.

The striking point to note from Fig. 8 is that irrespective of whether CCS and CSP are available and even for the demanding 450 ppm target, more than 90 % of the oil and natural gas supply potential is used. The absence of CCS and CSP technology makes the attainment of $CO_2$ goal challenging but, even in this case, essentially all the oil and natural gas is used. When CCS is available, more coal is used (see bottom panel in Fig. 8). Given the fact that most of the oil and natural gas is consumed by the end of the century, the emergence of alternative fuels is a necessary response even in the absence of $CO_2$ constraints.

## 4 Conclusions

We draw three main conclusions from this work.

First, there is no “silver bullet” vehicle or fuel technology. We have varied the costs of future vehicle technology over ranges that we believe to be reasonable (taken from government and industry research and development targets) and find large differences in the resulting lowest-cost solutions (Grahn et al. 2009b). For instance, for low battery costs ($150/kWh) electrified powertrains dominate and for higher battery costs ($450/kWh) hydrogen-fueled vehicles dominate. Given the current uncertainties in future costs and efficiencies for light-duty vehicle and fuel technologies, there is no clear fuel or vehicle technology winner that can be discerned. As shown in the plots in Figs. 4, 5, 6 and 7, in many cases over long periods of time no single vehicle technology is found to dominate on a global scale. In the past, ICEVs have effectively dominated vehicle technology. In the future perhaps several technologies will coexist (e.g., PHEVs may coexist with ICEVs and/or $H_2$_FCVs).

Second, a multi-sector perspective is needed when addressing greenhouse gas emissions. Connections between transportation and other energy sectors are likely to become far more important in the future. We have shown how CCS and CSP, technological options that have the potential to significantly reduce $CO_2$ emissions associated with electricity and heat generation, may affect cost-effective fuel and vehicle technologies for transport. We find that the availability of CCS and CSP has substantial impacts on the fuel and technology options for passenger vehicles in meeting global $CO_2$ emission target of 450 ppm at lowest system cost (see Fig. 7). By providing relatively low-cost approaches to reducing $CO_2$ emissions associated with electricity and heat generation, CCS effectively reduces the necessary $CO_2$ "task" for the transportation sector, extends the time span of conventional petroleum-fueled ICEVs, enables the use of liquid biofuels as well as GTL/CTL for transportation, and delays the introduction of the more expensive efficient technologies.

Third, oil and natural gas supply potentials were used almost completely in all scenarios (even for a 450 ppm $CO_2$ target). Oil and gas are cost-competitive fuel choices and conventional resources are likely to be largely consumed by 2100. Alternative fuels are needed in response to the expected dwindling oil and natural gas supply potential by the end of the century.

These findings have several policy and research implications. From a policy perspective, the findings highlight the need to recognize and account for the interaction between sectors in policy development. From a research perspective, the findings illustrate the importance of pursuing the research and development of multiple fuel and vehicle technology pathways to achieve the desired result of affordable and sustainable personal mobility.

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# Life-Cycle Analysis of Biofuels and Electricity for Transportation Use

**Michael Wang and Amgad Elgowainy**

**Abstract** As the global population and economy continue to grow, demand for energy will continue to grow. The transportation sector has been relying solely on petroleum, consuming more than 50 % of the global world oil production. The United States is the top oil-importer country. Two major issues facing the transportation sector in the U.S. and other major countries are energy security and environmental sustainability. Improvements in the energy efficiency of vehicles and the substitution of petroleum fuels with alternative fuels can help slow the growth in the demand for petroleum oil and mitigate the increase in greenhouse gas emissions. Biofuels and electricity are being promoted for their potential reduction of petroleum use and greenhouse gas emissions. This chapter examines the potential reduction of life-cycle energy use and greenhouse gas emissions associated with the use of biofuels in internal combustion engine vehicles and electricity in plug-in hybrid electric vehicles and battery-powered electric vehicles.

**Keywords** Alternative energy · Bio-fuels · LCA · Reducing fossil-fuel consumption · Sustainable energy solutions

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## 1 Introduction

In 1990, the world consumed 366 × $10^9$ GJ of energy; this total consumption was increased by 36 % to 499 × $10^9$ GJ in 2006. As the world economy and population continue to grow, total world energy use is projected to increase to 716 × $10^9$ GJ by 2030, a 44 % increase over 2006 consumption (Energy Information Administration 2009). Figure 1 shows the contribution of different types of primary energy to the total world energy consumption. Of the five primary types of energy, oil accounts for the largest share, coal the next largest, and natural gas the third largest. In 1990, worldwide, oil accounted for 39 % of total world energy use, coal for 26 %, and natural gas for 22 %. In 2030, the shares are projected to be 32, 28, and 23 % for oil, coal, and natural gas, respectively. The transportation sector is the largest oil-consuming sector worldwide. In 2005, the transportation sector consumed 52 % of total world oil production. In 2030, the transportation sector is projected to consume 58 % of that total. In the United States, the transportation sector already accounts for approximately two-thirds of its oil consumption. In

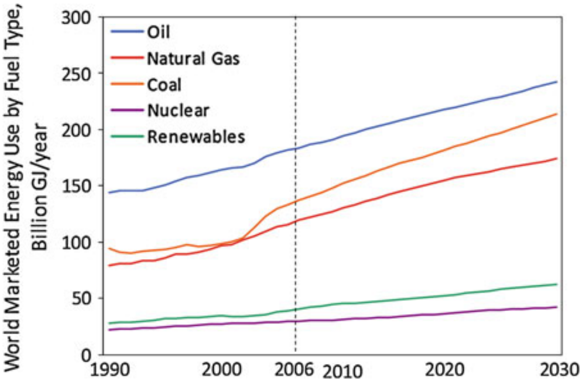


**Fig. 1** Shares of primary energy types to the total world energy consumption (Energy Information Administration 2009)

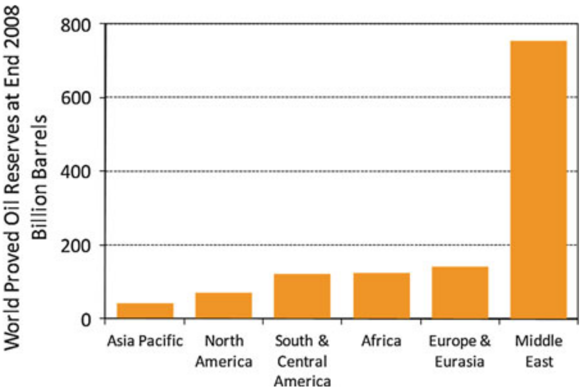


**Fig. 2** Geographic distribution of world proved oil reserve (British Petroleum 2009)

addition, the transportation sector relies solely on oil (over 95 % of transportation energy is from oil). The transportation sector is the major contributor to the fast growth of worldwide demand for oil. It is debated if, and when, the world will run out of oil. However, the geographic distribution of oil resources and oil demand are undoubtedly unbalanced. Figure 2 shows the geographic distribution of the proved world oil reserve as of the end of 2007 (British Petroleum 2009). This oil reserve distribution results in concentrated oil production in a few regions. In 2005, total world oil production was 82 million barrels a day (MM b/d). In 2030, oil production is projected to be 103 MM b/d (Energy Information Administration 2009). Of the total production, the 13 members of the Organization of the Petroleum Exporting Countries (OPEC) produced 35.3 MM b/d in 2005 and are projected to produce 47.7 MM b/d in 2030. Other non-OPEC countries (including Russia, Latin American countries, non-OPEC African countries, and Caspian area countries) produced 18 MM b/d in 2005 and may produce 31.3 MM b/d in 2030. These countries together produced 53.3 MM b/d in 2005 and will produce 79 MM b/d in 2030, accounting for 65 % and 77 % of total production in 2005 and 2030, respectively. Figure 3 shows the geographic distribution of world oil consumption in 2005 alongside 2030 (Energy Information Administration 2009). The geographic mismatch between oil production and oil consumption has prompted major oil-consuming countries to pursue policies of achieving energy independence by reducing the amount of oil imported, especially when oil prices rose to 140 US dollars a barrel in the summer of 2007.

Global greenhouse gas (GHG) emissions have grown from 28.7 gigatonnes (Gt) of $CO_2$ equivalents ($CO_2$-eq) in 1970 to 49 Gt in 2004, a 70 % increase in 34 years (Intergovernmental Panel on Climate Change 2007). With a business-as-usual scenario, the Intergovernmental Panel on Climate Change (IPCC) projects that global GHG emissions could increase by up to 36.7 Gt of $CO_2$-eq between 2000 and 2030. On the other hand, stabilization of global atmospheric $CO_2$

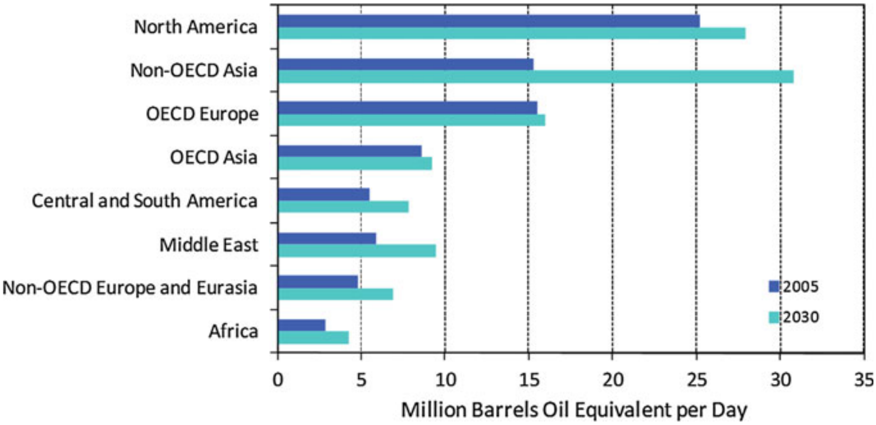


**Fig. 3** Geographic distribution of world oil consumption (Energy Information Administration 2009) (OECD is Organization for Economic Cooperation and Development)

concentration at 490–590 parts per million requires reduction of global GHG emissions in 2050 by as much as 60 % relative to the 2000 global GHG emissions, an enormous global challenge. In 2004, the global transportation sector alone emitted 6.3 Gt of $CO_2$-eq. While this accounts for only 13 % of total global GHG emissions, it accounts for 23 % of global energy-related GHG emissions (Intergovernmental Panel on Climate Change 2007). In developed countries such as the United States, the transportation sector already contributes 26 % of total GHG emissions and more than 33 % of energy-related GHG emissions (U.S. Environmental Protection Agency 2008). Global transportation GHG emissions could increase to 9.1 Gt by 2030 and 12 Gt by 2050.

The energy security and greenhouse gas emissions concerns associated with the transportation sector have prompted many nations to mandate higher standards for vehicles' fuel economy, and to explore alternative fuels in order to contain growth in the demand for petroleum oil and mitigate the projected increase in greenhouse gas emissions.

In the U.S., biofuels and electricity have been promoted for their potential reduction of petroleum use and greenhouse gas emissions. In general, they can be produced regionally and locally from various sources to provide fuels for motor vehicle use. Electricity and most biofuels can be delivered to vehicles' energy storage devices using existing delivery infrastructure. They are being considered and evaluated as near- and long-term alternatives.

## 2 Background and Objective

The carbon in biofuels is from the air during biomass growth, thus, biofuels have the potential to reduce GHG emissions significantly. However, the life cycle of biofuel contains activities such as fertilizer production, farming, biofuel production, and biofuel combustion. Life-cycle analysis (LCA) has been conducted to examine biofuel energy and environmental effects, and its methodologies have advanced in the past 20 years. In the early years of examining biofuels, the so-called energy balance (energy contained in biofuels minus fossil energy consumed to make them through the whole life cycle) was estimated for biofuels, especially for corn-based ethanol (Chambers et al. 1979; Pimentel and Patzek 2005). LCA models have been developed since the early 1990s, and detailed LCAs have been conducted to examine energy and emission effects of biofuels, especially corn-based and cellulosic ethanol in comparison to petroleum fuels (Delucchi 1991; Wang 1996; Wang et al. 1997). While LCA results of biofuels have generally shown energy and GHG benefits of biofuels relative to petroleum fuels, the magnitude of the benefits is determined by the types of feedstocks and production technologies. In addition, LCA results are influenced heavily by decisions on LCAs regarding the system boundary of a given analysis and the method of dealing with co-products of biofuels, among many other factors. The current focus of biofuel energy and environmental effect evaluation is on indirect effects such as land use changes (LUC) from biofuel production and on other environmental sustainability issues such as water consumption, biodiversity, and soil erosion, among many other issues (Searchinger et al. 2008; Kim et al. 2009; Wu et al. 2009).

Electricity can be used in plug-in hybrid electric vehicles (PHEVs) and battery-powered electric vehicles (BEVs). Since the U.S. electricity production is largely independent of petroleum fuel use, PHEVs and BEVs have been touted for their potential to reduce petroleum use and GHG emissions through their efficiency gains and using electricity. The PHEV category can cover a wide variety of options with respect. In addition, consumer driving behavior could also significantly affect the energy use and GHG effects of PHEVs. The magnitude of energy and GHG emission benefits of PHEVs and BEVs is affected by the type of electricity generation and vehicle energy efficiency. LCA has been conducted to quantify energy and GHG benefits of PHEVs and BEVs.

Many LCA studies were completed for PHEVs and BEVs as well as conventional gasoline internal combustion engine vehicles (ICEVs) and gasoline hybrid electric vehicles (HEVs) (Kromer and Heywood 2007; Thomas 2009; National Research Council 2009; Passier et al. 2007; Electric Power Research Institute and Natural Resources Defense Council 2007; Elgowainy et al. 2010). These studies concurred that the battery operation [also known as charge depleting (CD) operation] of PHEVs and BEVs reduces petroleum use since the electricity generation in the U.S. (as in most of the world's large economies) is powered by non-petroleum fuels.

For the LCA of alternative vehicle technologies powered by biofuels and electricity, we have been employing the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, developed by Argonne National Laboratory to estimate the energy use and GHG emissions associated with production, transportation, and consumption of these alternative fuels (Wang 1996). The energy and emissions accounting starts from the primary energy source (well) and ends with the vehicle's operation stage (wheels).

This chapter presents the important stages, results, and key issues associated with LCA of biofuels and electricity as alternative transportation fuels.

## 3 Biofuel Pathways

At present, the two major biofuels that are produced worldwide are ethanol and biodiesel. Ethanol is used in spark-ignition engines (or gasoline engines) from low-level blends such as E10 (10 % of ethanol and 90 % gasoline by volume) to high-level blends such as E85 in the United States and E100 (pure ethanol) in Brazil. While low-level ethanol blends can be used in gasoline vehicles without vehicle modifications, use of high-level blends requires modifying gasoline vehicles to make so-called dedicated ethanol vehicles, as in Brazil in the 1970s to late 1990s, or to make flexible-fuel vehicles (FFVs), as in the United States and currently in

Brazil. Ethanol is usually transported separately to distribution centers where it is blended with gasoline.

Pure biodiesel (B100) can be used in compression-ignition engines (diesel engines). However, there are issues associated with the use of pure or higher percentage of biodiesel in a blend with petroleum diesel. Using B100 requires modifying diesel vehicles in addition to special storage requirement to ensure fuel stability. In most cases, and with adequate biodiesel fuel quality, biodiesel blends with petroleum diesel up to 20 % by volume (B20) can be used in diesel vehicles without vehicle modifications.

Ethanol is currently produced from fermentation of starches and sugars in corn, sugarcane, cassava, wheat, sugar beets, and other crops. In the United States where the largest amount of ethanol production occurs, ethanol has been produced from corn since 1980. In Brazil, sugarcane ethanol has been produced for almost 100 years. Recently, China and Southeast Asia began to produce fuel ethanol from cassava (China also produces a significant amount of corn ethanol). In Europe, ethanol is produced from corn, wheat, and sugar beets. Cellulosic biomass such as crop residues (e.g., corn stover), forest residues, and energy crops (e.g., switchgrass) are being considered for producing cellulosic ethanol.

Biodiesel is produced from vegetable oils and animal fats via a transesterification process. In the United States, biodiesel is produced from soybeans. In Europe, biodiesel is produced primarily from rapeseeds. In Southeast Asia (particularly in Malaysia), biodiesel is produced from palm oil.

Besides the fermentation and transesterification processes, there are many other technology paths available for producing biofuels. For example, cellulosic biomass can be gasified to produce synthetic gas (syngas). Syngas can be then used to produce Fischer–Tropsch (FT) diesel via the FT synthesis process or ethanol via fermentation of syngas. Renewable hydrocarbon fuels such as gasoline and diesel could be produced from vegetable oils and animal fats via the hydrogenation process. Butanol, a fuel with higher volumetric energy content than ethanol, could be produced from sugars via fermentation processes. Recently, interest has heightened in producing hydrocarbon fuels from algae.

## *3.1 Biofuel Life-Cycle Analysis System Boundary*

Figure 4 shows the LCA boundary defined for the corn ethanol pathway in GREET. For other biofuel cycles, the boundary is defined in similar ways. In particular, the corn ethanol life cycle includes fertilizer manufacture, corn farming, ethanol production, and ethanol use in vehicles. All transportation activities involved in moving goods from one location to another (such as corn movement from farms to ethanol plants) are included. Co-product distillers' grains and solubles (DGS) and their emission effects are also included. Most recently, potential direct and indirect LUC by large-scale corn ethanol production have begun to be included as well.

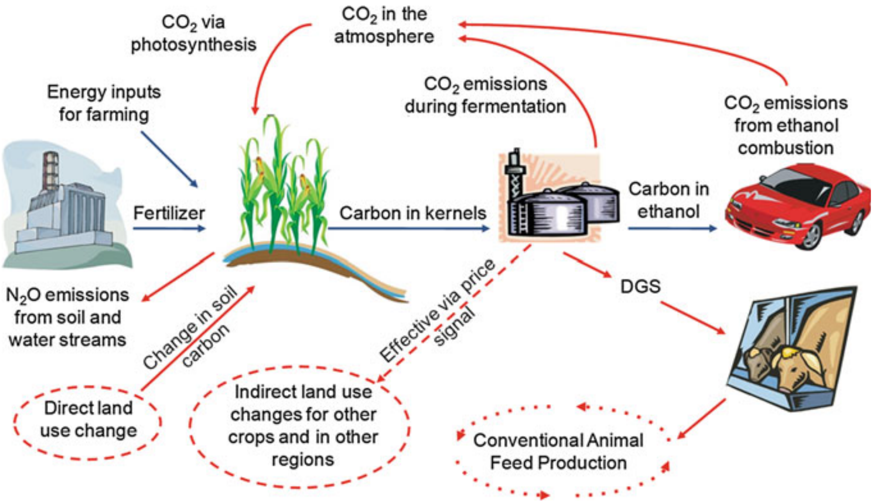
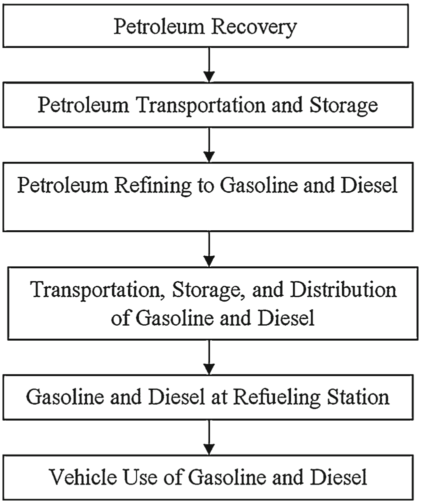


**Fig. 4** Life-cycle analysis system boundary for corn-based ethanol

An LCA of biofuels is usually comparative to an LCA of baseline fuels such as petroleum gasoline and diesel, so the life-cycle system boundary needs to be defined for gasoline and diesel. To make the comparison between biofuels and petroleum fuels valid, the system boundary between them needs to be defined as consistently as possible. Figure 5 shows the LCA system boundary usually defined for petroleum gasoline and diesel.

As Fig. 5 shows, the life cycle of petroleum fuels begins with petroleum recovery in oil fields and ends with gasoline and diesel combustion in motor vehicles. Besides production-related activities, all transportation-related activities

**Fig. 5** Life-cycle analysis system boundary for petroleum gasoline and diesel



to move goods from one location to another (such as crude oil from oil fields to petroleum refineries) are included. Again, infrastructure-related activities such as construction of drilling rigs and petroleum refineries are not included in the LCA of petroleum gasoline and diesel. Oil exploration, which occurs well before oil recovery, is also usually not included in petroleum fuel LCAs.

## *3.2 Life-Cycle Energy Use and Greenhouse Gas Emission Results of Key Biofuel Pathways*

### 3.2.1 Corn and Cellulosic Ethanol

Since the beginning of the U.S. corn ethanol program in 1980, production of U.S. corn ethanol has risen to 10.6 billion gallons in 2009 (Renewable Fuels Association 2010). The U.S. 2007 Energy Independence and Security Act established a goal of 15 billion gallons per year of corn ethanol production by 2015. The corn ethanol industry expanded quickly to reach that goal.

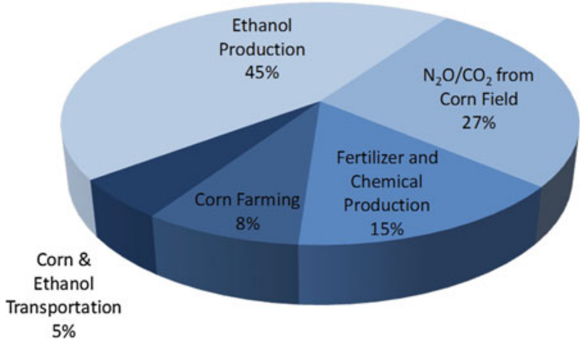
Historically, corn ethanol has been produced from both dry and wet milling plants with different front-end milling technologies and with different co-products. Wet milling plants were built in large sizes and with the flexibility of producing multiple co-products, but required large capital investments. Dry milling plants initially were built in small sizes and with a single co-product (i.e., DGS), and required small capital investments. Since 2000, all newly built corn ethanol plants in the U.S. have been dry milling plants. Recently, the size of dry milling plants has approached that of wet milling plants. Some of the newly built dry milling plants produce more than 100 million gallons of ethanol per year.

Corn ethanol plants require a large amount of steam for fermentation and distillation. Natural gas (NG) is the primary process fuel and coal is used in wet milling plants to generate steam. On average, 80–90 % of U.S. corn ethanol capacity is fueled with NG and the remaining 10–20 % with coal.

Since the beginning of the U.S. corn ethanol program, the energy use intensity of corn ethanol plants has been reduced from more than 19.5 mega Joules (MJ) per liter (70,000 British thermal units (Btu) per gallon) of ethanol (Chambers et al. 1979) to less than 8.4 MJ (30,000 Btu) (Liska et al. 2009; Wang et al. 2007). The more than 57 % reduction in energy intensity has been achieved by high ethanol yield, increased production of wet DGS in lieu of dry DGS, and better process designs, all of which were driven by the economics of ethanol plant operation.

Corn farming requires large amounts of nitrogen fertilizer and fuels, although since the 1970 s, usage intensities for chemicals and fuels of U.S. corn farming have been reduced significantly. For example, U.S. corn productivity in the amount of corn yielded per unit of fertilizer input to farms has increased by 88 % between 1970 and 2005 (Wang et al. 2007). This was accomplished by a continuous increase in corn yield per unit of land without a corresponding increase in

**Fig. 6** Shares of GHG emission sources for corn ethanol (estimated from the GREET model)



fertilizer use. Mainly because of the corn yield per unit of land increases, farming energy use per unit of corn yielded was reduced by 34 % between 1996 and 2001 (the two most recent years that the U.S. Department of Agriculture conducted farming energy expenditure surveys).

Figure 6 shows GHG emission shares by key activities for corn ethanol. Ethanol plants are by far the largest source of GHG emissions. $N_2O$ emissions from nitrogen fertilizer nitrification and denitrification in cornfields (and with small amount of $CO_2$ emissions from lime in cornfields) are the second largest GHG emission source. GHG emissions from nitrogen fertilizer and other chemical plants such as phosphorous fertilizer, potash fertilizer and lime, and from farming energy consumption are significant contributors as well.

Various cellulosic biomass feedstocks could be used for ethanol production, including crop residues such as corn stover, wheat straw, and rice straw; forest residues; dedicated energy crops such as switchgrass, miscanthus, willow trees, and hybrid poplars; and municipal solid wastes. The LCAs of cellulosic ethanol that have been completed at Argonne National Laboratory include ethanol from corn stover, forest residues, and switchgrass.

Wu et al. (2006) examined these cellulosic ethanol pathways (Wu et al. 2006). Corn stover is usually left in cornfields for soil protection and as a nutrient supplement for the next growing season. Extensive research has been done to examine how much stover can be removed from cornfields without causing soil quality deterioration. Within the LCA context, the operation of collecting and transporting corn stover from fields to cellulosic ethanol plants needs to be taken into account. In addition, the nutrients removed from cornfields as corn stover is removed need to be supplemented during the next season for growing crops. These factors were considered in Argonne's LCA for the corn stover-to-ethanol pathway. As for the forest residue-to-ethanol pathway, major activities for this pathway include stumping, collecting, and transporting forest wastes from fields to ethanol plants. In fact, the amount of diesel fuel used for these activities could be significant (Wu et al. 2006).

Switchgrass can be farmed as a dedicated energy crop. Managed switchgrass farms may require fertilizer applications in order to maintain a desirable yield per unit of land, though the amount of fertilizer used is less for switchgrass farming than for corn farming. Also, if switchgrass farming occurs in arid regions such as the U.S. Pacific Northwest, irrigation may be also required. If switchgrass is grown on marginal land or unmanaged prairie land, it is possible that growth of switchgrass could indeed help increase soil carbon content, a benefit for additional GHG emission reductions by switchgrass-based cellulosic ethanol.

In ethanol plants, cellulosic biomass goes through a pretreatment process so that cellulose and hemicellulose can be broken down into simple sugars for hydrolysis and fermentation. The lignin portion of the biomass cannot be fermented. Because of its high energy content, lignin can be used as a process fuel in cellulosic ethanol plants to provide needed steam. In fact, mass balance calculations indicate that the amount of lignin available in cellulosic ethanol plants can exceed the amount of lignin needed for steam generation. Combined heat and power systems are proposed to generate both steam and electricity in cellulosic ethanol plants. Some of the generated electricity can be exported to the electric grid to displace conventional electric power generation, which offer additional GHG emission reductions.

Figure 7 shows the GHG emission reductions of corn and cellulosic ethanol relative to gasoline for each unit of energy used for each type of ethanol to displace a same unit of energy of gasoline. GHG emission effects of corn ethanol here include emissions from direct and indirect LUC, which are subject to great uncertainties (see Sect. 3.3.1). GHG emission changes of corn ethanol vary from a small increase to up to 35 % reductions, depending on the type of process fuel and on production of wet or dry DGS. This shows that ethanol plant designs can significantly impact corn ethanol GHG emission results. On the other hand, cellulosic ethanol can reduce GHG emissions by more than 75 %, depending on the feedstock source for cellulosic biomass.

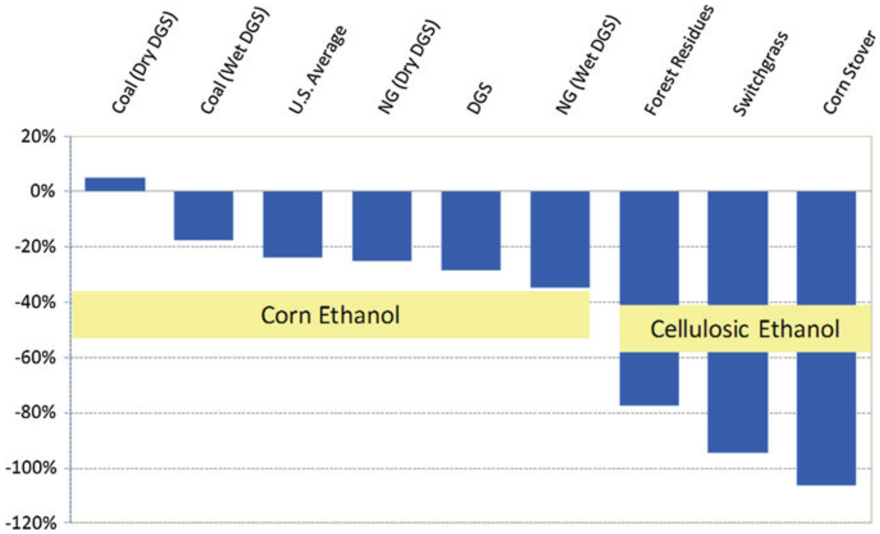


**Fig. 7** GHG emission reductions of corn and cellulosic ethanol (relative to gasoline, on the per-energy unit basis, estimated with the GREET model)

### 3.2.2 Sugarcane Ethanol

Wang et al. (2008) evaluated the GHG emission reduction potentials of Brazilian sugarcane ethanol for use in both Brazil and the United States (Wang et al. 2008). Similarly, Macedo et al. (2008) evaluated sugarcane ethanol production and use in Brazil (Macedo et al. 2008).

The sugarcane to ethanol cycle includes fertilizer manufacture, sugarcane farming, ethanol production, and ethanol use in vehicles. Traditionally, sugarcane is harvested by laborers, comprising the so-called "manual harvest" with open-field burning. Brazil is on a trend to replace manual harvests with mechanical harvests using farming machinery. Brazilian sugarcane mills produce ethanol and sugar. The split between the two products depends on market demand and prices. Bagasse, the leftover material after juice extraction, is burned in sugar mills to generate steam and power. A significant amount of electricity is exported from sugar mills. Figure 8 shows the system boundary for an LCA of sugarcane ethanol in the GREET model.

Figure 9 shows GHG emission shares by key activities of the sugarcane ethanol life cycle. $CH_4$ and $N_2O$ emissions from open-field burning in sugarcane plantations alone are responsible for 25 % of total GHG emissions for sugarcane ethanol. Overall, the five major contributors to sugarcane ethanol GHG emissions are open-field burning, $N_2O$ emissions from sugarcane fields, fertilizer production, GHG emissions from sugarcane ethanol transportation, and farming energy consumption. Sugarcane ethanol plants generate the least amount of GHG emissions, since combustion of bagasse for steam and power generation returns $CO_2$ untaken during sugarcane plant growth back to the air. The sugarcane ethanol achieves GHG emission reductions by 75–80 %, which is similar to the GHG emission reductions by cellulosic ethanol.

### 3.2.3 Biodiesel and Renewable Diesel from Soybeans

Biodiesel is produced from seed oils or animal fats via the transesterification process. In the U.S., most biodiesel is produced from soybean oil. The production

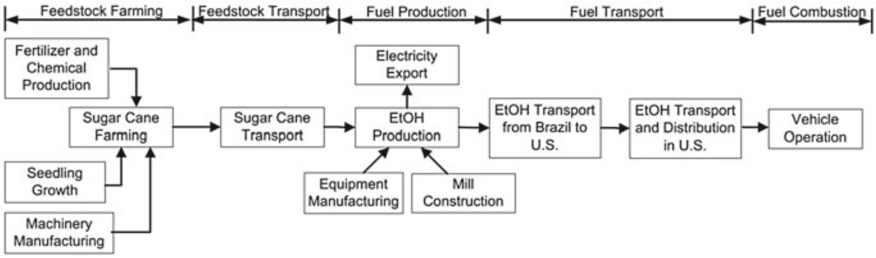


**Fig. 8** Life-cycle analysis system boundary of sugarcane ethanol life-cycle analysis

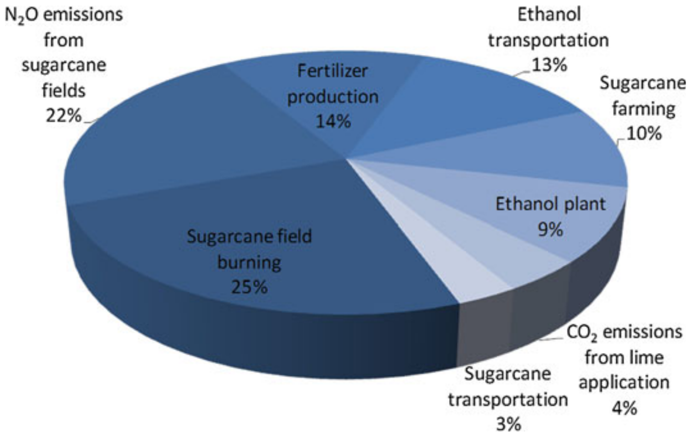


**Fig. 9** GHG emission sources of sugarcane ethanol

volume of biodiesel in the United States increased dramatically between 2000 and 2008 (National Biodiesel Board 2009). However, since then, U.S. biodiesel production declined because of high soybean feedstock costs, limited biodiesel demand in the U.S., and EU's policy restriction of biodiesel import from the U.S. It remains to be seen if these conditions will be changed in the future.

New process technologies based on hydrogenation to convert seed oils and animal fats to renewable diesel with properties similar to petroleum diesel fuels have recently emerged (Huo et al. 2008). Huo et al. (2008) conducted an LCA of soybean-based biodiesel and renewable diesel in the U.S. Soybean farming in the U.S. Midwest is usually rotated with corn farming (Huo et al. 2008). Because the soybean plant's legume has the ability to fix nitrogen in the soil, soybean farming requires much less nitrogen fertilizer than corn farming does, which helps increase the energy and emission benefits of soybean-based biodiesel and renewable diesel.

Before production of biodiesel or renewable diesel, soybeans are crushed to separate soy meals and soy oil. Soy meals are a high-value animal feed product. On a mass basis, 82 % of soybeans ends up in soy meals and the remaining 18 % in soy oil. Soy oil is then used to produce biodiesel or renewable diesel.

In biodiesel plants, glycerin, a specialty chemical, is produced together with biodiesel. On a mass basis, 82 % of soy oil ends up in biodiesel and 18 % in glycerin. In renewable diesel plants, fuel gas, heavy oils, and propane are also produced.

Figure 10 presents LCA results of GHG emission reductions by biodiesel and renewable diesel. In general, biodiesel and renewable diesel can reduce GHG emissions by more than 60 % relative to petroleum diesel. As the chart shows, the methods used in LCAs to address co-products have a significant effect on LCA results for biodiesel and renewable diesel.

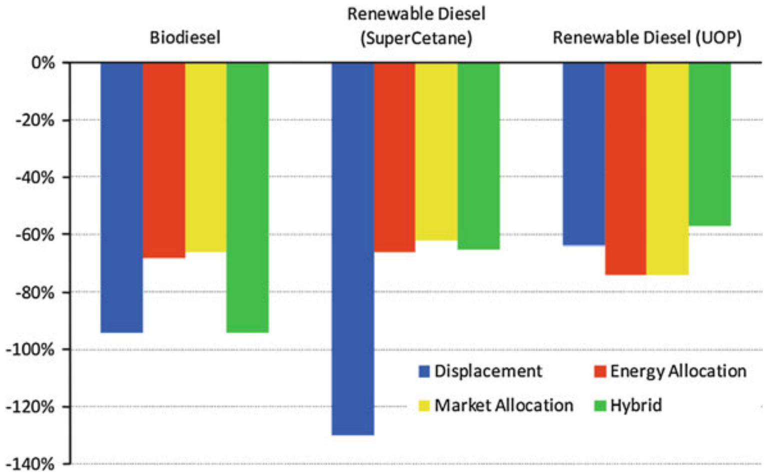


**Fig. 10** Greenhouse gas emission reductions of soybean-based biodiesel and renewable diesel (relative to petroleum diesel, on a per-unit energy basis) (CARB 2009). *Notes* Two renewable diesel production technologies (the Canadian SuperCetane and the U.S. UOP technologies) are presented; The *four bars* for each fuel group represent four methods of dealing with co-products of biodiesel and renewable diesel

## 3.3 Outstanding Issues of Biofuel Life-Cycle Analysis

This section presents three outstanding issues that are being debated now and that can significantly affect LCA results for biofuels.

### 3.3.1 Direct and Indirect Land Use Changes

Although the LUC issue for biofuels was not new, Searchinger et al. (2008) were the first to develop quantitative results for this issue and advocated against certain biofuel types based on their results (Searchinger et al. 2008). Conceptually, production of biofuels will require that biomass feedstocks are grown on land. Growth of a given feedstock on a piece of land changes the original land use pattern of that piece of land. This LUC is referred to as a direct LUC. Direct LUC are identifiable and measureable, since such changes can be directly observed and attributed to biofuel production. On the other hand, use of agricultural commodities such as corn causes an imbalance between supply and demand of agricultural commodities, which can trigger commodity price increases. The price increase signal can have ripple effects, causing cultivation of additional land for growing agricultural commodities somewhere in the world. This LUC is referred as to an indirect LUC. As one can expect, indirect LUC are supposed to be caused by increased commodity prices. Indirect LUC may be simulated with computational general equilibrium (CGE) models to take into account all interrelationships among all economic sectors and activities via the price elasticity of commodities. Searchinger et al. (2008) used the Food and Agricultural Policy Research Institute (FAPRI) model (which is a partial, not general, equilibrium model) to develop estimates of direct and indirect LUC (Searchinger et al. 2008). The Global Trade Analysis Program (GTAP) model developed by Purdue University is a general equilibrium model that has been used by several organizations to address LUC issues.

After publication of the Searchinger study, the simulation and data problems of that study were identified, as were the problems of LUC modeling by CGE models in general. Major efforts have been made to expand and upgrade these models to better simulate LUC issues for biofuels (CARB 2009; U.S. Environmental Protection Agency 2010; Hertel et al. 2010; Tyner et al. 2010).

Carbon emissions (carbon sequestration, in some cases) from LUCs are determined using changes in above-ground biomass and below-ground biomass and soil carbon contents of different land cover types. Even though there are data sources available regarding these, they are not comprehensive enough to cover all major land cover types in different global regions. Often, scarce data from a small set of regions are applied to different global regions (Intergovernmental Panel on Climate Change 2006). In addition, soil carbon content data cover only a shallow depth of soil (such as the top 30 cm). Adequate, comprehensive data on above-ground biomass, below-ground biomass, and soil carbon content will take considerable effort to collect and accumulate for use.

### 3.3.2 Co-Product Treatment in Biofuel Life-Cycle Analyses

As the results in Fig. 10 for biodiesel and renewable diesel show, LCA results for biofuels can vary significantly, depending on the method selected in dealing with biofuel co-products.

Wang et al. (2011) examined methodologies for dealing with co-products in biofuel LCAs (Wang et al. 2011). They explored five methods. First, with the mass-based allocation method, energy and emission burdens of a given biofuel pathway are allocated among all products according to their mass output shares. This allocation method is based on the presumption that energy use and emissions are somewhat related to the amount of mass processed. This method is widely used in LCAs of consumer products and embedded in some generic LCA models. The method is applicable as long as all products are used for their mass values (e.g., a kg of steel for use). However, this method becomes problematic when products have distinctly different uses. For example, in the cases of sugarcane ethanol and cellulosic ethanol production, electricity is co-produced but cannot be allocated by mass.

Second, with the energy-content-based method, the energy and emission burdens of a given fuel production pathway are allocated among products according to their energy output shares. The energy outputs of all products are calculated using the amount of products and their energy content (usually heating content of the products). This method is applicable where most of the products, if not all, are used for their energy content. The method becomes problematic when products have distinctly different uses. For example, starch-based ethanol plants produce ethanol and animal feeds. Even though animal feeds have energy content, they are used because of their significant nutritional values, not their heating values, which are on par with conventional animal feeds (such as corn and soybean meal).

Third, the market value-based method allocates energy and emission burdens based on economic revenue shares of individual products. The economic revenue of a given product is calculated from the product yield of a given pathway and the price of the product. Economists generally advocate use of this method. In fact, some LCA applications of general equilibrium models adopt this method. This method assumes that activities and decisions are driven by economics, and thus burdens should be disbursed according to economic benefits. One unique advantage of this method is that it normalizes all products to a common basis—their economic values. However, in practice this method is subject to great fluctuations in product prices.

Fourth, the process-purpose-based method estimates energy use and emissions of individual processes in a fuel production facility. The energy use and emissions of a given process are allocated to a given product, if the purpose of that process is solely for the production of the given product. An example is the dryer in a corn ethanol plant. The dryer is installed to dry DGS. Thus, energy use and emissions from the dryer operation are allocated to DGS. However, in many cases, individual processes in a facility may produce multiple products, causing the need to allocate energy and emissions of a given process among all products from the process. Furthermore, this method requires energy and emission data at the process level, not at the facility level, which may not be available to researchers for many biofuel facilities. Even if the process-purpose-based method is applied to a given facility, the activities upstream of the facility still need to be allocated. For example, this method can be used to allocate energy use and emissions of corn ethanol plants between ethanol and DGS. But the allocation of energy use and emissions of corn farming between ethanol and DGS still needs to be decided. This decision, in turn, might be based on the mass-, energy-content-, or market-based method.

Fifth, with the displacement method (also called the “system boundary expansion method”), the products that are to be displaced by non-fuel co-products are determined first. Energy and emission burdens of producing the otherwise displaced products are then estimated. The estimated energy and emission burdens are credits that are subtracted from the total energy and emission burdens of the biofuel production cycle. While the displacement method is generally advocated for LCAs, it poses some major challenges to implement. The method requires conducting LCAs for the conventional products that will be displaced, which could be time and resource intensive. Another major problem with the displacement method is that when non-fuel products are a large share of the total output, the method generates distorted LCA results for fuels (Wang et al. 2011).

It is far from being settled whether a given method can be uniformly and blindly recommended for LCA studies. Consistency of co-product method choices for evaluation of different biofuel production pathways may not serve the purpose of providing reliable LCA results well. Transparency of LCA methods is important in

LCA studies, and sensitive cases with multiple co-product methods may be warranted in LCA studies where co-products can significantly impact study outcomes.

### 3.3.3 Other Environmental Sustainability Issues

Environmental sustainability issues of biofuel production and utilization now are an important topic. Such issues include fresh water consumption for feedstock growth and biofuel production, soil erosion effects of growing certain feedstocks, biodiversity implications of feedstock growth, and air pollution and its health effects of producing and using biofuels. So far, these issues have not been addressed systematically on the life-cycle basis. Nonetheless, such issues as fresh water consumption were estimated by examining key (but not all) stages of the biofuel life cycle. In addition, some of the issues (such as biodiversity) are difficult to address quantitatively. Eventually, these issues should be addressed along the entire life cycle of biofuels. That is, all stages of the life cycle should be considered. More importantly, these issues should be addressed on a comparative basis, so that biofuels can be compared with baseline petroleum gasoline and diesel for relative environmental sustainability implications.

Wu et al. (2009) recently estimated the consumptive water requirements of ethanol and gasoline production (Wu et al. 2009). For biofuel production, the key determinants are feedstock and the amount of irrigation water needed to generate reasonable yields. For gasoline production, the key determinants are the characteristics of individual oil reservoirs, the recovery technology used, and the degree of produced water recycling. On average, corn ethanol production tends to consume more water than cellulosic ethanol production does on a life-cycle basis. Net water use for cellulosic ethanol production is comparable to that of gasoline. Biofuels production exhibits significant regional differences in water use. Consumptive water use for corn ethanol production varies significantly in the major U.S. corn-growing regions. Producing a liter of corn ethanol can consume as little as 10 or as much as 324 l of water, depending on the amount of irrigation water used for corn growing. On average, more than half of the U.S. corn ethanol is produced at a water use rate of 10 l of water per liter of ethanol. Switchgrass-based cellulosic ethanol production, when grown in its native habitat in the United States, can consume from 1.9 to 9.8 l of water per liter of cellulosic ethanol, depending on process technology. In comparison, net water use to produce a liter of gasoline varies from less than 3 l to nearly 7 l.

## 4 Electricity Pathways with PHEVs and EVs

PHEVs are similar to regular HEVs, except that it employs a bigger battery, which is recharged through a wall outlet by drawing electricity from the grid. The reduction in petroleum use by PHEVs increases with a corresponding increase in their electric range, which is proportional to the size of the employed battery. Fuel economy gains by PHEVs and EVs relative to conventional vehicles are another key factor determining their energy and GHG benefits.

While all previous studies predicted significant reductions in petroleum energy with the use of PHEVs and BEVs, they predicted mixed results for GHG emissions of these vehicles. At one end of the GHG emissions results spectrum, some studies estimated that PHEVs and BEVs (recharging from the U.S. average mix) generate fewer GHG emissions compared with gasoline ICE vehicles, but equal to (or more than) gasoline HEVs (Kromer and Heywood 2007; Thomas 2009; National Research Council 2009). At the other end of the spectrum, other studies estimated that PHEVs operating in CD mode can outperform HEVs in terms of GHG emission reductions if 75 % or more of the required electricity is generated from natural gas combined-cycle (NGCC) (Passier et al. 2007), and produce lower GHG emissions even with coal-based electricity compared with gasoline ICE vehicles (Electric Power Research Institute and Natural Resources Defense Council 2007). A recent study by Argonne National Laboratory (ANL) conducted detailed dispatch modeling simulations in different U.S. utility service areas with different charging scenarios for PHEVs, and explored "real-world" driving energy use for PHEVs versus gasoline vehicles (Elgowainy et al. 2010). The key factors impacting the WTW analysis of PHEVs and BEVs, and the findings of the ANL study are discussed next.

### 4.1 PHEV Fuel-Cycle Pathways

Since a PHEV consumes fuel and electricity, its pathway consists of two parallel paths for these two energy sources. The fuel path includes the recovery of the feedstock (e.g., crude), the transportation of the feedstock, the production of the fuel (e.g., refining of crude to gasoline), and the transportation of the fuel to the pump. The electricity path includes the recovery, processing, and transportation of the fuel used for electricity generation (e.g., natural gas, coal, and uranium), the technology used for electric power generation (e.g., steam power plant, natural gas combustion turbine, etc.), the transmission of the electricity to the wall outlet, and the charging of the vehicle's battery. The fuel and electricity production and transmission represent the well-to-pump (WTP) stage of the pathway, while the vehicle's consumption of fuel and electricity represents the pump-to-wheel (PTW) stage.

A PHEV charges the battery to a high state-of-charge (SOC) (e.g., 90 %). Then the vehicle operates in a CD mode by using the stored electricity in the battery until it reached a low SOC (e.g., 30 %). Once the battery reached the low SOC threshold, the PHEV operates in a charge-sustaining (CS) mode, which is similar to the operation of regular HEVs (Shidore et al. 2007). This operation strategy allows the vehicle to operate as a zero-emission vehicle in CD operation. However, battery cost and PHEV performance requirements have led automakers to consider a "blended" CD mode, through which the engine is intermittently turned on, resulting in increase in the CD range by utilizing the electric powertrain and the engine simultaneously (blended operation).

### *4.2 Fuel and Electricity Consumption by PHEVs*

Since PHEVs and BEVs are yet to be produced by the automotive industry, the fuel and electricity consumption of PHEVs and BEVs are estimated by employing vehicle simulation models such as Argonne's Powertrain System Analysis Toolkit (PSAT). PSAT can simulate different vehicle configurations through a standard or custom driving cycle to produce the fuel consumption by these vehicle technologies. PHEV designs in the Argonne study covered PHEV10 (i.e., 10 miles of electric range), PHEV20, PHEV30, and PHEV40. The higher the electric range of the vehicle, the less petroleum fuel the vehicle will need to consume. Nevertheless, increased electric range requires bigger battery resulting in increased cost and weight of the vehicle. The high cost of batteries led vehicle designers to explore ways to extend the electric range through a "blended" operation of the engine with the electric motor. However, the intermittent operation of the engine in blended mode has the potential to create bursts of emissions when the engine comes on, making it necessary to develop modifications of the emissions control systems in order to meet emissions standards. The blended operation of the engine and the electric motor extends the vehicle's electric range significantly while allowing for more efficient utilization of the battery.

One major complication associated with PHEVs is how to rate these vehicles with respect to their electricity and fuel consumption. EPA develops on-road fuel economy estimates that appear on the window stickers of all new cars and light trucks sold in the U.S. (U.S. Environmental Protection Agency 2006). The purpose of the fuel economy label is to assist consumers to compare the fuel economy of different vehicles for their purchase decision (Walsh 2009). However, the current fuel economy rating methodology is not adaptable to the rating of PHEVs due to the electricity consumption and intermittent engine use in the blended CD operation. Furthermore, fuel economy, expressed as miles per gallon (MPG), leads customers to falsely believe that the amount of gasoline consumed by an automobile decreases as a linear function of a car's MPG (Larrick and Soll 2008). The actual relationship is curvilinear as shown in Fig. 11. The figure shows that a 10 mpg improvement at lower fuel economy produces much higher fuel consumption savings compared to the same improvement at higher fuel economy. For example, increasing fuel economy from 10 to 20 mpg results in 5 gallons saving over 100 miles traveling distance, while an equivalent increase from 40 to 50 mpg results in a mere 0.5 gallon saving over the same traveling distance. Critiques of fuel economy labeling argue that representing fuel efficiency in terms of amount of gasoline consumed for a given distance (e.g., gallons per 100 miles), which is commonly used outside of the United States, would make the benefits of greater fuel efficiency more transparent (Larrick and Soll 2008). More recently, New York State Senate passed a bill requiring state car dealers to post a chart converting

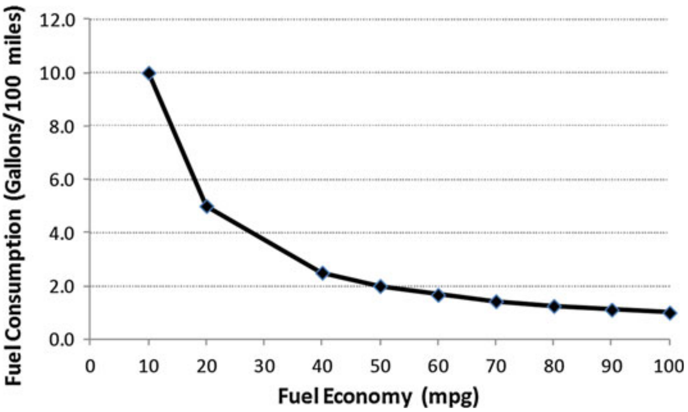


**Fig. 11** Relationship between fuel economy and fuel consumption

**Table 1** Fuel and electricity consumption for alternative gasoline vehicle technologies

| | | | PHEV10 | | PHEV20 | | PHEV30 | | PHEV40 | | BEV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ICEV | HEV | CD | CS | CD | CS | CD | CS | CD | CS | CD |
| Gallons per 100 miles | 3.52 | 2.41 | 1.35 | 2.24 | 1.24 | 2.25 | 0.28 | 2.91 | 0.16 | 2.94 | N/A |
| kWh per 100 miles | N/A | N/A | 22.6 | N/A | 22.1 | N/A | 38.7 | N/A | 39.0 | N/A | 40.4 |

MPG to gallons per 1,000 miles (the average monthly driving distance) in 5 mpg increments. The bill has to clear the State Assembly before it could be signed into law. Reporting gallons per 100 miles for fuel consumption and kWh per 100 miles for electricity consumption on the window sticker of PHEVs could be easily converted to the cost per 100 miles since the price per gallon of gasoline and per kWh of electricity are usually known in the locality surrounding the customer traveling. Table 1 depicts the fuel and electricity consumption of gasoline ICEVs, HEVs, and PHEVs, as well as BEVs based on the ANL recent analysis (Elgowainy et al. 2010).

### 4.3 *PHEV Electric Demand (Load) Profiles and Electricity Generation Mix for Battery Recharging*

PHEVs will draw electric energy from the electric grid. The extent of this electricity demand can be estimated by examining patterns of vehicle usage and estimating the potential number of PHEVs that will be plugged in. The daily electricity demands for various PHEVs can be estimated by analyzing the following four factors: (1) daily vehicle usage; (2) pattern of vehicle arrival at home at the end of the last trip; (3) number of PHEVs of different electric ranges that will be plugged in each day; and (4) amount of electric power that will be drawn by each PHEV and the time required for charging. For estimating electricity demand by PHEVs, the number of PHEVs that will be on road in a given year needs to be estimated.

Once the PHEV load profile is established, a dispatch model simulating the electric power generation and transmission system in a utility area can predict the marginal electricity generation mix dispatched for battery recharging in that area. The marginal electricity generation mix for battery recharging is a major factor impacting the WTW results of PHEVs and BEVs.

The generation mix at the time of charging is a strong function of the time of day, time of year, geographic region, vehicle and charger design, base and vehicular load growth patterns, and the associated generation expansion in the years prior to the charging event of interest.

Figure 12, developed by Shelby and Mui, is an illustration of the diurnal peaks of demand for a hypothetical summer day (Shelby and Mui 2007). Sharp summer peaks are caused by air-conditioning demand, although such peaks typically occur in the late afternoon and early evening. However, demand is at a minimum overnight when businesses are closed, lights are off, and air-conditioning load is at its lowest. As electricity demand increases, additional generating units are dispatched to meet the load. When a PHEV charger is activated, it causes additional load on the marginal generator (i.e., the last unit brought online). When that unit reaches full capacity, another unit is brought online as the marginal unit, and so forth. Therefore, when a large number of PHEVs are added to a system, several additional generation units may be required to meet the charging load. Consequently, the energy use and emissions of those units are allocated to the PHEV charging load. In an extensive interconnected region, transmission constraints can develop so that several geographically separated generating units must operate at part load to meet an increasing demand.

Seasonal load variations also affect the mix of units brought on-line to meet the PHEV charging demand. High summer electric loads are typical for most of the United States, reflecting power demand for air-conditioning. Electric heating loads tend to increase off-peak demands and may compete with the off-peak charging of PHEVs during the winter season.

The vehicle design characteristic with the greatest influence on PHEV charging load is the battery capacity, which is related to the electric range and weight of the vehicle. It is most commonly assumed that the charger will operate at normal household power levels, typically 110 V and no more than 20 amps. A sport utility vehicle (SUV) type of PHEV may require larger batteries than a compact or sedan type of PHEV. In order to charge these batteries in a reasonable length of time, more charging current is required. This could be accomplished with a charger operating on 220 V at 30 amps. Single-phase, 220-V service is available to all residential customers, but typically will require professional installation of additional circuit breakers, lines, and a dedicated outlet. The benefit of reduced charging time comes at an additional cost of the higher demand.

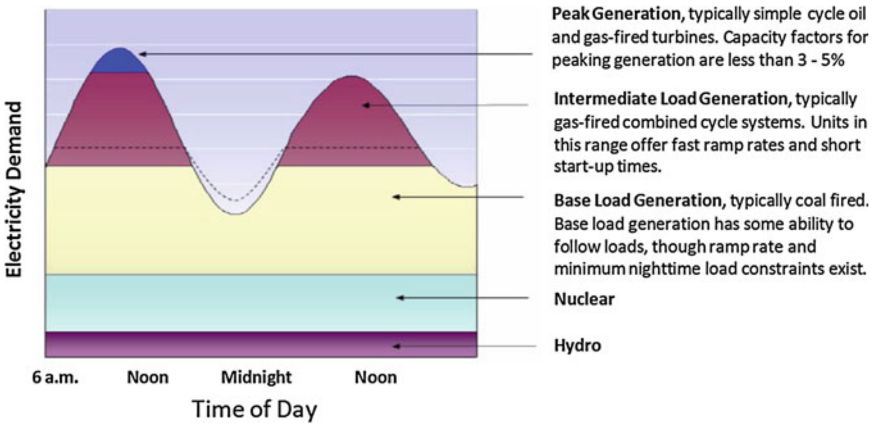


**Fig. 12** Typical summer electric load profile and dispatch scheme for many U.S. utilities (Larrick and Soll 2008)

The inventory of units available for PHEV charging is slowly changing as old units retire or are refitted with new environmental controls and as new units are constructed in anticipation of increasing demand. Also, existing units may change place in the dispatch order as they age or as new plants come on-line. Although commercial introduction of PHEVs is expected in 2010, it will likely take a long time before a substantial PHEV charging demand exists due to the low fleet turnover rate (approximately 7–8 % per year in the U.S.).

Generation expansion planning must take into account both the extent of likely demand growth and the daily and seasonal dynamic structure of the projected demand. Relatively constant loads are best served by large base-load units with low fuel and variable costs. Daily peak loads may best be served by units with low fixed (investment) costs, such as gas turbines. However, lower fuel-cost options, including hydro, will be applied to peak loads if capacity is available. The generation mix applied at a specific time is predicted by dispatch models. The dispatch models match available capacity to the dynamic load by using cost, emissions, or other criteria to optimize the system. Dispatch models also take reliability and scheduled plant outages into consideration.

## *4.4 Combining Charge Depletion and Charge-Sustaining WTW Results for PHEVs*

In order to combine the fuel and electricity pathways together for PHEVs, PHEV miles with electricity vs. with fuels must be estimated. The split depends on daily miles driven by individual drivers and the electric ranges of different PHEVs. With national daily mile distribution, Fig. 13 shows the miles that could be driven with electricity for given electric ranges of PHEVs base on U.S. national household travel survey data (Elgowainy et al. 2010).

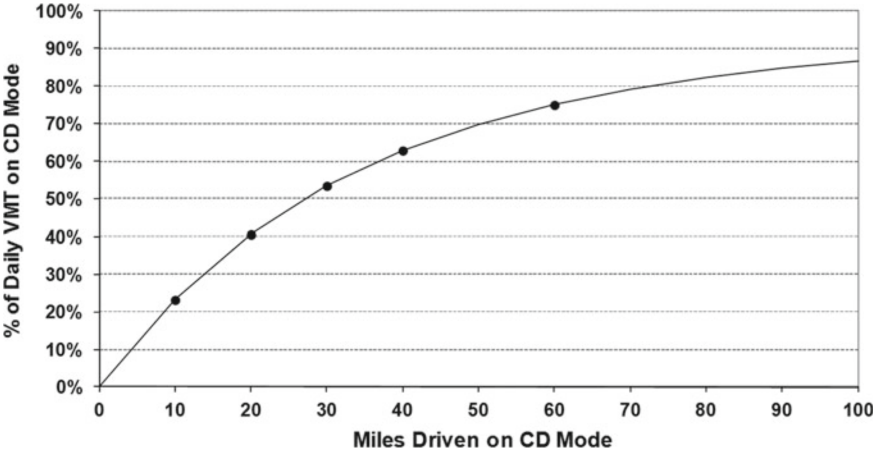


**Fig. 13** Percentage of daily VMT available for substitution by a PHEV in CD mode (Elgowainy et al. 2010)

## 4.5 WTW Results of PHEVs and BEVs

Figure 14 shows the WTW results of gasoline PHEVs, in addition to gasoline ICEVs, gasoline regular HEVs and BEVs. The implication of the electricity generation mix resides in the carbon intensity of the used fuel and the efficiency of the generation technology. The electricity generation energy use and GHG emissions increase progressively as the marginal mix becomes less efficient and dominated by coal or residual oil. PHEVs recharging from NGCC generation produce GHG emissions comparable to or less than regular HEVs, while PHEVs recharging from coal-based power generation produce GHG emissions comparable to or slightly higher than ICEVs. Usually, more petroleum savings and GHG emission reduction are realized with an increase in vehicle's electric range when the generation mix is oil independent. Furthermore, when the charging of PHEV occurs from a low-carbon generation mix (e.g., NGCC) or from a renewable source, PHEVs with high electric ranges provide significantly more petroleum savings and GHG emissions reductions. BEVs extend the savings in petroleum energy and GHG emissions further, and represent the upper limit in potential benefits from PHEVs.

## 4.6 Electric Drive Technology Life-Cycle Analysis Issues and Uncertainties

### 4.6.1 Electricity and Fuel Consumption of PHEVs

There are two main factors that impact the electricity and fuel consumption of PHEVs: the vehicle design configuration and the driving conditions. The vehicle configuration could assume “a variety of power ratings” for the battery, engine, and electric motor as well as a variety of control strategies of these powertrain components. The driving conditions include driving aggressiveness, extent of air-conditioning use, and cold-weather operation. Other uncertainties include the rate of technological advancement in the critical components of each vehicle technology, e.g., batteries and chargers, which decides the efficiency of battery charging and discharging efficiencies. Such uncertainties impact fuel and electricity consumption during vehicle operation, which in turn impacts the WTW results.

### 4.6.2 Electricity Generation Mix for Recharging PHEVs

Generation expansion planning, which optimizes changes to the generator inventory, is a complex process that takes into account load growth projections, the technical performance characteristics of current and future generator options, and known and potential changes in regulations. Existing and evolving policies aimed at reduction of electricity demand, GHG emissions, and other criteria pollutants [e.g., Energy Efficiency Resource Standard (EERS) and Renewable Portfolio

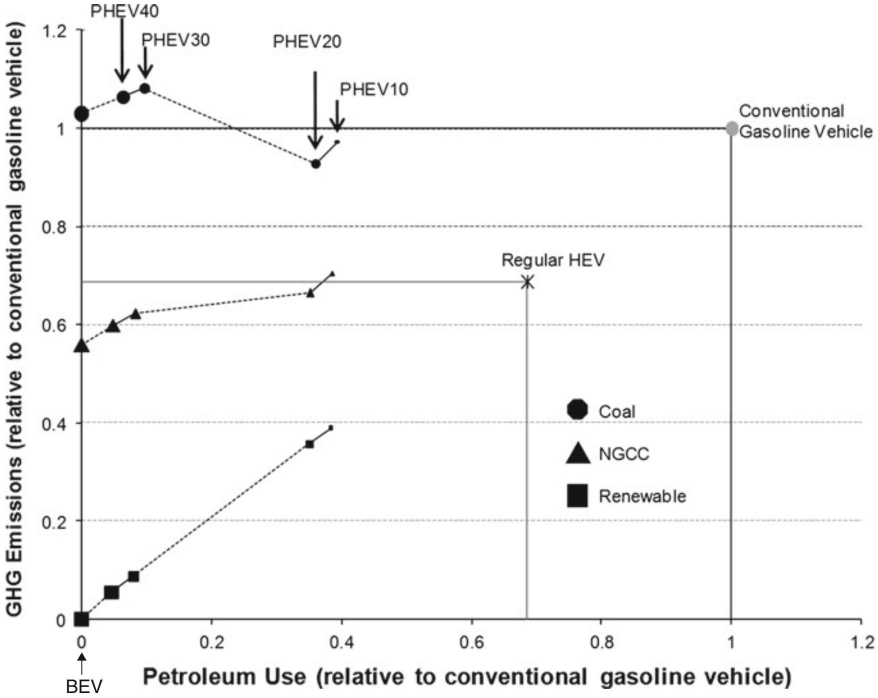


**Fig. 14** WTW petroleum use and GHG emissions for CD operation of gasoline vehicles (conventional, HEVs, PHEVs, and BEVs)

Standard (RPS) in many states, mercury regulations, and Clean Air Interstate Rule (CAIR)] impact the economics and ultimately the retirement of existing generation technologies, as well as the selection of future generation technologies. The final inventory in one or two decades, or more in the future, would likely be substantially different under these constraints than it would be in a business-as-usual case. Generation expansion may also be influenced by the PHEV charging demand itself, and this charging demand is likely to increase along with a general increase in transportation energy demand. Thus, generation expansion projections become linked to projections of transportation demand. Such transportation demand is determined by many uncertain factors which includes the number of PHEVs and BEVs that will be on road in a given region at a given year, the number of charges per vehicle per day, the time of day for each charging event, and the rate at which charging occurs.

### 4.6.3 Share of National Vehicle Miles Traveled Powered By Electricity

The "share of miles electrified", which directly impacts the petroleum energy savings, depends on many factors with considerable uncertainty. Adoption of PHEVs will be slow because of low vehicle fleet turnover rate. Furthermore, PHEVs will not be purchased by everyone as they will likely complement, rather than displace HEVs. Also, PHEVs will vary in terms of their electric range capabilities and will have different configurations of the electric machine, battery, and engine. The nominal electric range will not be realized because of variations in driving conditions, driver characteristics, accessory use, etc. The various control strategies for utilizing the engine and the electric motor could result in a myriad of vehicle miles traveled (VMT) shares in CD operation. Batteries may be charged more than once per day, and may not be fully discharged before recharging. Such factors impact the share of miles electrified, which decides the percentage of petroleum displacement, and impact the PHEV load profile, which decides the marginal generation mix and the corresponding GHG emissions profile of PHEV in different regions.

## 5 Conclusions

Biofuels can be produced regionally and locally to provide fuels for motor vehicles equipped with ICE technologies, thus reducing reliance on imported petroleum for many countries. Biofuels can potentially reduce greenhouse gas emissions. While LCA results of biofuels have generally shown energy and greenhouse gas benefits of biofuels relative to petroleum fuels, the magnitudes of the benefits are determined by the types of feedstocks and production technologies. Biofuel LCAs have shown clearly that benefits of different biofuels are not equal. It is critical to select the proper feedstocks and to use efficient technologies for biofuels to achieve significant reduction in energy use and emissions. In addition, LCA results are heavily influenced by decisions regarding LCA system boundary and methods of dealing with co-products of biofuels, among many other factors.

Electric drive technologies, as battery technologies evolve in the future, may provide a road to transportation electrification. This is especially intriguing since GHG emissions can be controlled at electric power plants from switching fossil power plants to renewable power plants and from future potential carbon capture and storage technologies. PHEVs and BEVs reduce petroleum energy use. However, to achieve significant reduction in GHG emissions, the electricity generation mix must be dominated by non-fossil sources such as renewable energy sources.

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# Liquid Biofuels: We Lose More than We Win

**Henrik Wenzel, Karsten Hedegaard, Kathrine Thyø**
**and Guido Reinhardt**

**Abstract** Throughout the world, nations are seeking ways to decrease $CO_2$ emissions and to reduce their dependency on fossil fuels, especially oil, for environmental as well as geopolitical reasons. Being a renewable, $CO_2$-reducing and easily storable energy carrier, biomass is a priority resource for fossil fuel substitution, and biomass is increasingly used for both the transport and the heat and power sectors, with increasing interest in using it for chemicals production as well. For the transport sector, the conversion of biomass to the liquid biofuels of biodiesel and bioethanol is at present a technological pathway promoted by governments in many countries. With the increasing interest in our biomass resource, however, the issue of competition for the biomass and the need for prioritising it has become evident. For several decades ahead, we still depend heavily on fossil fuels, and we can only replace them to the extent and with the speed that alternatives become available. As the magnitude of biomass that is or can be made available for energy purposes is small compared to the magnitude of the new potential customers for it, any long-term and large-scale prioritisation of biomass for one purpose will imply a loss of alternative uses of the same biomass. If the lost alternatives are, then, significantly more efficient as well as economically more attractive in fossil fuels substitution and $CO_2$ reduction, we lose more than we win. It is our claim that this is the case for most liquid biofuels, including first-generation bio-diesels

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(plant bio-diesels) as well as first- and second-generation bioethanols produced in Europe and the USA. When we prioritise biomass for these biofuels, we deprive ourselves the better alternative of using the same limited biomass for heat and power and running our cars on the fuels saved there.

**Keywords** Carbon emission · Biofuel · Transportation · Plant bio-diesel · Bio-ethanol

## 1 Constraints on Biomass Supply

Till now, the part of our economy being based on biological resources has largely been confined to the food sector. But due to the disappearing fossil resources, many new customers to biological resources enter the scene: electricity, heat, transportation, polymers and organic bulk chemicals. A look at the proportions and the magnitude of these newcomers compared to our agricultural sector as we know it illustrates how big they are.

With the average daily diet of around 2,700 kcal per person, the total calorific food intake is around 30 EJ per year by the world's population. The global fossil fuel consumption today is around 450 EJ per year, i.e. 15 times larger than the energy content of the world's food intake. So the new customers are big. The energy content of the crops deriving from this land is bigger than the 30 EJ/year, due to the losses in the supply chain for food, and based on data (FAO Statistics Division 2007), the gross energy production in agricultural crops today, thus, amounts to an estimated 150 EJ/year. The proportion is, thus, that using biomass for all energy demands, today satisfied by fossil fuels, would require an agricultural area around 3 times the present with similar crop yields. The present global average growth rates on both energy and food consumption are bigger than the agricultural yield increase, implying that the near-term future developments are not likely to improve the relation.

The magnitude of new agricultural land that earth can potentially provide is only around a doubling. Looking at climatic conditions, soil fertility and other biophysical factors essential for cultivating land, Ramankutty et al. (2002) found that earth can provide a maximum of 120 % new cultivable land, most of which is found in tropical South America and Africa. The figure is theoretical, and actually cultivating this land would imply deforestation including violation of nature preservation, and the realistic magnitude of new land cultivation is much lower. Moreover, forest and other land types have in many cases sequestered much more carbon than the agricultural land following the cultivation, and the release of carbon due to cultivation may be very high compared to the subsequent carbon offsetting by the crops substituting fossil fuels, around 2–9 times higher over a 30 year period (Righelato and Spracklen 2007). The conclusion of this rough look at proportions is that while we need 3–4 times more cropland in order to fully replace fossil fuels by biomass, we can at maximum double our cropland and we can do far from that without carbon releases exceeding carbon savings.

Even studies assuming very high increases in agricultural yields (including breeding and technological advancements) and the inclusion of the use of all residues from agriculture and forestry into account conclude that globally there might be a potential of 200–400 EJ of biomass available in 2050, whereas the world energy demand might be in the range of 600–1,400 EJ (Reinhardt et al. 2007; IEA 2007; Nakicenovic et al. 1998).

To conclude, biomass will only be able to contribute to part of the world's future needs for fuels, and as fossil fuels are depleted, competition for biomass and land will increase. Moreover, liquid biofuels are not able to compete in a liberal fuel market, and we need to subsidise it in one way or the other—and there is competition for subsidies as well. Therefore, there is not enough biomass for all potential end uses, not physically and not in terms of money to promote its use.

## 2 The Scope of Biofuel Studies: The Good, the Bad and the Ugly

Acknowledging the physical and economic constraints on biomass leads to the conclusion that, any use of biomass for energy purposes will have to compare to the lost opportunity of using it for something else. Looking at existing published biofuel studies, the implications of the constraints on and competition for land and biomass are not adequately addressed. However, some recent studies demonstrate that acknowledging the implications of the constraints in the assessment of biofuels will reverse the conclusion on their environmental impacts (Nielsen and Wenzel 2005; Jensen and Thyø 2007; Jensen et al. 2007; Thyø and Wenzel 2007).

Studies on the environmental aspects of biofuels are known to give a variety of different results and conclusions. A closer look at the causes behind the differences, however, reveals that the apparent large variations can be boiled down to simple differences in how the system boundaries of the studies are set. The studies fall into three main categories, which we have named: the good, the bad and the ugly; see the illustration in Fig. 1.

The category named 'ugly' comprises studies that look at the biofuel in isolation. They look at a narrow energy balance comparing the calorific value of total fossil fuels used to produce the biofuel to the calorific value of the biofuel itself. Some studies also comprise the co-product produced along with the fuel. They comprise studies on first-generation biofuels, typically on bioethanol, and include the system producing the bioethanol including the growing of the crop and conversion into ethanol. They find the calorific value of the consumed fossil fuels to be just as high or even higher than the calorific value of the ethanol itself and argue against the use of bioethanol on these grounds (Nielsen and Wenzel 2005). This system boundary, however, does not reflect the full environmental consequences of using biofuels.

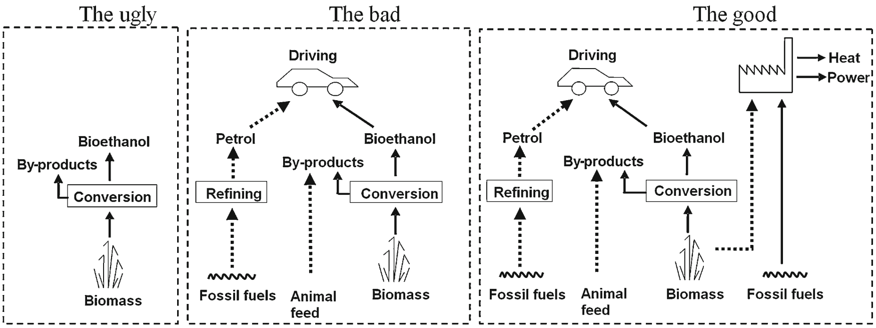

**Fig. 1** The three main categories of system boundaries in existing biofuel studies. *Full arrows* designate induced flows, *dotted arrows* designate avoided flows

When used as fuel, the ethanol will replace petrol, and the processes and fossil fuels used to extract and refine this petrol are avoided as well. Moreover, the co-product produced along with the ethanol is used as animal feed replacing other animal feed products, and fossil fuels to produce these are avoided as well. In not realising and comprising these system aspects adequately, such studies are not in line with international standards on environmental assessment methodology, i.e. the ISO standards on life cycle assessment (LCA), ISO 14040 and 14044.

The category named ‘bad’ comprises studies that look at transport in isolation. They do acknowledge the system aspects described above, and such studies potentially do comply with international standards, see overview in Quirin et al.’s work (2004). They find that in the overall picture, more fossil fuels are displaced than used.

Looking at transport in isolation, this system boundary, however, does not reflect the full environmental consequences of using biofuels either. When prioritising biomass for transport biofuels on a large and longer-term scale (including pay-back of investments), it must be acknowledged that we deprive ourselves the opportunity of using the same biomass (and money) to meet other demands in society—because the availability of biomass is limited compared to these demands. Obvious alternatives are use of biomass for heat and power or for green chemistry replacing fossil fuels in these sectors, and we must realise that we lose the opportunity of such replacements proportionally to our use of biomass for transportation. The studies looking at transport in isolation implicitly claim that the future prioritisation of biomass/cropland for transport biofuels has no impact on our ability to use biomass for heat and power and green chemistry, respectively, and thus on our future fossil fuel consumption for heat and power production and chemical products.

It is acknowledged that one saves fifty to several hundred percent more greenhouse gases and fossil fuel, if the same biomass is used for heat and power instead of for transport biofuels or if a given acreage is used to produce biomass for the same purposes in comparison (Nielsen and Wenzel 2005; Jensen and Thyø 2007; Jensen et al. 2007; Thyø and Wenzel 2007; Kaltschmitt and Reinhardt 1997; Nitsch et al. 2004; Fritsche et al. 2004). Thus, the lost opportunities strongly outweigh the benefits. Recent studies also indicate that there are many opportunities to save also 5–10 times more fossil fuels and GHG by using biomass for some pathways towards green chemistry like polylactic acids compared to transport biofuels as well (Reinhardt et al. 2007; Patel et al. 2006), or even up to 100 times more when using biomass to produce enzymes (Nielsen et al. 2008).

Although studies looking at transport in isolation may be in compliance with international standards on LCA, they do not comply with the principle of the latest developments within the concept of the so-called ‘consequential LCA’ stating that any essential consequences of the studied decision (e.g. to use biofuels), within the period of time considered, should be included in the study (Ekvall and Weidema 2004). Studying biofuels implies looking 20–30 years ahead, as this is the reasonable pay-back period for investments in biofuel facilities and as this, then, is the period for which the biomass consumption is locked into the biofuel conversion pathway. When claiming the high incentives to promote biofuels for transportation in terms of the need to reduce $CO_2$ and the dependency on oil, it is consistent to assume the same incentives for achieving exactly the same aims in other sectors, and it is not consistent to look away from the fact that the heat and power as well as the chemistry sectors are alternative and competing customers for the same limited biomass.

The category named ‘good’ comprises studies that look at transport in correlation with other biomass consumers in society, including heat and power production. The studies in question look 20–30 years ahead and assume a correlation between the transport sector and other sectors demanding biomass, i.e. that a given use of biomass in one sector will take place at the expense of an equivalent use in another sector. These studies unambiguously show that more is lost than gained when prioritising biomass and cropland for transport biofuels at the expense of heat and power. Looking at both $CO_2$ reduction and fossil fuel savings, the conversion of biomass to heat and power or its use in chemistry can imply from fifty up to several hundred percent higher savings per ton of biomass and/or per hectare than biofuels, depending on the type of biofuel (Reinhardt et al. 2007; Nielsen and Wenzel 2005; Jensen and Thyø 2007; Jensen et al. 2007; Thyø and Wenzel 2007).

The studies in this category are LCA studies and do not account for differences in socio-economic costs between the alternative biomass uses. But as socio-economic costs are higher for transport biofuels than for biomass for heat and power, the above approach is conservative with respect to the point we make in this chapter.

## 3 The Lost Alternatives

The key constraints that should be respected by any biofuel study are, thus, firstly that biomass and cropland are very limited compared to the new customers for it especially in the heat and power sectors and the transport sector. Secondly, that society will by all judgements use natural gas and other fossil fuels for heat and power production for at least the next 30 years ahead. For many years ahead, also oil is still used for heating purposes in large volumes, e.g. in many European countries. Throughout this period of time, the reference point is, therefore, that we can save fossil fuels in heat and power production and run our transport sector on the fuels that we save there. The fuel requirement of the heat and power sectors is much larger than the available biomass and can for several decades ahead take all available biomass and more. Any alternative biomass utilisation should, thus, be better than the use for heat and power in terms of $CO_2$ reduction, fossil fuel savings (especially oil) and costs. As they are produced in Europe and USA, liquid biofuels are worse on all these aspects, and it has been found that future second-generation bioethanol will not change this fact (Hedegaard et al. 2008).

In order to compete, the success criteria for any use of biomass for energy are: high crop yield, high conversion efficiency and high cost efficiency. Acknowledging this, it is easy to explain the bad environmental performance of the liquid biofuels: Bio-diesel from vegetable oil implies a very low crop yield, up to three times lower yield of dry matter per hectare compared to other energy crops. Bioethanol, both first and second generation, has a low energy-conversion efficiency being around 50–70 % including the by-products. The reason is that bioethanol suffers from several significant conversion losses: pre-treatment (second generation), low metabolic conversion to ethanol, subsequent need to dry residual unconverted matter, and distillation to separate ethanol from water. Besides these technical aspects, the $CO_2$ mitigation costs are very high for both plant bio-diesel and bioethanol compared to alternative uses of the biomass.

When using biomass to substitute fossil fuels in heat and power production, substitution efficiency close to 100 % can be achieved. The better alternative for $CO_2$ reduction and oil saving is, therefore, that biomass substitutes light oil in the heat sector or gas in the heat and power sectors by gas subsequently substituting oil in the transport sector. By taking these pathways, we overall achieve a much higher $CO_2$ reduction and save much more oil than by substituting oil via car engines using liquid biofuels, see the illustration in Fig. 2.

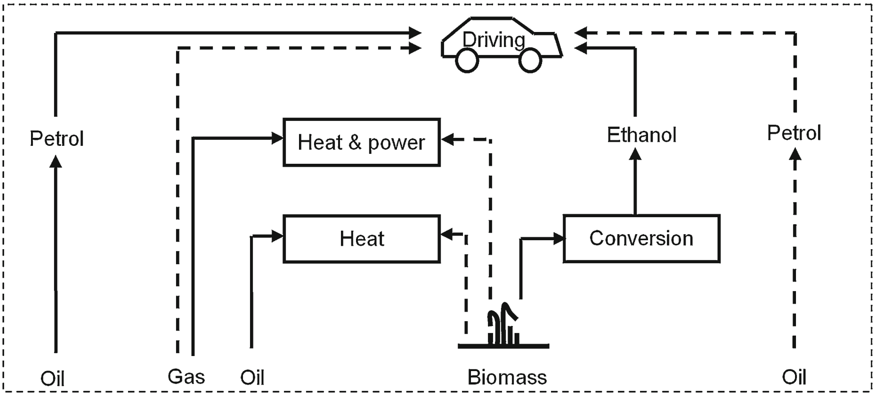

**Fig. 2** The better alternatives for energy uses of biomass are lost in the debate and in the priorities: using biomass to save light oil for heating purposes or natural gas in the heat and power sector with the subsequent use of gas to save oil in the transport sector. *Full arrows* designate induced flows, *dotted arrows* designate avoided flows

These two alternatives are much better in all aspects and can use much more than the biomass available. We lose the possibility of using these alternatives proportional to our use of biomass for liquid biofuels. Why is this point not on the agenda?

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# Part IV
# Sustainable Supply/Value Chains

# Meeting the Challenge of Sustainable Supply Chain Management

**Joseph Fiksel**

**Abstract** The pressures of social and environmental responsibility require companies to consider sustainability issues across the full product life cycle, from the conduct of upstream suppliers to the disposition of obsolete products. Leading companies have adopted a variety of sustainable business practices that reduce their supply chain footprint while generating increased value for stakeholders. Systems thinking and life cycle management are key elements in achieving measurable improvements in sustainability and profitability, and new life cycle assessment methods enable an understanding of supply chain dependencies on ecosystem services. However, incremental supply chain efficiency improvements are insufficient to slow the increases in carbon emissions and other adverse ecological impacts. Both developed and emerging economies will benefit from efforts by progressive multi-national companies to collaborate with governments and non-governmental organizations in order to decouple material flows from economic value creation. Current patterns of industrialization are unsustainable, and innovative breakthroughs will be needed to shift the global economy to a sustainable growth path. In this context, broad corporate adoption of sustainable supply chain management practices is a critical step in achieving a transition to a sustainable global economy.

**Keywords** Supply chain management · Full product life cycle · LCA · Economic value creation · Material flows

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## 1 The New Supply Chain Realities

Global competition and international sourcing have magnified the importance of supply chain management (SCM) as a core competency for major manufacturing firms. Indeed, the scope of SCM is expanding to include all of the business processes involved in fulfilling customer expectations, from product development to end-of-life disposition. Supply chains are increasingly seen as strategic assets, and companies are placing greater emphasis on collaboration with suppliers and customers that are part of their "business ecosystem". This broader "value chain" perspective of SCM encompasses not only physical assets such as facilities and vehicles but also intangible elements such as knowledge and relationships (Lambert 2006). Yet in a world of increasing complexity and turbulence, supply chain managers face enormous challenges in terms of both sustainability and resilience.

Outsourcing has blurred the boundaries of the enterprise, and companies are challenged to assure that their suppliers and service providers are complying with safety and sustainability expectations. Moreover, outsourcing may simply shift environmental burdens such as carbon emissions to less developed nations. Incidents such as discovery of corrupt labor practices and contamination of product constituents have raised public concerns, triggering renewed emphasis on supplier auditing and due diligence. Companies are increasingly expected to disclose the origins of products, including raw materials, and the conditions under which they were manufactured.

In addition, globalization has raised concerns about inequities between rich and poor countries, as well as the potential for adverse environmental impacts such as energy consumption, fresh water depletion, habitat destruction, and greenhouse gas emissions (IMF 2002). Tensions between economic opportunities and environmental and social concerns can be obstacles to global expansion, while varying regulatory requirements and cultural barriers tend to complicate the acquisition and integration of international businesses. For example, siting of production facilities in developing nations may disrupt traditional lifestyles, and the eventual closure of such facilities may adversely affect economic development.

Government directives in the European Union (EU) and elsewhere have invoked the doctrine of "extended producer responsibility" in the form end-of-life product recovery requirements, often called "product take-back". For example, the EU End-of-Life Vehicles directive of 2000 is aimed at reducing the waste generated by scrapped motor vehicles, while the EU Waste Electrical and Electronic Equipment directive of 2003 requires take-back of electronic products such as televisions, computers, and cellular phones. These policies have stimulated adoption of "reverse logistics" (Guide and Van Wassenhove 2002), and have prompted changes in product development practices throughout the affected supply chains, including design for recovery, reuse, or remanufacture of obsolete products, components, materials, and packaging.

At the same time, the adoption of "lean" manufacturing approaches, such as "just-in-time" replenishment, has made global supply chains more efficient, but also more susceptible to business interruption because their buffers and reserve capacity have been diminished. Threats ranging from technological failures to natural disasters require heightened awareness and rapid recovery capabilities; they also create opportunities for more agile companies to take advantage of openings for market penetration and growth. Advanced information technology now enables global tracking of assets and shipments, using technologies such as radio frequency identification tags. The capacity to monitor market fluctuations, communicate seamlessly with suppliers or customers, and control the flow of products and materials enables real-time, "adaptive" responses to changing supply and demand patterns, thus reducing wasted resources and increasing supply chain resilience.

The above trends have magnified the importance of corporate commitments to sustainability, social responsibility, transparency, and responsiveness to stakeholder expectations. Aside from reducing their supply chain environmental footprints, corporations are being held accountable for upholding ethical standards, respecting diversity, and demonstrating concern for employee and community well-being. A company's brand image and reputation can be deeply influenced—either positively or negatively—by the perceptions of customers and other stakeholders.

Many companies have worked hard to integrate environmental and social responsibility expertise into cross-functional teams throughout the supply chain. In the process, they have realized significant benefits—enhancing profitability, resource productivity, innovation, and growth. For example, the emergence of "environmentally preferable purchasing" has influenced the development of benign products that are more resource efficient, recyclable, and biodegradable. This chapter explores the value proposition for sustainable SCM, illustrates how early adopters have realized business value, and identifies the challenges that lie ahead.

## 2 Best Practices in Supply Chain Sustainability

Since the mid-1990s, the emphasis of leading companies has evolved from "greening the supply chain" to a recognition that excellence in environmental and social performance can contribute significantly to business value, including customer retention, revenue generation, cost reduction, and asset utilization. In particular, as companies recognize the synergies between environmental excellence and supply chain excellence, the Environmental, Health & Safety (EHS) function has gradually evolved from a reactive focus on compliance, cost containment, and risk management to play a broader role in enterprise strategy, innovation, and value creation (Fiksel et al. 2004).

A commitment to supply chain sustainability requires awareness of the full product life cycle, ranging from the conduct of upstream suppliers to the disposition of obsolete products. Life cycle awareness begins with the concept of *product stewardship*, which requires consideration of health, safety, and environmental protection as an integral part of designing, manufacturing, marketing, distributing, using, recycling, and disposing of products. For example, companies like HP and Wal-Mart have implemented green purchasing policies to assure that their suppliers adopt sustainable business practices. As multi-national firms extend into emerging markets, globalization and outsourcing have only accentuated the importance of corporate environmental and social responsibility in SCM.

Supplier–customer relationships are increasingly based on sustainability competencies. For example, many semiconductor fabrication plants, which purchase and use large volumes of chemicals, are now utilizing supplier turnkey services to provide total chemical management, including procurement, chemical handling, and waste disposition (Semiconductor Fabtech 2002). In these types of relationships, the EHS management capabilities of the supplier are an important competitive factor. Similarly, the push for supplier–customer partnerships enables companies to work more closely on designing integrated solutions for the end customer. Another global trend is the adoption of "ethical sourcing" codes, which specifically prohibit the use of forced labor, child labor, and other unfair practices.

EHS insights are also valuable for dealing with a byproduct of "lean" production and other time-sensitive order fulfillment approaches: the tendency to shift inventory burdens onto suppliers, which usually leads to demand for smaller, more frequent orders that may be less resource efficient. EHS innovations can help to reduce order fulfillment costs by devising lighter-weight, more energy-efficient packaging and transportation solutions. In addition, many companies are extending the use of business-to-business (B2B) Internet networks to handle reverse logistics and management of waste materials. B2B processes and "material pooling" could give companies much broader access to low-cost sources of recycled materials or components, and to potential market channels for unwanted byproducts.

Table 1 provides selected examples of how supply chain sustainability initiatives are helping companies to become more competitive and create sustainable value for their shareholders. The following summarizes four main strategies that companies use to redesign their products and supply chain processes in order to achieve both profitability and sustainability (Fiksel 2009).

1. *Design for Dematerialization*. Minimize material throughput as well as the associated energy and resource consumption at every stage of the life cycle. This can be achieved through a variety of techniques such as product life extension, source reduction, process simplification, remanufacturing, use of recycled inputs, or substitution of services for products. Dematerialization represents the best opportunity for decoupling economic growth from resource consumption.

   For example, in 2008, in response to a challenge from Wal-Mart to reduce packaging, HP introduced the Pavilion dv6929 notebook PC in a recycled laptop bag with 97 % less packaging than typical laptops. The carrying bag contains no foam, only some plastic bags for consumers to dispose of. The bag

**Table 1** How sustainability initiatives benefit supply chain management

| Value creation pathway | Company example |
|---|---|
| *Assure compliance* of products and business processes with laws, regulations, and industry standards | *Texas Instruments* anticipated customer needs by developing a process to verify compliance with forthcoming regulatory requirements regarding banned and restricted substances |
| *Minimize risks* and maintain business continuity by assuring product and process safety across the supply chain | *Dow Chemical* has adopted a behavior-based approach to transportation safety that cuts accident rates while decreasing fuel consumption and costs |
| *Maintain health* and well-being, both for employees and local communities, through responsible management of operating sites | *Abbott Laboratories* reduced contractor safety incidents to well below the industry average by integrating safety protocols into its automated contractor performance management system |
| *Protect the environment*, including public health and natural resources, through waste elimination, pollution prevention, and ecological stewardship | *FedEx Express* redesigned its overnight letter packaging to utilize 100 % recycled fiber without compromising product performance or long-term costs. *Coca-Cola* has adopted a water stewardship strategy to continuously improve water efficiency and ultimately achieve water neutrality |
| *Raise productivity* through material conservation, energy efficiency, waste minimization, recycling, and improved asset utilization | *Intel* saved millions of dollars annually by developing lighter-weight plastic trays for transport of microprocessor units. *Caterpillar* has established a remanufacturing division to refurbish worn-out engines to like-new condition |
| *Further relations* with customers, suppliers, and other stakeholders that influence supply chain effectiveness and license to operate | *Eastman Kodak, Hewlett-Packard, and Motorola* have published their expectations for suppliers' *EHS* performance, including corporate citizenship, product stewardship, and sustainable business practices |
| *Support innovation* in products, services, and technologies that enhance financial performance or customer satisfaction | *Kodak* and *Procter & Gamble* have used "design for environment" principles to reduce the mass of their consumer products and packaging while improving the products' functional performance |
| *Enable growth,* including acquisition and sales expansion, by performing due diligence and supporting access to new markets | *Anheuser-Busch* re-engineered its supply chain systems to cope with the increasing complexity of its products, simultaneously improving operating efficiency and environmental performance |

itself, save for the buckle, strap, and zipper, is made out of 100 % recycled fabric. Three bags fit into a box for shipment to stores, thus reducing energy use and transport costs.

The most radical approach to dematerialization is to substitute services for products. For example, car sharing services offer a convenient alternative to car ownership, enabling people to use the most effective combination of motor vehicles, walking, biking, or public transportation. The largest U.S. provider, Zipcar, claims that each of its cars replaces over 15 privately owned vehicles, thus reducing fuel consumption and emissions while relieving urban congestion.

2. *Design for Detoxification*. Minimize the potential for adverse human or ecological effects at every stage of the life cycle. This can be achieved through replacement of toxic or hazardous materials with benign ones, introduction of cleaner technologies that reduce harmful wastes and emissions, or waste modification using chemical, energetic, or biological treatment.

   For example, SC Johnson has established a Greenlist™ program to classify all the ingredients that go into its consumer products according to their impact on the environment and human health. In one case, the company reformulated a popular metal polish product so that it could be packaged in a non-PVC bottle (PET), and reduced overall life cycle costs. The new formula uses fewer chemicals, requires no hazard warning label, and can be warehoused together with other products.

   Similarly, BASF has developed a novel line of synthetic plastics, called Ecoflex®, that are completely biodegradable, and will decompose in soil or compost within a few weeks. Introduced in 1998, it has become the world's leading synthetic biodegradable material and is commonly used for trash bags or disposable packaging. Another product line, Ecovio®, is a blend of Ecoflex® and polylactic acid made from corn, and is used in flexible films for shopping bags.

3. *Design for Revalorization*. Recover residual value from materials and resources that have already been utilized in the economy, thus reducing the need for extraction of virgin resources. This can be achieved by finding secondary uses for discarded products, refurbishing or remanufacturing products and components at the end of their useful life, facilitating disassembly and material separation for durable products, and finding economical ways to recycle and reuse waste streams. Revalorization goes hand in glove with dematerialization, since repeatedly cycling materials and resources within the economy reduces the need to extract them from the environment.

   For example, Xerox pioneered the practice of converting end-of-life electronic equipment into new products and parts. Xerox began a systematic "asset recovery" program in 1991, and by 2008 remanufacturing and recycling had given new life to more than 2.8 million copiers, printers, and multifunction systems. Besides diverting nearly two billion pounds of potential waste from landfills, the program saved more than $2 billion over that period.

   Similarly, Caterpillar has established a profitable Remanufacturing Division that oversees the worldwide take-back and refurbishment of engines and components. The remanufacturing process reduces waste, minimizes the need for virgin materials, and helps ensure the recovery of end-of-life products through a closed loop reverse logistics process. In 2007, the company took back over two billion pounds of material—achieving a global return rate of 93 %. Remanufactured parts are assembled into finished products that Caterpillar warranties the same as new products.

4. *Design for Capital Protection and Renewal.* Assure the availability and integrity of the various types of productive capital that are the basis of future human prosperity. Here "capital" is used in the broadest sense. *Human capital* refers to the health, safety, security, and well-being of employees, customers, suppliers, and other enterprise stakeholders. (Also important is the preservation of social capital; namely, the institutions, relationships, and norms that underpin human society, including bonds of mutual trust.) *Natural capital* refers to the natural resources and ecosystem services that make possible all economic activity, indeed all life. *Economic capital* refers to tangible enterprise assets including facilities and equipment, as well as intellectual property, reputation, and other intangible assets that represent economic value. Capital protection involves maintaining continuity and productivity for existing capital, while renewal involves restoring, reinvesting, or generating new capital to replace that which has been depleted. Thus renewal may include attracting new talent, revitalizing ecosystems, and building new factories.

   For example, Herman Miller is known for incorporating environmental design into high-quality office furniture such as the famed Aeron chair. The company is also recognized as a leader in sustainable facility design, which builds human capital as well as natural capital. Herman Miller headquarters was one of the first "green" offices and manufacturing complexes built in the U.S., and the enhanced workplace led to noticeable increases in employee satisfaction and productivity.

   Another example is Intel Corporation's investment in preserving natural capital. The company uses ultra-pure water in its semiconductor fabrication plants, some of which are located in water-stressed areas such as Arizona and Israel. At Intel's Chandler, Arizona facility, treated process water is sent to an off-site municipal treatment plant, brought up to drinking water standards, and re-injected into the underground aquifer at a rate of about 1.5 million gallons per day.

To assure that sustainability is addressed in a pro-active fashion, most leading companies are including environmental and social responsibility managers in the cross-functional teams that guide supply chain business processes. These teams frequently work with customers, suppliers, and contractors to coordinate sustainability initiatives in areas such as product development, health and safety, process streamlining, supply chain logistics, and risk management.

Another type of collaboration that has flourished recently is the formation of joint sustainability initiatives among companies within an industry sector, often including direct competitors. In such cases, the participants have decided that it makes more sense to work collectively on managing environmental and social performance in their respective value chains. For example, the Electronic Industry Citizenship Coalition, which includes HP, Intel, and a host of international companies in the computers and telecommunication industries, has developed a supplier code of conduct and supplier assessment tools that address environmental releases, workplace health and safety, labor practices, and business ethics.

In addition to collaboration with suppliers, customers, and industry peers, many companies have pursued voluntary collaboration with government agencies. This enables them to anticipate and respond to emerging regulatory issues, such as end-of-life product take-back schemes, and at the same time help to ensure that public policy development is based on realistic information about business constraints and options. Although regulatory agencies focus primarily on enforcement, they have a growing interest in more innovative, voluntary programs that offer alternative approaches for achieving environmental goals in a more flexible manner. For example, the Green Suppliers Network is a collaborative venture among industry, the U.S. EPA, and the U.S. Department of Commerce's National Institute of Standards and Technology's Manufacturing Extension Partnership. The program works with large manufacturers to engage their small- and medium-sized suppliers in low-cost technical reviews that focus on process improvement and waste minimization. Teaching suppliers about "Lean and Clean" manufacturing techniques has helped them to increase energy efficiency, identify cost-saving opportunities, and optimize resources to eliminate waste.

Finally, the influence of non-governmental organizations (NGOs) in the sustainability field has changed dramatically with their recent mastery of information technology and the mass media. Many companies are establishing alliances with NGOs to support and validate their efforts to pursue environmental and social responsibility. For example, the Alliance for Environmental Innovation, an outgrowth of Environmental Defense, an influential NGO, has collaborated with leading companies such as FedEx Express to help design environmentally benign products and supply chain processes.

## 3 Systems Thinking and Life Cycle Management

The expanding scope of corporate sustainability concerns has gradually led to a broader scope of environmental and social governance—going beyond the process or facility fence-line to the full range of enterprise and supply chain operations. Broadening the "system" boundaries eventually encompasses the entire product life cycle, and extends beyond company operations to the supporting socioeconomic and ecological systems. Understanding the interdependencies among these systems and, in particular, quantifying the value of ecosystem services—such as carbon sequestration and nutrient cycling—has become an important new frontier for sustainability assessment (Bakshi and Fiksel 2003).

Traditional approaches to socioeconomic and environmental sustainability are based on static business models that assume a stable equilibrium. But the ecosystems and supply chains that we try to manage are actually coupled and dynamic systems which often operate far from equilibrium and exhibit nonlinear and sometimes chaotic behavior. To better understand these dynamics, we need to characterize the interdependencies and feedback loops among networks of industrial and biophysical systems. The Center for Resilience at The Ohio State

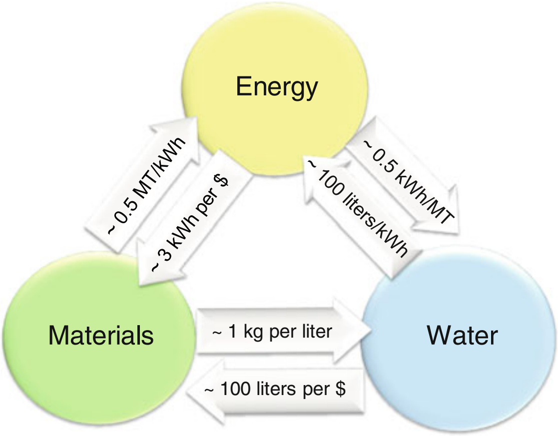

**Fig. 1** The material-energy-water nexus of essential supply chain resources

University is investigating the flows of information, materials, energy, financial capital, and labor among economic systems (including resource extraction, agriculture, and industry), societal systems (including urban centers, education, communication, and human interactions), and natural systems (including atmospheric, aquatic, biological, and geological). This type of systems thinking, with a broad life cycle scope, is essential for an enterprise to understand strategic risks and opportunities in its supply chain.[1]

A shortcoming of traditional environmental management is the separation of resources, emissions, and impacts into separate categories, as if they were independent. As companies gain insights into the drivers of their supply chain performance, they are beginning to understand the linkages among different indicators of sustainability. For example, water use and energy use are closely related—we need water to supply energy and vice versa—this is known as the "energy-water-nexus". In fact, the global water cycle is closely linked to the global carbon cycle, with vegetation playing a vital role through photosynthesis (Mauser 2007). By extension, supply chain managers must recognize the "material-energy-water nexus", depicted in Fig. 1. Materials are essential to the supply of both energy and water, and vice versa. In fact, the root cause of the enormous U.S. carbon footprint—over 7 billion metrics tons per year—is *material throughput*, which drives the consumption of energy throughout the economy.

The practice of *life cycle management* involves adopting a systems view of the enterprise supply chain, and understanding implied costs and benefits for stakeholders, as shown in Fig. 2. Resources are consumed and wastes or emissions are generated at each stage of the life cycle, from natural resource extraction through material processing, transportation, manufacturing or assembly, distribution, customer use, and eventual recycling or disposition.

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[1] The Center for Resilience website, www.resilience.osu.edu, provides information on a variety of ongoing projects and software tools that support enterprise sustainability and resilience.

**Fig. 2** Each stage in the value chain consumes natural resources, generates environmental impacts, and creates costs or benefits for stakeholders

However, the complexity and global reach of modern supply networks, which may involve hundreds of suppliers and customers, makes it challenging to measure and manage their performance. In particular, with regard to both financial and environmental performance, *life cycle analysis* tools are needed to support business decision making regarding new product introduction, supplier selection, capital investment, supply chain operations, and product take-back processes. Some companies have adopted new techniques for life cycle *cost* analysis, which quantify indirect or hidden costs across the life cycle of a facility, product, or process. These are an extension of life cycle costing methods used in the defense sector to manage weapon system programs where major costs are associated with deployment, logistical support, and decommissioning. Similar techniques have been used in construction, information technology, and other industries to capture total "cost of ownership".

*Life cycle assessment* (LCA) consists of a collection of modeling methods that seek to rigorously analyze the environmental implications of a product, process, or service from. The objective of LCA is to estimate the net energy or material flows associated with a product life cycle, as well as the associated environmental impacts (Curran 1996). By understanding these flows, companies can develop strategies to reduce their adverse impacts in ways that are cost-effective, and potentially even profitable. LCA methods have been standardized through guidelines developed by the International Organization for Standardization (ISO 14040:2006 and ISO 14044:2006). These guidelines assure that all assumptions are transparent, that the system boundaries and functional unit of analysis (i.e., product or service value delivered) are clearly defined, and that data quality, uncertainty, and gaps are clearly stated.

For example, Fig. 3 provides a simple, illustrative example of an LCA model for disposable paper cups. The life cycle is divided into five major stages—raw

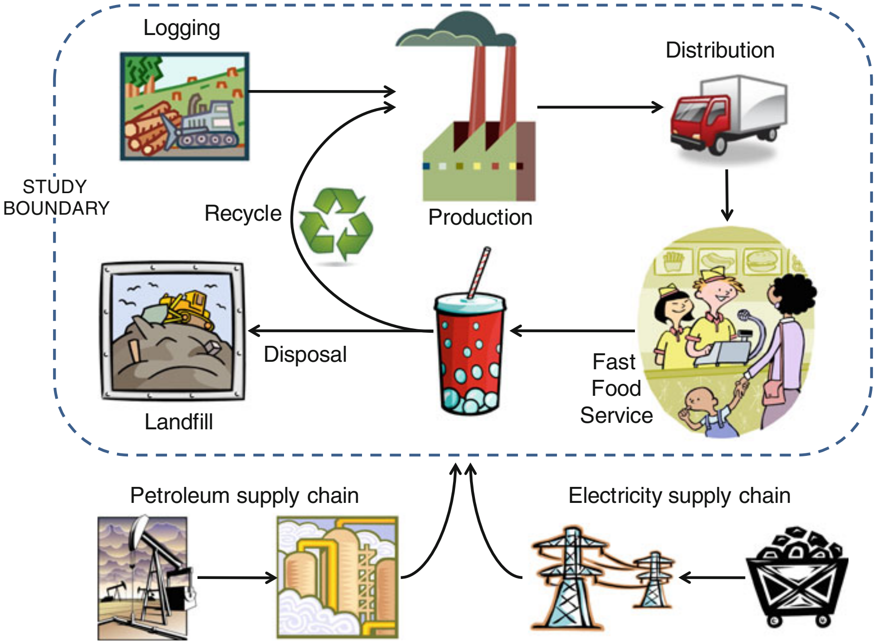


**Fig. 3** Simplified life cycle model for disposable paper cups

material extraction, production (involving multiple process steps), distribution, customer use, and end-of-life. Some fraction of used paper cups will be recycled back into the paper production chain, and the rest will go to landfill. A critical issue in LCA is establishment of the system boundary for detailed analysis in order to keep the study manageable. In Fig. 3, the system boundary excludes the supply chains that produce fuel and electric energy for paper cup manufacturing. LCA study boundaries typically exclude secondary supply chain components such as truck manufacturing and maintenance as well as infrastructure maintenance. They may also exclude secondary manufacturing inputs such as catalysts, cleaning agents, and auxiliary supplies. These practical scoping decisions can lead to important omissions that may have significant impacts.

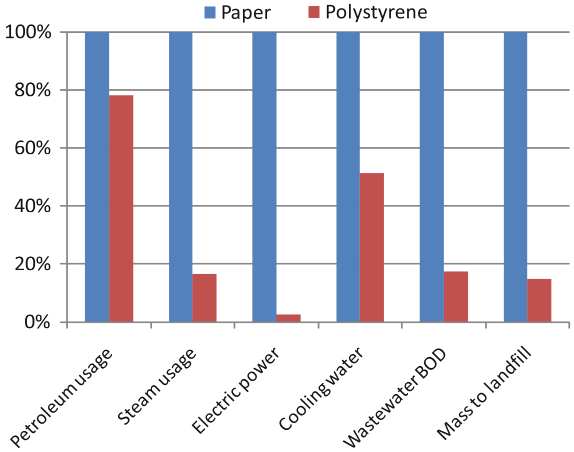
LCA begins with the development of a life cycle inventory through step-by-step analysis of each process within the study boundary (logging, production, etc.) in order to estimate the resources consumed and the waste or emissions generated. The resources typically analyzed include different types of energy and materials, and accounting for resource flows in a supply network often requires *allocation* of the environmental burdens based on relative mass or cost. Rapidly renewable energy (e.g., wind power) and materials (e.g., wood) have traditionally been regarded as resource-neutral, since they can be replaced through ecological processes, whereas consumption of non-renewable resources depletes the available stock. More recent LCA methods have begun to account for the use of water and other ecological goods and services that are necessary for continued availability of renewable resources.

An example of inventory results is shown in Fig. 4, comparing paper versus polystyrene cups in terms of resource consumption and emissions on a relative scale (Hocking 1991). A later, more comprehensive life cycle inventory study funded by the American Chemistry Council found that a 16-ounce polystyrene cup is roughly equivalent to a paper cup, but slightly preferable when the paper cup is combined with a corrugated paper sleeve (Franklin Associates 2006). In general, LCA studies often yield conflicting or inconclusive results, and are highly dependent on specific assumptions such as the end-of-life recycling rate.

The next step in LCA—considerably more challenging—is characterization of the impacts associated with resource use and environmental emissions during each life cycle stage. These impacts may include EHS impacts upon humans and ecosystems as well as economic impacts such as land use restriction and resource depletion. Moreover, impacts may be local, regional, or global in nature. The assessment of impacts is problematic because we have a relatively poor understanding of the complex physical and chemical phenomena that determine the fate and effects of substances released to the environment. Despite a great amount of continuing scientific research, our knowledge remains fragmentary and largely theoretical. In some cases, such as greenhouse gas emissions or energy consumption, the impacts are cumulative and broadly distributed, but in other cases, such as mercury emissions or water resource consumption, the impacts are highly localized and dependent upon specific environmental conditions.

Traditional methods for environmental impact assessment are not appropriate for product development purposes because they are detailed and site-specific; whereas LCA is applied at a broader system level. Instead, life cycle impact assessment uses simplified models that provide *relative* measures of impact within broad categories. These categories reflect "midpoint" indicators of potential impact rather than final endpoints; for example, the TRACI tool developed by the U.S. EPA is widely used in North America (Bare et al. 2003). Based on such

**Fig. 4** Example of life cycle inventory results for disposable cups



indicators, using simplified impact assessment coefficients, it is possible to compare design options in terms of their *potential* adverse effects on humans or the environment.

In general, there are a number of limitations to the LCA methodology described above:

- Rigorous application of LCA requires specialized expertise and training, and can involve considerable time and expense
- Process-level data are difficult to obtain and may have large uncertainties, especially with new technologies that have not been in widespread use
- LCA requires a number of assumptions and subjective judgments that may be difficult to validate, and therefore results from different investigators cannot be readily compared
- Drawing system boundaries is necessary, but may omit important stages in the upstream supply chain or downstream product use chain
- Inventory assessment alone is inadequate for meaningful comparison, yet impact assessment is fraught with scientific difficulties
- Conventional LCA does not account for ecosystem goods and services and the impacts of renewable resource use, nor does it compare the results against the biocapacity or availability of such resources.

Notwithstanding these limitations, with appropriate definition of system boundaries LCA can be a useful tool for identifying the environmental advantages or drawbacks of various design options, thus supporting product or process development decisions (Keoleian and Spitzley 2006). However, caution should be exercised in using the results of such analyses for external marketing and communication.

## 4 Supply Chain Sustainability Indicators

Because of the limitations of LCA, many companies have turned to *footprint* indicators as a less complex and more meaningful way to measure their environmental performance. Most practitioners conceive of the environmental footprint of a company, a household, or a community as being an aggregate measure of the total burden that it places on the environment. However, some have interpreted this in terms of a single metric, such as a “carbon footprint”, while others have interpreted it as a collection of indicators representing different environmental burdens (e.g., energy use, solid waste, air emissions). In the latter case, plotting these indicators on a “radar chart” enables a company to track its progress over time as the footprint shrinks toward zero (see Fig. 6).

A variety of different boundaries are commonly used for footprint analysis. For example:

- An energy consumption footprint may include only non-renewable energy sources (e.g., petro-fuels, coal, nuclear) or may include renewable sources (e.g., solar, wind, geothermal).
- A carbon footprint may focus only on greenhouse gas emissions due to fuel combustion and electricity use, or may try to account for indirect emissions (known as Scope 3) in the supply chain (WBCSD 2004).
- A material footprint may analyze total mass throughput, may focus only on consumption of input materials, or may focus on wastes, which in turn may include solids, liquids, and/or airborne emissions.
- A material footprint may include only products purchased within the economy, may include consumption of materials derived from ecological sources, such as biomass (e.g., grass, wood, fish), or may include ecological resources that are not consumed but can be degraded (e.g., water).
- An ecological footprint may use land area as an aggregate indicator of resource consumption. For example, the national footprint is estimated to be 12.3 hectares per capita in the U.S. and 6.3 hectares in Germany (Wackernagel 2001). Alternatively, newer methods such as *exergy* analysis quantify the utilization of specific ecosystem services such as climate regulation, water purification, and pollination (see Eco-LCA$^{TM}$ below).
- A water footprint may account only for direct withdrawals, or may include the total volume of fresh water used in the supply chain, known as "virtual" or "embedded" water (Gerbens-Leenes and Hoekstra 2008). For example, the total water footprint of common foods can range from about 1000 l per kg of grain to about 16,000 l per kg of beef.

To calculate supply chain footprints, some companies use streamlined LCA tools such as economic input–output (EIO) methods that model the entire economy from a top–down perspective (Hendrickson et al. 2005). The Ohio State University has developed an on-line, streamlined tool called Eco-LCA$^{TM}$ that combines an EIO model of 488 sectors of the U.S. economy with an ecological resource consumption model based on exergy, i.e., the available energy that can be extracted from a resource (Hau and Bakshi 2004). This tool can calculate a variety of supply chain indicators, ranging from a simple carbon or water footprint to a comprehensive profile of the consumption of ecosystem services such as climate regulation, water purification, and pollination.[2]

A recent LCA study of bio-based fuels, funded by the National Science Foundation, used a hybrid methodology that coupled a detailed process model of ethanol production with the Eco-LCA$^{TM}$ model of the U.S. economy. As shown in Fig. 5, this enables comparison of biofuel supply chains in terms of two important

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[2] With support from the National Science Foundation, a public version of the Eco-LCA$^{TM}$ tool is available at www.resilience.osu.edu.

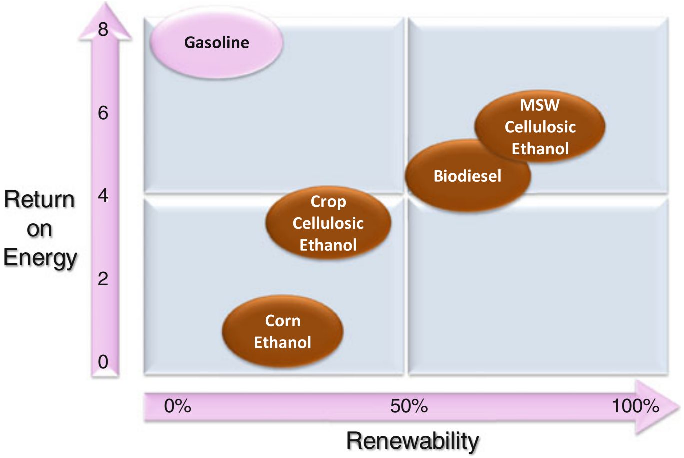

**Fig. 5** Life cycle sustainability comparison of alternative automotive fuels

sustainability indicators: *renewability* (% from renewable sources) and *return on energy* (megajoules delivered per megajoule consumed over the life cycle). For example, the study found that the renewability of municipal solid waste is far greater than corn ethanol, which requires energy-intensive harvesting. Gasoline has a far superior return on energy, although it is not renewable (Baral and Bakshi 2010).

Finally, it should be noted that environmental footprint reduction is only half the story in sustainability performance measurement. Traditional environmental footprint indicators tend to focus on emissions generated or resources consumed per ton of product delivered (see the left-hand side of Fig. 6). Perhaps more important is the measurement of value creation, i.e., delivery of human or environmental benefits through sustainable business practices. Ideally, sustainable products should address unmet human needs such as water purification and poverty alleviation. In other words, companies should strive not only to shrink their supply chain footprint but also to expand their "value footprint". Examples of value indicators used by leading companies include lifetime energy conserved per pound of product (Owens Corning insulation), lives saved per year (DuPont safety products), and percent of agricultural goods purchased through sustainable, ethical sourcing (Unilever tea).

## 5 The Challenge of Sustainable Growth

The good news is that the business goals of SCM are synergistic with the resource productivity goals of sustainability. As a result, supply chain managers are collaborating with purchasing, environmental, and other functions to enhance shareholder value throughout the supply chain. If all companies were to adopt the

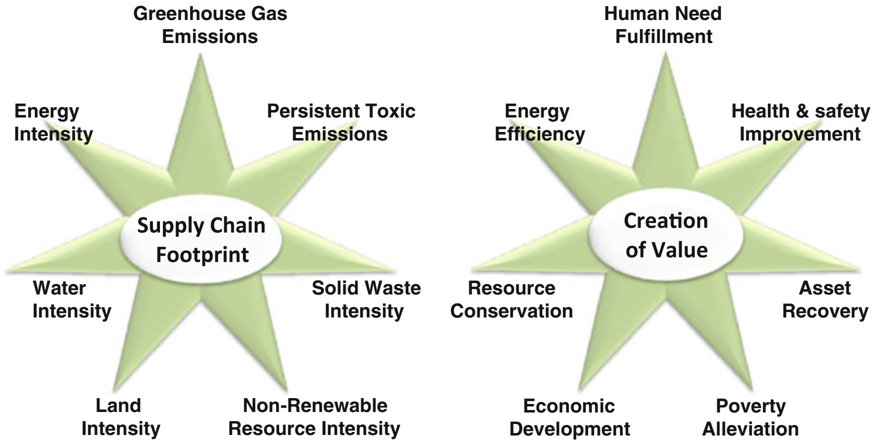

**Fig. 6** Enterprise sustainability metrics combine reduction of environmental footprint with creation of value for customers and other stakeholders

best practices described above, it might be possible to gradually reduce the enormous flows of material and energy that are required to support the expanding global economy. However, this optimistic scenario does not seem to be unfolding. Rather, it appears that global atmospheric concentrations of greenhouse gases will continue to rise, and that environmental resources will continue to be depleted or degraded, with potentially catastrophic consequences for future generations. For example, one worrisome side effect of increasing atmospheric levels of carbon dioxide is ocean acidification, which could cause corals to go extinct. If corals cannot adapt, the cascading effects in reef ecosystems will reduce global biodiversity and threaten food security for hundreds of millions of people dependent on reef fish (Carpenter et al. 2008).

A 2007 study, published by the National Academy of Sciences, showed that global $CO_2$ emissions from fossil-fuel burning and industrial processes have been accelerating, with their growth rate increasing from 1.1 % per year for the decade 1990–1999 to more than 3 % per year for the period 2000–2004 (Raupach et al. 2007).The observed rise in worldwide greenhouse gas emissions since 2000 can be attributed to increases in both the energy intensity of global supply chains as well as the carbon intensity of energy generation, coupled with continuing increases in population and per-capita gross domestic product (GDP). Not surprisingly, the growth rate in emissions has been strongest in rapidly developing economies, particularly China. The economic recession of 2008–2009 caused a temporary lull, but the long-term pattern is alarming.

The overall ecological burdens of global economic growth can be understood from the following equation, which is a generalization of the well-known Kaya identity (Yamaji et al. 1991).

$$\begin{aligned}\text{Total burden} = {} & \text{population} \times (\$\text{GDP/capita}) \times (\text{resources}/\$\text{GDP}) \\ & \times (\text{burden/resource unit}).\end{aligned}$$

The same equation holds whether the resources are fossil fuels and the burdens are greenhouse gas emissions, or whether the resources are material flows and the burdens are ecosystem service degradation. The first two factors are inexorably rising, and even if population growth slows the GDP per capita will most likely continue to rise in developing nations. Yet scientific projections indicate that we need to sharply reduce our overall emissions and waste in order to stabilize atmospheric $CO_2$ concentrations and protect natural capital. Therefore, the focus of sustainability strategies needs to be on the latter two factors:

- *Resource intensity* (resources/$GDP) can potentially be reduced by decoupling material and energy throughput from economic growth. This is as much a behavioral challenge as it is a technological challenge. Despite improvements from 1970 to 2000, resource intensity seems to be flattening out, and could even begin to rise again as personal wealth increases in developing nations. Dematerialization strategies are the best avenue for achieving further reductions in this factor.
- *Burden intensity* (burden/resource unit) can potentially be reduced through process innovations; for example, the carbon intensity of energy consumption will decline if we can scale up the use of biofuels or carbon sequestration. Likewise, the waste generated per unit of material throughput will decline if we can achieve greater eco-efficiencies through product life cycle management.

The implication is that we need to seek disruptive innovations in both production and consumption of goods and services in order to drastically reduce our material and energy requirements. For developed countries, this could mean significant lifestyle changes, but not necessarily diminished quality of life. It is conceivable that a shift toward smaller-scale distributed production, reduced reliance on motorized transportation, denser living communities, more modest consumption patterns, and reduced waste generation might actually result in less stressful and more healthful lifestyles. For developing countries, sustainable growth would imply a non-traditional pattern of growth that favors highly efficient “clean” technologies with an emphasis on social equity and inclusion. Arguably, much can be accomplished simply by scaling up existing technologies such as alternative energy sources and green buildings (Sokolow and Pacala 2006).

Achieving sustainable growth will require global collaboration on an unprecedented scale aimed at public education, environmental policy, and innovation. Companies will need to push the boundaries of their DFE efforts beyond the individual enterprise, working with customers, suppliers, competitors, and other interested parties. Governments will need to become more innovative in developing policies and strategies for large-scale infrastructure systems—urban systems, water resource systems, regional transportation systems, and energy distribution systems. To avoid the paralysis of parochial debate and traditional lobbying, we will need to form joint industry-government task forces and public–private partnerships.

For example, the United Nations has set in motion the Marrakech Process, a series of global initiatives through which countries are working toward sustainable consumption and production. Seven government-led task forces are addressing the following areas: sustainable products, lifestyles, education, building and construction, tourism, public procurement, and cooperation with Africa.

The greatest challenge to achieving environmental sustainability may be the tendency of business and government leaders to deal with issues piecemeal rather than striving for a more holistic perspective. The Kaya logic above, while it provides helpful insights, is a perfect illustration of the prevalent linear, reductionist, and incremental approach toward analyzing sustainability opportunities. As a result, sustainability policies and practices have focused mainly on *reducing unsustainability* rather than strengthening the systemic underpinnings of sustainability (Ehrenfeld 2005). Indeed, most of the company programs discussed earlier are directed largely at reducing environmental burdens, measured in terms of resource consumption and waste emissions. Little is understood about the broader impacts of these material and energy flows, or about the qualitative differences among sustainability conditions in different social and economic settings. Considering the whole system may reveal breakthrough opportunities that are not evident when one is busy optimizing the individual parts of the system (Senge et al. 2008). One example is Dow AgroSciences' innovative Sentricon™ system, which achieved a 10,000-fold reduction in pesticide volume by rethinking how termites could be detected and controlled.

Implementation of systems thinking is more difficult than it sounds. Many analysts are tempted to model complex systems from a static perspective, as if they were in "equilibrium." In truth, the ecosystems and industrial systems that we try to "manage" are dynamic, open systems operating far from equilibrium, exhibiting non-linear and sometimes chaotic behavior. Forces of change, such as technological, geopolitical, or climatic shifts, will inevitably disrupt the cycles of material and energy flows, sometimes leading to unintended consequences. For example, few people foresaw that corn-based ethanol production in the U.S. might drive up food prices in Mexico, or that floods in the Mississippi basin might cause fuel shortages. To better understand these interdependent systems, sustainability analysts need to develop new models that account for the flows of information, wealth, materials, energy, and resources among industrial systems (energy, transportation, manufacturing, food production, etc.), societal systems (urbanization, mobility, communication, etc.), and natural systems (soil, atmospheric, aquatic, biotic, etc.) (Fiksel 2006).

## 6 Conclusion

Practicing world-class SCM requires operating in a lean, agile, and responsive manner, with a focus on continuous improvement. In addition, the characteristics of a responsible company include engagement with key stakeholder groups, transparency of communications, diversity of workforce and suppliers, assurance of ethical practices, and concern for the communities in which it operates. Companies that consistently deliver shareholder value combine a relentless drive for technological superiority with an acute awareness of the expectations of stakeholders. They continuously re-examine emerging challenges and opportunities, identify critical drivers of superior performance, evaluate the competitive position of their products and processes, and pursue purposeful innovation to achieve sustained excellence. Sustainability issues have become a key consideration in this adaptive feedback loop.

As discussed above, achieving supply chain sustainability requires an understanding of the deep interdependence among global systems for the production and distribution of food, energy, and industrial goods. Moreover, a high degree of uncertainty is inherent in large-scale complex systems. The turbulence of natural, political, and economic forces exceeds our ability to predict the outcomes of our actions with any confidence. Who could have anticipated the sequence of events that swept through the U.S. in the early twenty-first century, including the September 11, 2001 attack on the World Trade Center, the devastation of Hurricane Katrina, the economic collapse of 2008, and the Gulf of Mexico oil spill in 2010? In a time of turbulence and discontinuity, old business models based on precision, stability, and repeatable processes are no longer viable. Instead, companies must hone their resilience capabilities so that they can sense and adapt to change (Pettit et al. 2010).

Current efforts at supply chain sustainability improvement have focused mainly on incremental efficiency gains, such as shorter transport distances and pooled urban distribution via common carriers. However, the real sustainability challenge is to reduce the growth of material requirements—to decouple economic well-being from resource consumption. What is needed is a paradigm shift from a *material-based* economy that emphasizes throughput, product delivery, and material wealth to a *value-based* economy that emphasizes knowledge, service delivery, and quality of life. Integrated life cycle thinking will help companies to achieve breakthrough innovation, and to collaborate with governmental and NGOs to realize the vision of a sustainable and prosperous society.

The barriers that prevent companies from making progress in sustainability are similar to those that have impeded past efforts at supply chain innovation: resource limitations, resistance to change, lack of adequate models, and lack of champions for integrated thinking. Just as earlier impediments have been overcome by articulating a clear business case to gain senior management endorsement, so too can barriers to sustainability initiatives. Enterprise leaders need to recognize that short-term profitability is not sufficient—that responsible governance and social responsibility are necessary to assure supply chain continuity and profitability over the long run.

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# Sustainable Consumption and Production: Quality, Luxury and Supply Chain Equity

**Roland Clift, Sarah Sim and Philip Sinclair**

**Abstract** Sustainable development is presented as a response to the recognition of long-term limits on the human economy, expressed as three sets of constraints: techno-economic efficiency, environmental compatibility and social equity. Assessing and improving the sustainability of products and services necessarily requires a life-cycle approach, considering the complete supply chain, and examining the role of consumption as the driver for production. The economic and environmental dimensions can be explored by integrating value chain analysis (VCA) and life-cycle assessment (LCA) to show the distribution of economic benefits and environmental impacts along the supply chain. Environmental intensities (i.e. impact per unit of added value) are frequently high for material extraction and refining, and reduce progressively along the supply chain through manufacturing and distribution. Amongst other conclusions, this finding reveals inequity and unsustainability in many supply chains. Incorporating consideration of social equity in analysis of supply chains will require further methodological development, not only to record the social benefits of activities in the supply chain but also to analyse the relationship between the agents in the supply chain. This will require "soft system" analysis to complement the "hard system" approaches of VCA and LCA. From the consumption perspective, sustainable development requires not only reduction in the environmental intensity of products and services

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but also more equitable distribution of economic and social benefits along the supply chain. For consumers in affluent societies, income is the main determinant of consumption. A popular and acceptable message for such consumers could be that sustainable consumption is consistent with purchasing expensive items with low environmental impacts and equitable supply chains, rather than cheap and frugal items; i.e. quality and luxury rather than quantity.

**Keywords** Sustainable consumption · Supply chains · Equity · Decoupling · Ecometrics

# 1 Introduction

## *1.1 Sustainability: Living within Constraints*

Given the way literature on the subject of "sustainability" and "sustainable development" has blossomed since the words were placed firmly in the international lexicon by the report of the Brundtland commission (WCED 1987), a contribution featuring "sustainability" must declare at the outset how the term is interpreted. When the concept was first articulated, the focus was on the developing world, to insist that economic development must not be pursued at the expense of environmental degradation. Increasing awareness of the interconnectedness of the global economy and realisation that some environmental impacts, notably global climate change and depletion of stratospheric ozone, affect everyone on the planet has since raised sustainable development to a universal imperative.

This particular contribution is written from the perspective of relatively affluent societies and consumers. "Sustainability" is interpreted in the sense summed up by Jackson (2010): "Sustainability is the art of living well, within the ecological limits of a finite planet", with "living well" to be interpreted in a moral sense, not merely equated with material consumption or physical comfort. "Sustainable development" is taken to mean *enhancement of quality of life and well-being.*[1] This interpretation dates back at least to the Brandt Commission: "One must avoid the persistent confusion of growth with development, and we strongly emphasize that the prime objective of development is to lead to self-fulfilment and creative partnership in the use of a nation's productive forces and its full human potential" (Brandt 1980). More recently, it has been reinforced by arguments that, for people living above subsistence levels, well-being and quality of life are not necessarily correlated positively with economic measures such as per capita GDP or

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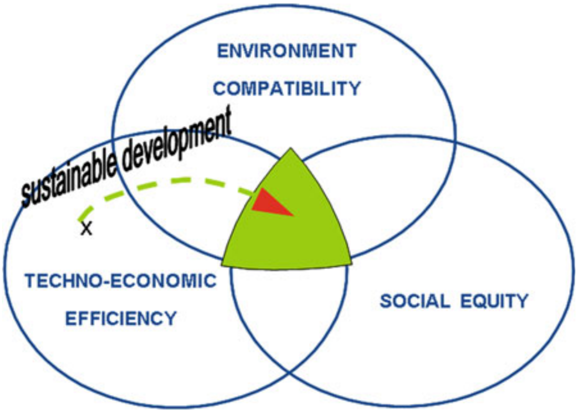
[1] Although the point is not explored here, we suggest that this approach to sustainable consumption is compatible with the views of those, like Ehrenfeld (2008), who interpret "development" in the narrow sense of growth in conventional economic output and therefore conclude that it cannot ever be sustainable.

**Fig. 1** Sustainability and sustainable development (after Clift 1995)



disposable income (e.g. Layard 2005; Jackson 2006) and that development should be interpreted as increase in freedom (Sen 1999).

The underlying principle is that we are living on a planet which is finite both in the material and energy resources available for human use and in its capacity to adapt to human activities and emissions without catastrophic change to the biosphere. It is helpful to distinguish between three sets of constraints which limit long-term human activities, and to represent them in the form of a simple Venn diagram, shown here as Fig. 1[2]. “Techno-economic efficiency” represents the ranges of activities available to us, limited by our technical skills and ingenuity, by the unassailable physical limitations represented by the laws of thermodynamics and by the need to be efficient as defined by the economic system within which we deploy our skills and ingenuity. “Environmental compatibility” represents the range of activities which can be pursued indefinitely within the resource and carrying capacity of the planet. “Social equity” represents the moral imperative implicit in the original Brundtland statement and subsequently articulated, for example in some of the UK Government’s policy statements, as “the simple idea of ensuring a better quality of life for everyone, now and for generations to come” (DETR 1999). It is related to the principle of Environmental Justice; see Blewitt (2008).

Interpreting each of the labels in Fig. 1 as a set of long-term constraints underlines that there are limits on any trade-offs between the three components. For any sustainable futures to exist, the three sets of constraints must overlap. Thus “sustainable” ways of living are represented by the region at the centre of Fig. 1. While the current human economy generally operates within the Techno-economic Efficiency lobe, as indicated by point X in Fig. 1, it clearly does not comply with either of the other sets of constraints. “Sustainable development” is then

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[2] This three-component model and its significance for the engineering profession in particular is explored in more detail elsewhere (e.g. Clift 1995, 1998, 2006; Mitchell et al. 2004; Royal Academy of Engineering, 2005). It embodies the “triple bottom line” approach to sustainability accounting.

represented by a trajectory moving from present practice to the "sustainable" region. Given that equity is essentially an ethical concept, ethical concerns about "living well" must guide this trajectory (see e.g. Mitchell et al. 2004).

Attention in the industrialised world has concentrated on environmental technology; i.e. on moving into the overlap between "Techno-economic Efficiency" and "Environmental Compatibility". Sustainability requires a "whole system" approach (Clayton and Radcliffe 1996). One of the essential tools guiding the development and deployment of environmental technologies is therefore life-cycle assessment (LCA), whose role is to reveal and quantify environmental impacts and resource use along the complete supply chain of a product or service. Attributional LCA, which describes an existing or potential supply chain, measures environmental efficiency. However, measurement of environmental compatibility in a broader sense requires consideration of the system effects of changes in economic activities. The associated tool is consequential LCA, which considers alternative uses for scarce resources, notably land in the case of biofuels (Wenzel et al. 2013), although subject to limitations in evaluating the broader consequences of macro-economic changes.

Moving to the third lobe in Fig. 1, i.e. moving from assessing environmental performance to considering sustainability, concern for "quality of life" inevitably begs the question "quality of whose life?" Applying the whole system approach to social equity within supply chains requires examination not only of the distribution of environmental impacts but also of the social and economic benefits along the supply chain, to reveal the relationship between the consumers of the products or services and the agents whose actions make up the supply chain. This contribution introduces some of the problems and possible approaches in attempting to address all three components of sustainable development in supply chains, including the shift from a production to a consumption perspective.

## *1.2 Production and Consumption*

Some of the challenges in reducing the environmental impacts of human economic activities—for example, "decarbonising" the economy—are summed up in Fig. 2. Although there are powerful arguments that total material consumption must be reduced (e.g. Arrow et al. 2004), conventional economic thinking assumes that economic activity (as measured by Gross Domestic Product, GDP, as distinct from material consumption or energy use) will continue to increase over time. To reduce the associated environmental pressure, i.e. to achieve absolute decoupling, requires the environmental intensity of economic activity (e.g. GHG emissions per unit of GDP) to decrease more rapidly than the increase in GDP. Slower reduction in environmental intensity merely leads to relative decoupling: environmental pressure continues to grow, albeit less rapidly than GDP. There is scant evidence that absolute decoupling has ever been achieved except in limited geographical areas or industrial sectors, leading to the current active debate over whether growth in GDP can be sustainable (e.g. Victor 2008; Jackson 2009a, b; Ekins 2000, 2010).

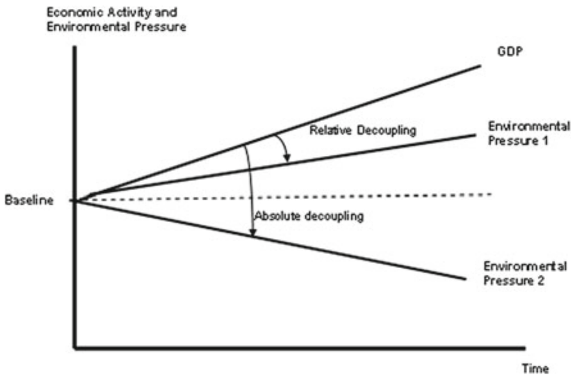

**Fig. 2** Absolute and relative decoupling of environmental pressure from economic activity (schematic)

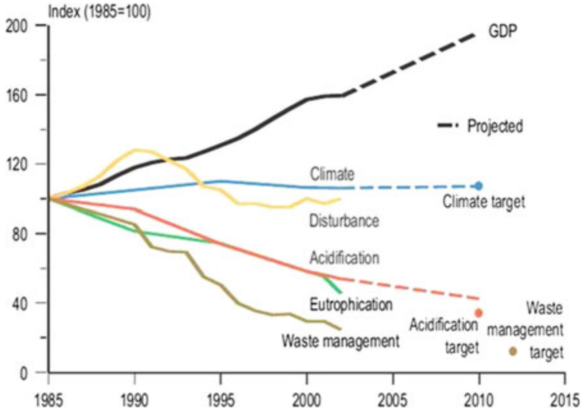

**Fig. 3** Decoupling in the Netherlands: changes in GDP and environmental impact 1985–2010 (Netherlands Environmental Assessment Agency and National Institute for Public Health and the Environment 2005)

Relating environmental pressure to GDP hides a further problem, illustrated by Fig. 3 which summarises the economic and environmental performance of the Netherlands since 1985. Whilst GDP has grown rather steadily, absolute decoupling has apparently been achieved in some components of environmental pressure and emissions of greenhouse gases have been almost constant. However, this period has also seen significant restructuring of the Netherlands economy with some environmentally intensive industries migrating elsewhere. For the specific impact of climate-forcing emissions, this phenomenon is known as "carbon leakage". The key point is that a country's environmental performance can appear to improve solely because the more polluting industries in the country are closed down and their output is imported rather than produced domestically. The environmental intensity of an economy measured allowing for the environmental pressures embodied in international trade can be radically different from that measured solely by domestic economic activities (e.g. Peters and Hertwich 2008).

Current international negotiations focus on domestic or "production" accounting, which considers only domestic activities. Whether the basis should be "consumption" accounting, based on the environmental impacts of goods and services consumed in a country, is a difficult issue which is starting to be recognised in international negotiations on mitigating climate-forcing emissions. One of the approaches being considered is imposition of "border taxes", to ensure that imported goods are subject to the same costs or taxes on emissions as those produced domestically (see e.g. Ismer and Neuhoff 2007; Izard et al. 2010). While border taxes may be compatible with current rules on international trade (Ismer and Neuhoff 2007), they are unlikely to be implemented rapidly in the absence of any international agency with the authority to regulate them. There is also discussion over the principle of border taxes on the basis that the country where the emissions arise obtains the economic benefit of the activities generating the emissions. Analysis of the different stages in the supply chain, outlined below, sheds an interesting light on this discussion.

# 2 Sustainability of Supply Chains

## *2.1 Economic Benefits and Environmental Impacts*

The relationship between these two concerns—the principle of equity (or environmental justice) which underlies the concept of sustainable development and the migration of polluting industries from developed to developing countries—can be clarified by examining the extent to which supply chains meet the general principles of sustainability outlined above. It is informative to examine supply chains in terms of a common type of ecometric (see Biswas et al. 1998) which represents the micro-level equivalent of the economy-wide environmental intensity introduced above. Each of the major steps in the supply chain is assessed in terms of its environmental pressure (e.g. the emissions of greenhouse gases) per unit of economic activity. Economic activity is measured by Added Value (i.e. the sales price of the outputs minus the costs of inputs, ancillaries and energy) rather than other economic metrics such as Gross Margin (which is net of labour costs) because Added Value represents the contribution of each operation in the supply chain to the GDP of the economy in which it is located.

This ecometric can be used to identify industrial sectors, products or processes associated with environmental impacts disproportionate to their economic value and therefore to be targeted for environmental improvement (Clift and Wright 2000). It is given by the gradient of the chord OA in Fig. 4 which represents the total impact per unit of economic value for a product entering use.[3] Figure 4 actually shows a section through an (N + 1) dimensional surface, with N environmental dimensions corresponding to different environmental impacts and one economic dimension. Aggregation across the impact categories, as in the

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[3] Figure 4 is drawn approximately to scale but without numerical values to preserve commercial confidentiality.

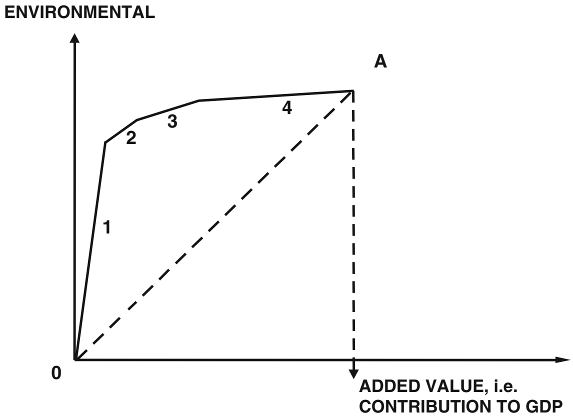

**Fig. 4** Accumulation of added value (i.e. contribution to GDP) and environmental impact along supply chain for a manufactured product (Clift and Wright 2000):
1. Resource extraction;
2. Processing and refining;
3. Manufacturing; 4. Retail and distribution

Valuation phase of LCA, collapses the surface to two dimensions but loses information and can therefore be misleading.

The ecometric can also be estimated separately for the principal stages in the supply chain by combining results from LCA and value chain analysis (VCA). Figure 4 shows the form obtained for mobile telephones (Wright 1999; Clift and Wright 2000), with the supply chain broken down into resource extraction, processing and refining, manufacturing and retail and distribution.

Figure 4 is remarkable for its extreme convexity. The environmental intensity, indicated by the gradient of each segment, is very high for the initial extraction stage and reduces progressively along the supply chain: following primary extraction and materials processing, the impacts of manufacturing as well as retailing and distributing are very much lower. This feature appears to be shared by many other manufactured products, and by textiles and garments and by food products (Sim 2006; Brandão et al. 2010): typically, primary industries have low added value and disproportionately high environmental impacts, whereas distributors and retailers (and the financial sector) realise large added value with low environmental impacts (Clift and Wright 2000). This convexity has important implications (Jackson and Clift 1998; Clift and Wright 2000; Clift 2003). Applying the principle of Environmental Justice which is central to sustainability (see above), disproportionate environmental impact in part of a supply chain indicates lack of equity and therefore unsustainability in the supply chain (Clift 2003), because an operator is either suffering local environmental damage without economic compensation or causing impacts, such as climate change, affecting others without compensating for the "externalities".[4]

A further implication of Fig. 4 is that economies seeking to expand by growing their primary sectors will not generally see an economic benefit proportionate to the environmental damage. A specific recent example is provided by the political

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[4] Whether taxes or charges to "internalise the externalities" would straighten out production curves like that in Fig. 4 is an interesting but unexplored question.

debate in New Zealand over proposals to re-open or expand mining in protected areas. The arguments against the proposals included the point that the direct economic value would not compensate for the damage to New Zealand's pristine "brand" image, backed up by analyses which showed relatively low levels of economic and social welfare in mining areas (Evans et al. 2009)—which in turn provides indirect support for the finding that primary industries are associated with disproportionately low added economic value.

Although Fig. 4 only covers the first cycle of use of a manufactured project, it has implications for re-use and recycling (Clift and Wright 2000). The undervaluing of primary resources acts as a strong economic disincentive to recovery and recycling or re-engineering of manufactured goods. While global carbon constraints could in principle lead to reduced emissions through comparative advantage effects (Strømman et al. 2009), in the absence of any international agency to minimise emissions (or regulate border taxes) the tendency is for the most polluting industries to move to countries with low or zero emission charges or loose regulation. When economic and environmental impacts are distributed as in Fig. 4, migration of primary industries from industrialised to developing countries transfers environmental impacts without proportionate economic benefit. From the perspective of the product, it means that the main environmental damages arise in the parts of the supply chain most remote from the end consumer.

As a further example of the information to be obtained from combining LCA and VCA, Fig. 5 shows the distribution of economic added value and emissions of greenhouse gases (GHGs) in the supply chains for fresh watercress[5] distributed to a particular chain of retail outlets in the UK (Sim 2006). In this case, the three principal stages in the supply chain are cultivation, harvesting and chilling; transport to the supplier's packaging plant; and final packaging and storage prior to transportation to the retail outlet. Watercress is sold all year round not differentiated in terms of price to the consumer (except for in-store promotions that may occur, for example when there is a glut in production) although the country of origin may be indicated. Therefore, the total added value is identical for watercress from all sources. The principal sources in Europe are two areas in Southern England (Hampshire and Dorset) and one in Southern Portugal. However, during the winter months supply from these sources is insufficient to meet demand; watercress is then brought in by air freight from the Southern USA. The economic returns to the US producer are lower than for the European producers, due to the higher cost of air transport. However, the most significant feature of the transatlantic trade, shown in Fig. 5, is an order-of-magnitude increase in GHG emissions. This illustrates one of the few points which apply with generality to the environmental impacts of supply chains: when air freight is used, it dominates (RCEP 2002; Sim et al. 2006). Put in a slightly different

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[5] Watercress is a green vegetable sold mainly as a constituent of prepared salads. In this form, it has become a commodity sold all year round although it is possible to substitute it by other green vegetables when it is out of season locally.

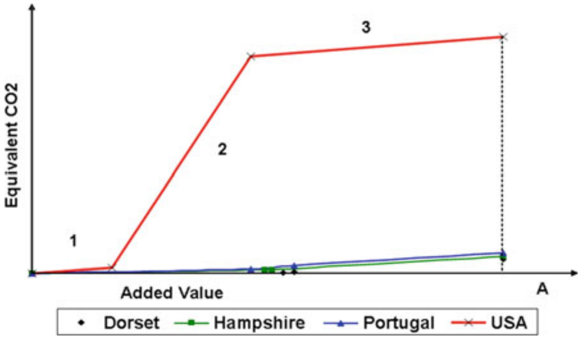

**Fig. 5** Greenhouse gas emissions associated with supply of fresh watercress in the UK (from Sim 2006). 1. Cultivation, harvesting and chilling; 2. Transport to packaging plant; 3. Final packing and storage

perspective, Fig. 5 illustrates the environmental impacts which can result from year-round consumption of a seasonal product.

The supply chains for the three European sources are relatively linear, in fact slightly concave, notably free from the gross convexity of Fig. 4 which seems to characterise most product supply chains. Sim (2006) concluded that this relatively equitable distribution of impacts and economic benefits along the supply chain results from a balanced relationship between producer and retailer, arising from the fact that few other producers are capable of providing watercress to the retailer's standards. This highlights the importance of understanding not just the technological performance but also the governance of supply chains and the relationship between the different agents (Baumann 2009). This is a particular feature of food supply chains. It is well known that LCA, a tool originally developed for analysing manufacturing supply chains, has to be modified and adapted for agricultural systems. Part of the difference lies in the fact that operations in the manufacturing and processing sectors are subject to controls which mean that the performance of a technology varies rather little according to who operates it. As a specific example, the carbon efficiencies of European petroleum refineries only vary by about 25 % (Holmes 2008). By contrast, agricultural production is much more sensitive to the practices of individual operators; this is reflected in the great range of performance of different producers, even when producing the same crop in the same geographical locality. "Soft system" approaches to analysing the governance of supply chains therefore need to be combined with the "hard system" approach of LCA (Sim 2006).

## 2.2 *Social Benefits*

Following the three-component model of sustainable development summarised by Fig. 1, the distribution of social benefits along the supply chain must also be considered in assessing sustainability. Added value is used as the economic metric in Fig. 4 because it represents the economic return to each stage in the supply chain but this does not necessarily correlate with the social benefit to the workforce (Sim 2006). The recent UNEP/SETAC initiative (UNEP 2009) represents a first attempt to assess social benefits by incorporating them into the framework of LCA. It remains to be seen whether such a formulaic approach can provide useful information; it may be that assessment of social benefits will need to be more flexible. To take an obvious example, child labour is regarded as a feature of supply chains to be eschewed; this is a valid judgment if the alternative to child labour is education, but not obviously valid if the alternative is child prostitution or enforced military service. A more flexible approach to assessing the distribution of social benefits will also need a better understanding of the governance of supply chains, again implying a "soft systems" approach to assessment.

The importance of assessing the distribution of benefits is highlighted by a real question which arises in sustainable management of supply chains. Fresh vegetables and other produce, including cut flowers, are grown in parts of sub-Saharan Africa and air-freighted to consumers in wealthier parts of the world. The environmental impacts are large, in terms of contribution to climate change from the air freight (Sim et al. 2006) and also water use in water-stressed regions. The former represents impacts on the whole planet which are not internalised into the cost of transport, while the latter is an example of local impact which consumes a scarce resource and reduces its availability for crops for local consumption. However, if the trade were to be stopped suddenly, on the basis that the environmental impacts are unsustainable, there would be serious social and economic consequences for workers in this industry in producer countries. From the point of view of the actor controlling the supply chain, most commonly the retailer (see below), the trade might be justified in terms of an argument articulated, for example, by Cramer (2006), that the core business of a responsible company should support the development of countries from which they source products, but this would constitute a strategic purchasing decision to be taken after appropriate deliberation. An approach which might be explored is to investigate whether the social and economic benefits can legitimately be considered to outweigh the environmental impacts, provided that the benefits accrue to producers in developing countries rather than to privileged consumers in relatively affluent groups or societies. Thus recognition of the Social Equity component of sustainable development has implications for sustainable consumption which merit further exploration.

## 3 Sustainable Consumption and the Role of Luxury Spending

For consumers in affluent societies living at levels way above mere subsistence, consumption is determined not by needs but by disposable income (e.g. Kok et al. 2006; Lenzen et al. 2006); it would be naïve or impossibly idealistic to suggest that consumers will only spend what is necessary to meet their needs and will save or

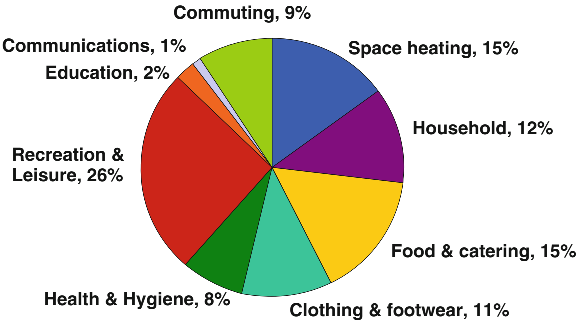

**Fig. 6** Life-cycle $CO_2$ emissions allocated to aggregated high-level functional uses for an average UK household in 2004 (from Druckman and Jackson 2009)

give away their surplus income. Furthermore, the current economic paradigm requires consumption in order to support economic activity, demonstrated graphically by moves throughout the industrialised world to promote consumption as one of the principal tools to combat recession.

The analysis outlined here shows why sustainable consumption in the developed world needs to shift towards products which not only cause less resource use or environmental damage but also provide equitable social and economic benefits back along the supply chain. Most current efforts to influence consumer spending, such as ecolabels and "carbon footprint" labels, focus on identifying products with reduced environmental impacts and only report the overall performance—in effect, OA in Fig. 4. To give information on the distribution of impacts and benefits along the whole supply chain will require a different (and largely unexplored) approach to communication with consumers. The information imparted will inevitably be multi-dimensional and complicated and therefore not reducible to simple labels. Communication will therefore depend on retailers for implementation and its effectiveness will depend on maintaining the trust of consumers in the retailers providing this information. The enhanced role for the retailer represents further reinforcement of the trend already established by ecolabels and carbon labels (Clift et al. 2005, 2009). The beginnings of labelling for equitable economic and social benefits can be seen in the "Fair Trade" movement, whose objective is to identify and promote products which ensure a flow of economic and social benefits to the agents in the earlier stages of the supply chain. The wide acceptance of the Fair Trade movement has shown that this approach to promoting sustainable consumption can influence consumer behaviour. However, systematic empirical assessment of the benefits of Fair Trade and similar schemes appears to be lacking; at present, the movement is based on the assumption that better processes in the management of a supply chain automatically lead to more equitable outcomes.

Against this background, we can consider how a responsible consumer might direct their spending to promote sustainability by reducing the environmental impacts and improving and spreading the social benefits caused by their consumption. Figure 6, from Druckman and Jackson (2009), shows the distribution of greenhouse emissions associated with routine expenditure of an average UK household; broadly similar patterns of the impacts of household consumption have been identified for other European countries (e.g. Carlsson-Kanyama et al. 2005; Moll et al. 2005; Peters and Hertwich 2006; Hertwich 2006; Girod and de Haan 2009).

The first clear conclusion is that environmental impacts are spread across most forms of consumer spending.[6] One of the more depressing findings is that average environmental intensity differs rather little between most aggregated categories of consumer expenditure; all but the most environmentally damaging or benign forms of consumer expenditure in Europe differ by only about a factor of three in aggregated life-cycle impact per euro spent (Huppes et al. 2006; European Commission 2006). Thus there is limited scope for consumers to reduce their environmental impact by redistributing their spending between different categories of goods and services (see also Gutowski et al. 2008), although there is some scope to redirect spending from "bad" to "good" outliers. Under these circumstances, with total consumptive expenditure limited by disposable income (see above), "rebound"—the phenomenon whereby reduction in environmental impact, for example through improved technology, is countered by increases or shifts in consumption—is difficult to avoid (e.g. Hertwich 2005). To give an obvious example, money saved on "Space Heating" through improved household insulation can lead to even larger impacts if the disposable income is spent instead on recreational air travel in the "Recreation and Leisure" category.

Thus, it is generally necessary for responsible and motivated consumers to look within each category of expenditure to identify purchases with reduced environmental impact and increased social benefit per unit of expenditure. A specific example—avoiding out-of-season produce shipped by air freight—was introduced above. Changes in diet, notably to reduce consumption of meat and dairy produce, represent a more general way to reduce the impact of food consumption (e.g. Carlsson-Kanyama et al. 2005). Another, less obvious, example of consumption to be promoted rather than discouraged, purely on the basis of its contribution to sustainable development, is relatively expensive, high-quality, luxury "Fair Trade" chocolate: low impact for the expenditure, chosen because the purchase should benefit all the agents along the supply chains and, according to most tastes, an enjoyable as well as equitable form of consumption—an example of "living well within the ecological limits".

Similar arguments apply to other categories in Fig. 6, notably "Household" and "Clothing and Footwear". In these cases, more sustainable consumption is represented by durable purchases which are usually associated with relatively high initial cost, contrary to the general trend for service life to be limited by obsolescence due to unfashionability rather than loss of function (Stahel 2006; Clift and Allwood 2011). Longer service lives obviously reduce not only the environmental impacts of production but also the impacts of waste disposal. It is recognised that

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[6] The relatively large contribution of "Recreation and Leisure" in Fig. 6 is due to air travel for vacations (Druckman A, 2010, personal communication), a further illustration of the disproportionate impacts of aviation noted above.

this proposal runs contrary to current social trends. For example, the fashion for cheap discardable clothing in Europe has led to a measurable increase in the proportion of textiles entering the municipal waste stream.[7] However, Girod and de Haan (2009) have explored the possibility that quality-oriented consumption can be more sustainable, specifically for Swiss households. Their empirical results show, inter alia, that "low emitters opt for higher prices while high emitters pay lower prices" and "high emitters spend a higher amount on mobility while low emitters opt for leisure" reinforcing the argument advanced here. Some companies, particularly those in the retail sector whose market niche includes perceived "quality" (e.g. Marks and Spencer 2011), are already starting to adopt sustainability as a company and product characteristic, although it is not clear whether business generally sees this as anything more fundamental than a "megatrend" (Lubin and Esty 2010).

Quality clothes and durable household goods are examples of directing consumer spending to quality goods; i.e. products and services with higher initial cost but with low environmental impact over their life cycles and high skilled labour per unit of consumer expenditure. In effect, we are advocating quality, high cost purchases with equitable supply chains as a key component of sustainable consumption. In terms of the behavioural change models identified by Tukker et al. (2010), we are advocating promoting quality as the "symbolic or identity value" guiding consumption, at least for the most affluent.

For the most affluent inhabitants of the planet, even quality purchases of essential items will not use up their disposable income. Pursuing the argument that consumption is determined not by needs but by disposable income, we therefore ask how surplus income should be spent; i.e. what principles should guide luxury spending. "Sustainable luxury" would entail purchases with low environmental impact and equitable supply chains, rather than more obviously "luxurious" purchases such as fuel-inefficient personal vehicles or air travel.

Although Alfredsson (2004) has questioned whether this approach could bring about a real reduction in the environmental impacts of consumption, Girod and de Haan (2009) argue that Alfredsson underestimates the influence of "green consumers" as role models and overestimated the "rebound" of such a shift in consumption patterns. The argument here is that, if luxury or quality purchasing were to become more widespread in affluent societies, Alfredson's argument—which is essentially that a few individual purchases are too insignificant to be influential—would become irrelevant. More demand for luxury goods would promote high-labour low-impact activities: more skilled seamstresses and fewer sweat-shops; more artists and fewer air crew.

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[7] In the UK, this has become known officially as "the Primark effect" (House of Commons 2010) after a successful clothing retail chain.

We illustrate the principle of luxury consumption by a specific example: purchase of a work of art, a cast bronze sculpture—“Sarabande” by Philip Jackson. The carbon intensity of the purchase is estimated at about 0.01 kg $CO_2$ (eq) per € (see Appendix). This makes it clearly a “good” outlier in the range of consumer expenditure, way below the average impact for Europe, much better even than the broad categories of “education” and “health” which show the least contribution to climate change per unit of expenditure (Huppes et al. 2006). The carbon intensity is more than 100 times lower than for air travel within Europe. These figures are stark enough to justify another general conclusion: it is more sustainable to purchase works of art as luxury items than to undertake luxury travel by air to view them.

# 4 Concluding Remarks

To sum up, the three-component model of sustainability must be applied to complete supply chains or life cycles if the notion of sustainable consumption is to be made operational. However, much more work is needed to characterise and measure equity in supply chains. Consumer purchasing, particularly by the more affluent members of society, should be directed to expensive quality or luxury goods with low environmental impact per unit of expenditure and equitable supply chains. This interpretation of quality and luxury needs more exploration, but the message is that sustainable consumption does not necessarily require frugality; it can be consistent with a luxurious life—“living well” in both senses. Following Faiers et al. (2007), we suggest that this message could represent a way to popularise and promote the idea of sustainable consumption to the more affluent inhabitants of the planet.

In brief: angels, rather than devils, wear Prada. By contrast, no matter how well managed its supply chains, a company whose business model turns capital or durable purchases into mere consumer goods is not promoting sustainability.

# 5 Appendix

## *Estimation of Carbon Intensity of “Sarabande”*

The statue of Sarabande, by Philip Jackson, is cast bronze, weighing about 200 kg. Carbon dioxide emissions for primary metal production are taken as 2.63 kg per kg bronze (Ecoinvent 2009). Therefore the GHG emissions embodied in the metal are about 525 kg $CO_2$ eq. This figure is conservative, because it assumes that virgin metal only is used.

The energy required to cast bronze is assumed to be similar to the latent heat of fusion of Copper, about 205 kJ/kg (Engineering Toolbox 2010). Assuming that gas is used as fuel in the foundry with 60 % efficiency of energy transfer to the metal, and that the greenhouse gas emissions over supply and use are 0.053 kg $CO_2$ eq/MJ, the emissions associated with melting 200 kg of bronze are

$$200 \times 205 \times 0.053/(0.6 \times 1000)\,\mathrm{kg\,CO_2\,eq} = 3.62\,\mathrm{kg\,CO_2\,eq}$$

Therefore the total GHG emissions associated with producing Sarabande are approx 525 + 4 = 529 kg $CO_2$ eq, about 530 kg $CO_2$ eq. Note that this figure is dominated by the metal with relatively small contribution from the casting process. Transport and installation will be small by comparison and have therefore been ignored. The embodied energy would therefore not be lost if some barbarian decided to fashion the bronze into something else.

With a purchase price of nearly £40,000, the GHG intensity of the purchase is

$$530/4 \times 10^4 = 0.013\,\mathrm{kg\,CO_2\,eq\ per\ £}$$

For comparison, a return flight from London to Gothenburg, a typical distance for a flight within Europe, costs typically £120 (fare plus taxes and fuel surcharge) and the associated carbon dioxide emissions are 273 kg per passenger (SAS 2010), roughly half the emissions associated with making Sarabande and corresponding to 2.3 kg $CO_2$ eq per £ spent. The type of aircraft on this route (MD82) is relatively old and fuel-inefficient. However, there is an argument that the radiative forcing should be estimated allowing for other effects, such as condensation trails, by multiplying the carbon dioxide emissions by a factor approaching 3 (RCEP 2002). This figure also puts the flight slightly below the average figure estimated by Huppes et al. (2006) for private transport, which is to be expected since the climate impacts for air travel are somewhat less than those for a single passenger in a typical gasoline-powered car (RCEP 2002). Furthermore, the estimates by Huppes et al. were obtained by input/output analysis so that exact agreement with process-based LCA figures derived here cannot be expected. In fact, the consistency is remarkably good. We therefore retain the simple estimate for the current aircraft.

The figures for environmental intensity, based on currency exchange rates at January 2010, are:

| kg $CO_2$ per | £ | € | $ |
|---|---|---|---|
| Sarabande | 0.013 | 0.01 | 0.008 |
| London–Gothenburg | 2.3 | 2.0 | 1.4 |

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# Transforming Supply Chains to Create Sustainable Value for All Stakeholders

**Fazleena Badurdeen, Thomas J. Goldsby, Deepak Iyengar and I.S. Jawahir**

**Abstract** Promoting sustainability in business operations requires that products, processes as well as the entire supply chain (the system) is designed and operated taking account of not only economic benefits but also environmental and societal implications. Creating value along these three dimensions—that is sustainable value—to all stakeholders is not easy because it requires companies to deliver value to shareholders (one group among the many stakeholders) without transferring value from other stakeholders. From a supply chain perspective, economic value-added has long been used as a measure to evaluate supply chain performance. However, to generate sustainable value to all stakeholders it becomes necessary to also address environmental and societal impacts/benefits as those are two areas through which value is gained or lost for other stakeholders. This chapter presents the concept of sustainable value creation and why the scope of conventional supply chain management processes must be broadened to generate sustainable value, supported by a discussion of successful/disastrous case examples.

**Keywords** Supply chain · Sustainable value · Stakeholder · Triple bottom line

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## 1 Introduction

The move toward sustainable business practices is no longer a choice but a necessity. A number of major trends—some generating opportunities and others demanding compliance—are forcing companies to reconsider their exclusive emphasis on creating shareholder value (Laszlo 2008). These trends include: (1) rising sustainability expectations of the civil society; (2) the gap between social needs and public sector solutions offered; (3) information and communication technology (ICT) driven low-cost collaborative platforms for companies to create virtual communities; (4) the regulatory and other costs attached to environmental/social impacts in some markets and (5) tougher performance standards mandated by local, national, and international legislation.

Supply chain management, the process of managing internal business practices as well as those across organizational boundaries, traditionally emphasized generating value for the company's shareholders; Economic value-added or EVA (Lambert 2008a, b, c) has been an often used metric of performance. However, the transition toward more sustainability-oriented practices requires a shift toward sustainable supply chain practices and the use of sustainability value-added (SVA) to evaluate performance.

Following the Bruntdland Commission's report, sustainable development is defined in terms of what is needed "…to meet the needs of the present without compromising the ability of future generations to meet their own needs" (UNWCED 1987). This all encompassing description makes it difficult to discern the boundaries of what does, or does not, constitute sustainable development. A more practical description that resonates better with the corporate world and relates to business practices was presented by Elkington (1998) who described the goal of sustainability as achieving the triple bottom line (TBL): economic value, environmental protection, and societal well-being.

To promote sustainability in business operations the products, processes, and the system need to be designed and operated taking into account the TBL implications; that means, the entire supply chain must be sustainable. Corporations have long realized the importance of managing their relationships with their partners—suppliers as well as customers—to increase profitability by providing customers with better quality products/services faster and more cost-effectively. Except for a few progressive companies, for most organizations the key performance driver in all supply chain decisions has been increasing the economic value-added (EVA). With the need to incorporate sustainability thinking in business practices, companies must now also consider the environmental and societal implications of their operations. There is also a need to evaluate products and their usage at end-of-life. Extended producer responsibility regulations in some regions have mandated such practices by companies in several industries. This means sustainable supply chains require a much broader emphasis that incorporates a number of aspects not conventionally addressed in supply chain management. There is a need to reconsider the relevance and comprehensiveness of conventional supply chain frameworks and models used for decision making in terms of their ability to integrate the TBL and total life-cycle perspectives necessary for sustainable supply chain operations. This chapter is an attempt to address that void by comprehensively examining one of the supply chain management models to appraise the various factors that must be integrated to develop sustainable supply chains.

The remaining sections of the chapter are organized as follows. Section 2 provides an introduction to the concept of sustainable supply chains and their management in comparison to how supply chains have been looked at traditionally. The concept of sustainable value (Lazlo 2008)—important to provide benefit to all stakeholders—is also discussed in this section. Some of the more widely used supply chain management models are briefly discussed in Sect. 3. Section 4 is devoted to an in-depth discussion on how sustainability considerations can be integrated to the supply chain management model presented by the Global Supply Chain Forum (GSCF). Concluding remarks are presented in Sect. 5.

## 2 Sustainability in the Supply Chain

The Council of Supply Chain Management Professionals (CSCMP) describes that supply chain management 'encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers' (CSCMP 2010). This definition illustrates the focus on delivering a product/service to consumers by managing the flow from raw materials to finished goods to maximize the economic returns. However, a sustainable supply chain requires a broader emphasis along multiple dimensions.

The most significant and challenging shift in emphasis is called for in how supply chain performance is evaluated; it requires a move from short-term financial emphasis to the pursuit of long-term benefits for all other stakeholders as well. That is, the need to incorporate environmental integrity and social well-being in business decision making as well as performance evaluation. The narrower conventional focus of supply chain management is indicative that managers have for a long time only considered three of the four stages in a product's life-cycle: pre-manufacturing, manufacturing, use, and post-use. Promoting environmental and societal well-being inevitably requires paying attention to what comes of the products at the end-of-life. For example, are the lead-containing components disposed of responsibly without harm to society, is the value remaining in components/materials recovered for refurbished/new products, etc. None of these kinds of questions can become part of supply chain practices unless the last stage—post-use—is explicitly considered at all levels from procurement to distribution. Therefore, sustainable supply chain management (SSCM) also calls for a holistic and total life-cycle-based approach. One approach to incorporate such a holistic view is to adopt the 6R's—reduce, reuse, recycle, recover, redesign, and remanufacture (Joshi et al. 2006)—across multiple life-cycles, moving away from the earlier 3R's (USEPA 2008), an approach primarily concerned with the environment.

## 2.1 Sustainable Supply Chain Management

Given the need to incorporate a holistic and total life-cycle-based approach in sustainable supply chains, most of the existing definitions (e.g. NZBCSD 2003) do not fully capture all relevant aspects. One approach that extends the supply chain management definition (of CSCMP 2010) to capture the enlarged focus describes SSCM as involving "the planning and management of sourcing, procurement, conversion and logistics activities involved during pre-manufacturing, manufacturing, use and post-use stages in the life-cycle in closed-loop through multiple life-cycles with seamless information sharing about all product life-cycle stages between companies by explicitly considering the social and environmental implications to achieve a shared vision" (Badurdeen et al. 2009).

This view of SSCM is illustrated in Fig. 1. In the figure, the product life-cycle stages are overlaid on a supply chain map to illustrate that companies spanning it are engaged in activities relating to different stages of a product's life-cycle. As shown, the 6R's provide a platform to link the forward and reverse flows for closed-loop flow in supply chains.

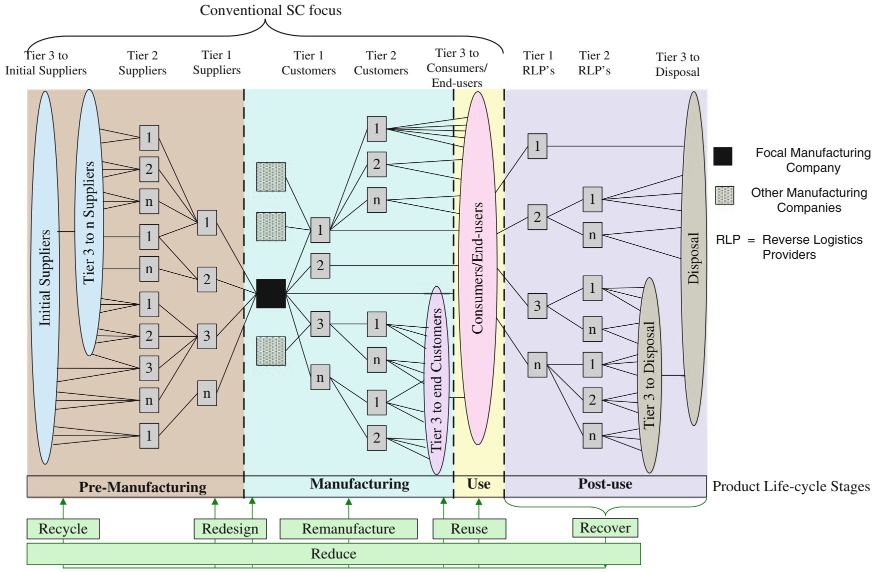

**Fig. 1** Integrated approach to SSCM (Badurdeen et al. 2009)

## 2.2 Sustainable Value-Added

Business practices have conventionally focused on increasing shareholder value, in other words boosting economic performance. With the emergence of sustainability concerns, other stakeholders—who according to one definition is anyone that can help or hurt a business (Laszlo 2005)—and the benefits or costs to all of them resulting from a company's business operations have turned out to be more important than previously considered. EVA (Lambert 2008a, b, c; Elkington 2004) is one means to assess the value created by corporations. However, this economic (or shareholder) value created by a business can generate positive or negative value for other stakeholders (Laszlo 2005). The explosion aboard the Deepwater Horizon offshore rig in the Gulf of Mexico led to millions of gallons of crude oil spillage, threatening wildlife and livelihood of people in the region. This incident, which preliminary reports show was a result of various steps taken to cut time and cost (Waxman and Stupak 2010) exemplifies the impact of companies focusing only on increasing shareholder value at the expense of creating sustainable value (Badurdeen et al. 2010). Sustainable value will be generated only when business practices deliver value to shareholders without transferring it from other stakeholders (Laszlo 2008). Any situation leading to complete value transfer from shareholders to other stakeholders or away from the two groups will lead to unsustainable business practices, as shown in Fig. 2.

Thus, for supply chains (and enterprises within) to create sustainable value there are two requirements that must be satisfied. First requirement is that value must be generated (not lost) for all stakeholders (including shareholders). However, what is value to one stakeholder group is likely to be different from that to another group. This means that sustainable value cannot be evaluated merely by

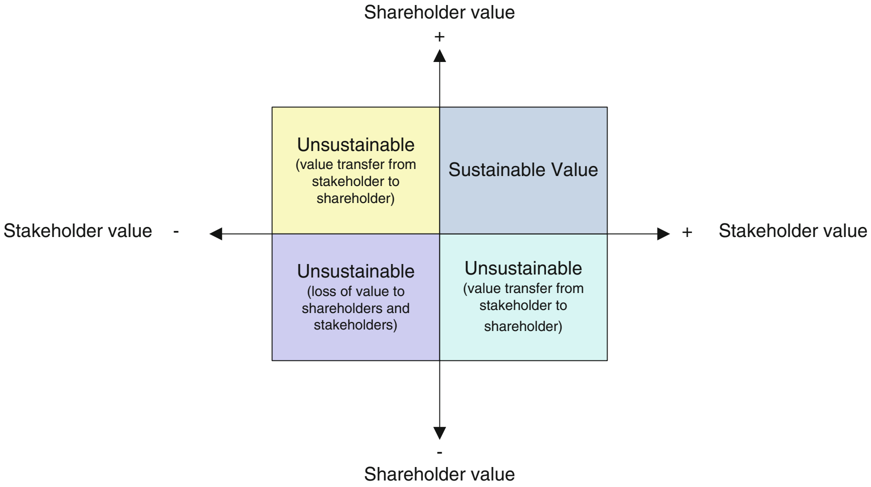

**Fig. 2** Sustainable value framework (adapted from Laszlo 2008)

considering the economic value to all stakeholders. Environmental and societal performance are the two areas through which value is often gained or lost for other stakeholders (Elkington 2004). Therefore, the second requirement to sustainable value generation is a focus on generating economic, environmental, and societal benefits (or minimizing the negative aspects of the latter two)—the TBL—to all stakeholders.

When it comes to supply chain performance evaluation, EVA is the widely used to measure and it is limited to only evaluating the value of business to shareholders; it cannot fully capture the benefits or costs to other stakeholders. Thus, the transition to sustainable supply chain practices will be futile unless accompanied by methods to evaluate the sustainable value-added (SVA) to all stakeholders. Including methods to evaluate environmental value-added (EnVA) and societal value-added (ScVA) in supply chain operations is necessary if SVA is to be assessed. However, most of the existing measures of assessing sustainability are limited to studying the impacts at the company level, not the supply chain [a notable exception is the joint effort by the World Business Council for Sustainable Development and World Resource Institute to develop standards for product life-cycle and value chain accounting (WBCSD-WRI 2009)]. Supply chain operations transcend internal practices to cover those outside organizational boundaries, upstream and downstream. That means evaluating SVA in a supply chain must include the impacts upstream and downstream from the focal company, which span the activities involved in the entire life-cycle of the product from pre-manufacturing through post-use stages. While the need to focus on the entire supply chain in pursuing sustainability has been pointed out (Minter 2010), it is still a new concept for many companies; there are no agreed upon metrics for assessing sustainability at the supply chain level (Wiedmann and Lenzen 2006).

Also relevant to generating sustainable value is the question of who should be involved in its creation. Conventionally, value creation was considered to take place within the enterprise and customers were outside, hence the notion of the 'value chain' which did not include the customer (Porter 1980). However, lately companies have begun to realize that customers are not willing to be passive recipients of products and services; they are interested in playing an active role in creating value (Prahalad and Ramaswamy 2004). When it comes to generating sustainable value, the process of engaging the key stakeholders is even more important. Ueda et al. (2009) present three models for value creation based on the nature of interactions that take place between different stakeholders: producers, customers, and the environment (they cluster everything external to the two former groups as the environment). The three models are: Class I—Providing value model, Class II—Adaptive value model, and Class III—Co-creative value model (Ueda et al. 2009). The nature of interaction between the different agents in each case is illustrated in Fig. 3. The class III model of co-creation is based on the premise of customers and producers creating sustainable value together (as previously presented by Prahalad and Ramaswamy 2004), interacting and exchanging information with each other and how it affects all other stakeholders.

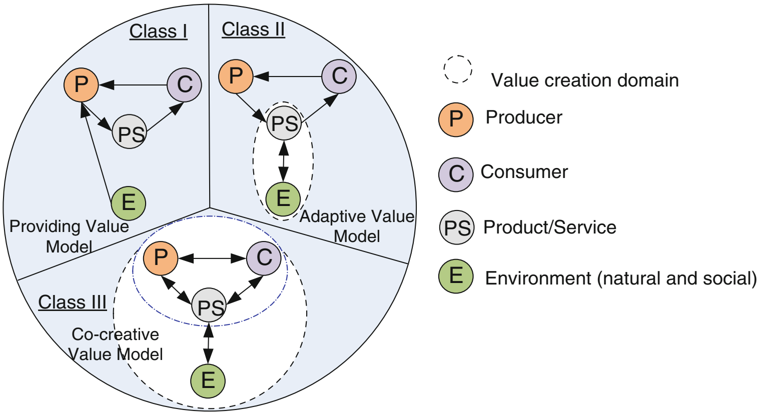

**Fig. 3** Models for sustainable value co-creation (based on Ueda et al. 2009)

This concept of sustainable value co-creation must be extended for application to the supply chain. The supply chain being a group of companies who rely on each other to get the product or service to market, sustainable value co-creation must address contribution to/impact on each of them as well.

## 3 Supply Chain Management Models

Several supply chain management models have been presented to help promote a more formalized and objective approach to managing supply chain operations. While the Supply Chain Council's Supply Chain Operations Reference (SCOR) model (CSCMP 2010) and The Ohio State University's GSCF model (Lambert 2008a, b, c) are better known, other models available include the American Production Quality Control's (APQC) Process Classification Framework (PCF) and Supply Chain Consortium's Best Practice Framework (Moberg et al. 2008). Given the scope of sustainable supply chains as explained above, assessing the more widely used supply chain management models to evaluate to what extent, if any, they include sustainability issues is a logical first step.

SCOR is a process reference model that aims at promoting standardized metrics by member firms based on benchmark cross-industry management practices. The latest version of the model (SCOR 9.0) devises five distinct management processes: plan, source, make, deliver, and return. SCOR is an operational level tool that can be used to improve supply chain processes by identifying key metrics that are organized in a multi-level framework; however, it is unable to capture the complexities in the supply chain, for example, the interactions between various processes or between those of different members in the supply chain. While the latest version of the model includes a 'return' process, societal and environmental impacts (important in sustainable supply chains) on all stakeholders (including shareholders) cannot be captured effectively; SCOR being an operational model does not have the strategic focus necessary to plan for or evaluate the supply chain partner relationships important to promoting sustainability. The GSCF model has eight supply chain processes (discussed in detail below) covering strategic and operational aspects. The GSCF model also pays especial emphasis to the importance of managing supply chain partner relationships, which from a sustainability perspective, is critical given the need to integrate activities across all four life-cycle stages of a product. However, both the SCOR and GSCF models have a singular focus on managing and evaluating the EVA of supply chain practices, a limitation that must be addressed if they are adopted for use to manage sustainable supply chains and assessing SVA. Given that the GSCF framework has a strategic focus and emphasizes managing supply chain partner relationships to improve the processes, it is better suited to incorporate sustainability considerations than the SCOR model. [For a more comprehensive comparison of the SCOR and GSCF models for their applicability to sustainable supply chains, the reader is referred to Badurdeen et al. (2009)]. The GSCF is also more promising in terms of capability to accommodate the holistic and total life-cycle emphasis needed to increase SVA in SSCM. Therefore, we present a comprehensive review of its eight supply chain processes from a sustainability perspective in the following sections.

## 4 Extending the Global Supply Chain Forum Model for SSCM

Though more difficult to implement the GSCF framework is believed to be broader than SCOR (Lambert et al. 2005); it is the broader view that makes its application to sustainability worth careful examination. The GSCF view includes eight key business processes:

- Customer Relationship Management (CRM)
- Supplier Relationship Management (SRM)
- Customer Service Management (SCM)
- Demand Management (DM)
- Manufacturing Flow Management (MFM)
- Product Development & Commercialization (PD&C)
- Order Fulfillment (OF)
- Returns Management (RM)

Several of these processes appear similar to the five processes established in the SCOR model (Lambert 2008a). For example, DM resembles SCOR's Plan process; SRM, MFM, and OF resemble Source, Make, and Deliver while RM and SCOR's Return process appear similar. Yet the GSCF processes focus on more than the management of physical flows in the supply chain. Its larger framework focuses on the management of relationships among supply chain members between whom the

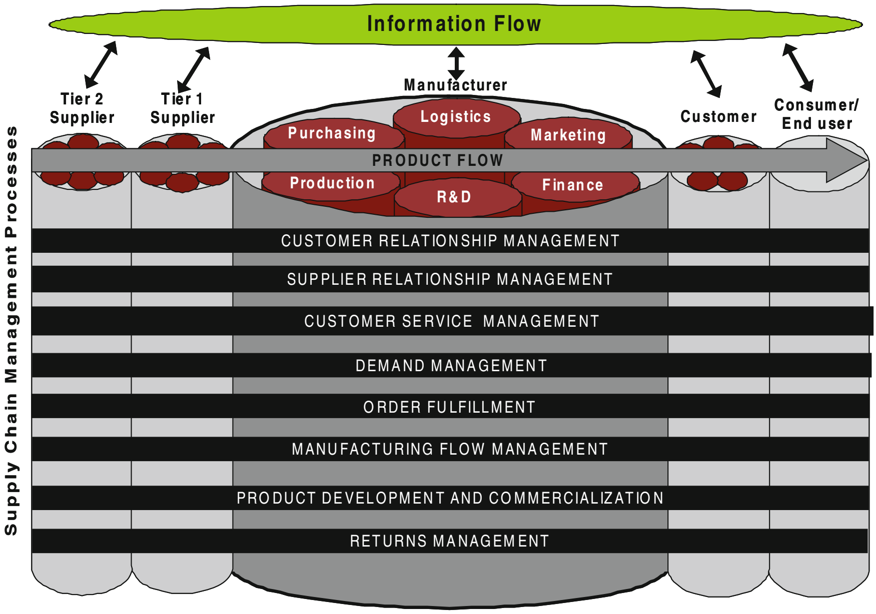

**Fig. 4** The global supply chain forum model (Lambert 2008a)

physical flows are one part. To be fair, it must be noted that SCOR is intended as an operations model. GSCF's broader, more holistic perspective to managing the supply chain makes it attractive for potential use in SSCM. The integration of manufacturer and upstream and downstream supply chain partner functions through the eight supply chain processes is illustrated in Fig. 4.

The GSCF presents strategic and operational sub-processes for each of these supply chain processes. While the strategic sub-processes are aimed at formulating a structured approach to execute the processes, the operational sub-processes involve the actual execution and evaluation of these processes (Lambert 2008a). A re-examination of the scope of matters covered during the strategic sub-processes in each of the GSCF processes is needed in the context of sustainable supply chain; this is particularly so given the total life-cycle coverage required and the need to incorporate environmental and societal implications in supply chain decisions. Therefore, in the following sections, we elaborate further on each supply chain process and how to incorporate sustainability considerations within them.

## *4.1 Customer Relationship Management*

The GSCF (Lambert 2008b) describes CRM as the business process that provides the structure for how relationships with customers are developed and maintained, including the product-service agreements (PSAs) between the firm and its customers. In forming the commitments with customers the focal firm establishes its priorities for value creation in this process. Several companies today are integrating environmental and societal causes with the core mission of the company and associating these causes with the company's brand image. What Ben and Jerry's did for environmental stewardship beginning in the 1980s, Toms Shoes does for outfitting shoeless children in underdeveloped regions of the world (Binkley 2010). However, not all companies have such sustainability-integrated brand image, or even wish to pursue it. Rather, they may choose to engage selectively in "cause marketing"—aligning the company and its brand with a specific promotion in support of a singular, worthwhile cause. The term "cause marketing" was first applied to American Express when it championed the Statue of Liberty restoration effort in 1983 (Wong 2009). It is also different from a not-for-profit business that is focused solely on benefiting others, where the economic returns of the business are used solely to fund the operations and growth of the cause.

Still other times companies will devise customer relationships on a selective basis, electing to engage differently with distinct segments of the market and entering into unique product/service arrangements across the segments. Segmentation is often conducted in order to maximize profits (i.e., creating segments of customers from most profitable to least profitable for the focal firm), but several bases for segmentation exist with common considerations being: the volumes that customers purchase, the geography of customer locations, growth/potential, competitive position, and market knowledge of customers. The preponderance of segmentation schemes embraces immediate-term economic benefit to the focal firm, with firms only recently enacting measures to align closely with choice customers characterized by environmental or societal conscientiousness. For instance, consumer goods manufacturers are increasingly embracing segmentation based on environmental sensitivity today. Automakers produce gas-electric hybrid vehicles to cater to their environmentally sensitive customers, with the balance of the product portfolio consisting of less fuel-efficient vehicles to serve the remainder of the market. In consumer packaged goods, Procter & Gamble markets Cold Water Tide as an energy efficient alternative to its mainstay product. While these products must be economically viable in their own right, they represent niche offerings relative to the companies' diverse array of products.

It has long been believed that such segmentation was only viable when a customer was willing to pay more for a sustainability-conscious offering. In addition, it was typically believed that a product that was comparably better for the environment was inferior in conventional performance. Researchers today still refer to a "sustainability penalty" when consumers perceive that a product conveying sustainability is inferior in quality (Luchs et al. 2010). Modern wisdom, though, espouses that consumers' value proposition is changing, such that they expect products to be not only sustainable but also of comparable—if not better—quality in terms of performance and also in line—if not cheaper—than conventional products. As sustainability-sensitive products continue to make inroads with consumers in terms of performance and value, they will eventually shed the niche role and become mainstream choices.

So, while segmentation by environmental or societal characteristics is becoming more common in consumer markets with niche offerings, such segmentation is believed to be less common in business-to-business marketing. As expectations for sustainable products and services grow in the consumer market, it is anticipated that pressures will rise for those who sell to consumers to exert influence upstream in the supply chain for overt demonstrations of sustainable planning and action. This will be discussed further in the topic of supplier relationship management.

## *4.2 Supplier Relationship Management*

Described by Lambert (2008c) as the "mirror image" of CRM, the supplier relationship management process provides the structure for how relationships with suppliers are developed and maintained, including the PSAs between the firm and its suppliers. The focal firm is therefore establishing its priorities for working with suppliers, setting expectations for the conditions of the exchange and the extent of collaboration desired. The focal firm must determine which relationships call for more attention and resources to support its commitments to customers and meet its business objectives. Given the complex network of relationships that compose a company's supply network, it is typically impossible for the focal firm to manage all of its relationships back to original supply of material inputs. Consider, for instance, the automaker that employs 350 tier-1 (immediate) suppliers. Each of these suppliers employs several of its own immediate suppliers (who represent tier-2 suppliers to the focal company). One can readily recognize the difficulties of managing such a complex network of relationships with several tiers of supply.

Similar to CRM, the fundamental economic problem of scarce resources factors significantly in managing supplier relations. There simply is not enough time, money, or labor resources to commit to complete surveillance of supplier decisions and operations. The focal firm must, therefore, determine how to allocate its limited resources to select supplier relationships. This calls for an understanding of where the greatest benefit can be achieved from close collaboration and also where the greatest risk can be alleviated from close scrutiny. The practice of segmentation can help to reduce the size and scope of the problem by separating those choice suppliers calling for close attention from the masses that may not. Companies must be careful, however, not to overlook material and service suppliers that provide inputs or services that may be low in expense or considered tangential to the core product or service, yet can have a significant influence on the customer. A case in point is found in the U.S. ice cream distributor that hired a tank truck operator that had failed to properly clean its equipment after hauling raw, unpasteurized eggs before transporting the company's dairy products. This transaction of less than a thousand dollars resulted in an estimated 224,000 cases of Salmonella poisoning among its consumers (Hennessy et al. 1996). Firms must therefore be careful that material suppliers and service providers uphold the same standards of quality as the customer.

The trend of outsourcing of operations has given rise to increased management of supply risks. Massive recalls of toys produced in China containing lead paints gained much attention in the summer of 2007 (Story and Barboza 2007). Earlier that same year, vegetable proteins imported from China for livestock and pet feed were found to be contaminated with melamine, resulting in the recalls of more than 100 brands of pet food in the United States (MacLeod 2007). Research illustrates that supply chain disruptions not only impact customers, but also the company's shareholders. Hendricks and Singhal (2003), using an event study methodology, find that shareholders on average lose about 10 % of their stock value in the two days following announcement of a supply chain disruption. Subsequent work by Hendricks and Singhal (2005) shows that firms experiencing significant disruptions report 33–40 % lower stock returns relative to their competition over a 3-year time period around the disruption, and that it takes at least 2 years for the firm to recover from such disruptions.

While such findings have reinforced some companies' determination to in-source the work that was once outsourced, or to near-shore work that was conducted in distant offshore locations, others have elected to step up the vigilance directed toward their suppliers. Supplier qualification and certification programs have gained widespread adoption as a means to gain enhanced visibility of the policies and operational practices of these outside firms. In addition, many firms have adopted formal corporate social responsibility (CSR) policies and ISO 26000 standards as outward, demonstrable indications of self-governance that not only meet the parameters of legal compliance, but often exceed them. Embracing such standards has important implications for not only how the firm will manage its operations and employees, but also extends to expectations that the firm places with its business partners. Even when relationships are deemed critical enough to warrant company resources and managing directly, the firm must exert influence through its managed relationships to effectively monitor these more distant relationships. Most realize, however, that such scrutiny will not release the company from liability or harsh market reactions should a problem arise with a product bearing the company's brand. "Out of sight" cannot translate into "out of mind" in today's environment. The growing influence of social media is empowering grassroots movements to convey concerns much more broadly and rapidly, heightening firm's responsiveness to egregious acts—both real and perceived (Steel 2010).

Though the avoidance of downside risks is the focus of much supplier relationship management activity, the upside potential is sometimes explored. Companies are increasingly seeking co-branding opportunities with suppliers recognized as particularly innovative or progressive in the domains of society and environment. As an example, the Klean Kanteen Company produces metal drinking bottles that are intended to supplant the now ubiquitous plastic containers of the bottled water industry. The business proposition for the Klean Kanteen largely consists of lending its environmentally friendly brand to business customers who seek to align by brandishing the metal containers with the customer's logo. In this way, companies are pursuing win–win benefits similar to what Intel has achieved with its long-lasting "Intel Inside" campaign that has benefited Intel by creating a brand for what could otherwise be regarded as an important yet unseen computer component. Given the strength of the Intel brand, computer makers can charge a premium price for machines that employ Intel technology and sport the Intel brand. Co-branding activity directed toward sustainability is expected to increase markedly in the coming years as companies seek to bolster their respective and collective images as stewards of products and services delivered to market in an environmentally benign and socially conscientious manner.

It is also noteworthy that closed-loop supply chains call for firms to sometimes manage the CRM and SRM processes in unison, as customers sometimes serve as the source of supply. This is true of products that enjoy multiple life-cycles through reuse, remanufacturing/refurbishing, or recycling. Under these circumstances the seller must not only entice the customer to purchase but also to return the reusable/recyclable content post-use. This presents a unique marketing challenge, as companies are conventionally concerned solely with one-way flows in distribution and are not accustomed to managing the reverse flow. The challenge may not be so great for business-to-business transactions which tend to be fewer in number and larger in batch quantity. For instance, returnable shipping containers are used commonly in many industries as a means to convey parts and goods. Empty containers are often collected at the time of delivery and then used for subsequent shipments in a closed-loop system. Research demonstrates that such systems, though calling for management attention to be effective, can be both cost-effective and improve customer service (Mollenkopf et al. 2005). However, business-to-consumer programs are often more difficult as the business relationships tend to be less structured, less frequent, smaller in quantity and, hence, more disaggregated, making it difficult for the seller to plan these flows and achieve scale economies. This presents opportunities for intermediaries who can collect the merchandise of many sellers. Specialized third-party logistics service providers are sometimes called upon to facilitate such systems.

CRM and SRM also place an emphasis on the sharing of benefits from process improvements. These benefits are typically accrued in financial terms. Sustainability with its TBL perspective, however, may allow benefits to be allocated in financial and non-financial terms. In a related vein, the final step to the CRM and SRM processes, according to Lambert (2008a), is the measurement of process performance. Similar to the measurement of benefits noted above, this assessment yields the impact of the process actions on the firm's economic value-added (EVA) as well as the EVAs of its key customers and suppliers. EVA is a widely accepted measure of comprehensive financial performance of the firm, as it incorporates the company's sales, cost of goods sold, expenses, and investments in current and fixed assets. Presently much debate centers on whether sustainable business practices that deliver benefits to the societal and environmental bottom line must, necessarily, deliver favorable results to the economic bottom line in the immediate term. Arguably, practices that fail to be sustainable cannot be sustained, as external forces—whether they be the government or the market—offer no reprise. However, the counter may also be true—that practices may prove to be overly generous in the sense of offering demonstrably low prices, high wages, or high supplier rates that cannot be sustained. Clearly, there is interplay among the three bottom lines. But must they all result in favorable economic returns in the immediate term or is there a grace period for so-called sustainable investments? If there is a grace period, what is its duration? For these reasons, the matter of performance measurement must be examined more thoroughly such that the firm can reconcile the three bottom lines in way to guide decisions and actions.

### *4.3 Customer Service Management*

The CSM process provides the firm's face to the customer, including management of the PSAs, and provides a single source of customer information (Knemeyer et al. 2008). A central aspect to an effective CSM process is anticipation of "events"—circumstances within or beyond the control of the focal company that may call for action in the business relationship. The product-service agreement established in the CRM process provides the level and breadth of responsiveness that is commensurate with the individual customer or segment of customers. The most valuable customers tend to have more extensive handling, with the majority receiving a level of service that is deemed acceptable in the marketplace.

In determining the array of options available to customers, the focal company must understand its own capabilities and resources as well as the customers' wants and needs. Firms should, therefore, only offer service capabilities that are within their abilities to deliver. Conventional wisdom suggests that customers expecting higher levels of service than the company is able or willing to provide should either not be served, lower expectations, or increase the value proposition for the supplier (i.e., be willing to pay more for heightened service). If the company does not have enough viable customers to carry the business, then the business itself is not viable.

Many businesses today seek to distinguish themselves from the competition based on service elements that may be considered supplementary or outside the core offering. Nordstrom's, Southwest Airlines, and Four Seasons Hotel—all companies that serve the consumer market– are among the most renowned companies for the level and array of services they offer customers. Accolades are usually garnered for kind, conscientious handling of the customer during the business transaction, and afterwards in the case of complaints or returns. However, to provide such handling on a consistent basis requires tremendous commitment, policies, and training, representing an important basis of the company's strategy. It bundles the service squarely with the core offering such that the customer is often willing to pay more to enjoy the benefits of premium service.

In accordance with the CSM process, companies are increasingly embracing sustainability as a means for distinguishing customers and distinguishing the business in the eyes of customers. Many retailers, for instance, are encouraging customers to bring their own carryout bag for groceries, sparing the use of expendable paper and plastic bags. IKEA is cited by some as the first retailer to offer an alternative to these conventional bags, but providing alternatives is commonplace today.

In fact, the city of San Francisco banned the use of non-biodegradable plastic bags by supermarkets, drug stores, and other large retailers entirely. Changes in the hospitality industry have been equally compelling with simple policies like sheet and towel re-use policies that reduce water and energy consumption (and reduce the hotel's labor, utility, and material costs) to LEED certified facilities that cater to the service expectations of sustainability-minded guests. Companies in various industries are finding that customer services with a sustainability focus are gaining in number, and market reception is encouraging their growth.

## *4.4 Demand Management*

The DM process is "concerned with balancing the customers' requirements with the capabilities of the supply chain" (Lambert 2008a). Some of the key subprocesses at an operational level to manage demand are better forecasting techniques, reducing the affect of demand amplification across the supply chain, and to increase the flexibility of the supply chain to rapidly adapt to changes in demand. Corcoran et al. (2010) have argued that for successful sustainable management of freshwater and wastewater, (a) long-term forecasting be adopted for future scenarios in freshwater consumption and wastewater management, (b) reduce demand amplification of both freshwater and wastewater facilities by proactively using preventive practices in generating water pollution, capture polluted water, and then recycle water after its appropriate treatment, (c) increase flexibility of response through public–private investment and operations while being sensitive to local cultures and environment but by being economically sound solutions.

Organizations are using innovative methodologies to address the issue of sustainability through good demand management practices. In a manufacturing environment, demand management is undergoing a change from assemble-to-order and stock-to-order to build-to-order to closely match demand and supply. Companies like Toyota Motor Manufacturing build-to-order cars as per the requirements of Toyota Sales and Dealerships. Build-to-order decreases the amount of inventory at hand-freeing up working capital, decreasing obsolescence hence reducing landfills, avoiding discounts of final products, reducing returns from customers and hence saving transportation, energy, and remanufacturing costs. Some marketing firms are increasing good demand management practices while increasing their "greenness" at the same time by targeting green customers, predicting and promoting green products, positioning and promoting recycled products, and building competitiveness based on build-to-order on the demand side of the equation (Sharma et al. 2010). In the supply side the strategies being pursued by firms to be more sustainable are to reduce supplies through make-to-order, enabling reverse logistics for recycling and remanufactured products, design for modularity and disassembly, giving incentives to consumers to return products after their useful life. As an example, most printer manufacturers like Lexmark, Dell, HP, and Canon have programs with giant retailers such as Staples and Office

Max to offer coupons for return of spent cartridges. These returned cartridges help in keeping solid wastes (in the process of creating new cartridges) out of streams and thus help the environmental efforts of the company.

"Sustainability is the result of a strategic process trying to deal with uncertainty and unpredictable emerging properties by means of adaptive flexibility" (Sartorius 2006). The availability, visibility, and use of point-of-sale (POS) data across the entire supply chain enables firms to increase forecasting accuracy, reduce the demand amplification gap, and increase the flexibility of the process itself in adapting to changes in the final consumer demand and thereby increase the TBL of the focal firm. A sausage manufacturer has found that focusing on the three main elements of demand management (forecasting, demand amplification, and flexibility) has improved their overall sustainability efforts (Taylor and Fearne 2009). Reduced wastage of agricultural products due to better demand management has led to increased profitability (economic benefit), significant lower use of artificial fertilizers (improved environmental performance), and happier customers, suppliers, and community members (positive societal contribution).

Demand management across the supply chain is often implemented through programs like Collaborative Planning, Forecasting, and Replenishment (CPFR) or Vendor Managed Inventory (VMI). Depending upon demand uncertainty and demand volume, different approaches to forecasting can be used (make-to-order, people-driven forecasts, data-driven forecasts). Also the flexibility (risk-hedging, agile, efficient, and responsive) strategy within a supply chain can be determined through the supply uncertainty and demand uncertainty present within each organization of the supply chain (Lambert 2008a, b, c). Putting together a cross-functional team and making POS data available to all organizations within a supply chain can significantly reduce the demand amplification effect. Hence, lowering the amount of raw materials used, lowering total inventory held across the supply chain, reducing returns, and having a proactive end-of-life strategy for products significantly helps the TBL of any organization within a supply chain.

## *4.5 Order Fulfillment*

Order fulfillment consists of "generating, filling, delivering and servicing customer orders" (Lambert 2008a). Sustainability gains recorded by firms are often in the process of order fulfillment. These measures are often provided in sustainability reports or CSR reports of various organizations. For example, Walmart Inc. claims to have increased fleet efficiency by 25 %, and decreased landfill by 55 % through better management of packaging material and store disposals through coordination with their suppliers (Walmart 2009).

At a strategic level, having clear order fulfillment goals backed by an appropriate logistics network and relevant and appropriate set of metrics help firms convert the order fulfillment process from being just a competitive advantage to a *sustainable* competitive advantage. L.L.Bean Inc., a catalog seller, has clearly identified usage of recycled paper as being a big driver of its sustainability efforts. As part of their measurement system, the firm has mandated that 90 % of the fiber used in their catalogs be sourced through a credible certification system and contain 20 % recycled fiber. Internally the firm uses 100 % recycled paper for their documentation needs. They have modified the logistics fleet by changing to biodiesel and recycle approximately 5,000 tons of cardboard, 82 % of their wastes and made their plastic shipping bags into a closed-loop system where the plastic is pelletized and resent to their suppliers. From 2006 onwards, the company has committed to make all new buildings as per LEED standards. As of 2009, the company has witnessed record sales of $1.4 billion through 11 million customer contacts. Several facilities have since achieved OSHA's prestigious Voluntary Protection Program (VPP) status (L.L.Bean 2010).

At an operational level, order fulfillment consists of generating and communicating the order, entering the order, processing the order, handling documentation, filling the order, delivering the order, and measuring the performance of the process. Using information technology to communicate across and within the supply chain improves order fulfillment processes through better visibility of resources, use of optimization tools to efficiently flow materials and orders through the logistic network, and efficiently allocate scarce resources. These in turn improve the economic bottom line of the firm. SAP Inc. estimates that Lexmark Inc.'s targeted impact on its shipping cost is a 90 % reduction in costs. Non-operational shipping costs are expected to reduce by 8 %. Order fulfillment related measures which contributed to the overall cost decline were a 2-day reduction in travel expense turnaround time, significantly less usage of paper receipts, 80 % reduction in document retrieval time, 60 % reduction in paper Bill-of-Ladings, 75 % reduction in cost of paper Bill-of-Ladings, and 25 % reduction in Bill-of-Lading processing time (SAP 2010).

The process of order fulfillment is one of the first areas that companies can implement strategies for sustainability improvement as most of the process elements are within their span of control. Hence, it is not surprising to see that most measurement systems that are related to sustainability are often those that encompass the order fulfillment process.

## *4.6 Manufacturing Flow Management*

"Manufacturing flow management is the supply chain management process that includes all activities necessary to obtain, implement, and manage manufacturing flexibility in the supply chain and to move products through the plants" (Lambert 2008a). The main challenge that organizations face in the manufacturing flow management process is to determine the pull–push boundary, which would in turn dictate the generic manufacturing strategy that the firm would follow. At a very broad level, a company's decision to make or buy, and within the make-buy continuum the decision to ship-to-stock, make-to-stock, assemble-to-order, make-to-order, and buy-to-order determines the decoupling point between the pull–push boundaries. The degree of manufacturing flexibility is determined by a combination of organizational flexibility (manufacturing/operations, market demand, supply base, and information systems alignment) and production flexibility (product mix, volume, modularity, material handling capability, process routing, machine changeability, and labor adaptability).

An organization's decision to exert different degrees of control over their manufacturing strategy and flexibility has large impacts on their TBL. In the era of globalization, firms in the U.S. have outsourced their manufacturing capability to other firms, often in different geographic locations. Nike and Mattel found out the hard way that outsourcing of their manufacturing capabilities left them very vulnerable to their economic, environmental, and societal bottom line (Story 2007). Both companies did not exert control on their suppliers and hence had massive sales, profits, and reputation erosion and increased public scrutiny on their operations due to presence of sweatshops and lead in their products. Nike subsequently learnt their lesson and are now actively working with other stakeholders like NGOs, key customers, local Governments, and their suppliers to proactively address problems relating to the environment and society to protect their top and bottom lines.

Most measures of sustainability concerning manufacturing are often related to material use, emissions of different kinds, and energy usage of the process itself. However, not relating the manufacturing flow management to other key processes tends to sub-optimize the sustainability effort. Also, activities both upstream (design phase) and downstream (use and post-use phases) of the manufacturing phases need to be integrated together to optimize the sustainability initiative of the organization. The different phases of the product, pre-manufacture, manufacture, use, and post-use are often spread across the supply chain and coordination and information exchange becomes a vital element in the sustainability effort.

## *4.7 Product Development and Commercialization*

In the GSCF framework the process of providing 'the structure for developing and bringing to market new products jointly with customers and suppliers' is referred to as product development and commercialization (PDC) (Lambert 2008a). The process involves the integrated planning and execution of activities related to PD&C in collaboration with supply chain partners to derive long-term benefits and competitive advantage, a task made more complex by rapidly changing customer needs and technological advances.

The broader emphasis called for to promote sustainability also brings about the need for a much wider approach to address the PDC process. The development of new product platforms, derivatives of existing products, incremental improvements to existing products or fundamentally new products are all activities that come within the scope of the PDC process. If companies are to incorporate sustainability considerations in their operations, the total life-cycle thinking must be embedded into the product development process so that broader consequences beyond the cost and functional performance are considered at each stage of the value chain (Fiksel 2009). The current practice in many companies is an apparent and overarching focus on activities involved up to getting the products to the end user or consumer, which in terms of the product life-cycle stages only covers pre-manufacturing through use stages. Though there can be significant environmental and societal implications, product management in post-use is not incorporated into the PDC process by many companies. Given that almost 80 % of a product's cost is decided during its design (Boothroyd et al. 1994) most of the costs (and benefits) incurred across the supply chain, including the post-use stage, depend on decisions made during PDC. Therefore, the scope of PDC process must be broadened so that companies look at the total life-cycle to increase the TBL benefits.

Another trend that is compelling companies to embrace this broader life-cycle thinking for PDC is the extended producer responsibility (EPR) regulations. With EPR the producer's responsibility for a product is extended to the post-consumer stage of a product's life-cycle (OECD 2001) and in recent years, a number of countries/regions have mandated manufacturers to follow EPR regulations. For example, the European Union (EU) directive on end-of-life vehicles (ELV 2000) mandates the take-back of vehicles after use. Other regulations, such as the waste electrical and electronic equipment (WEEE) directive (WEEE 2003) and restriction of hazardous substances (RoHS 2003), impose various substance/disposal bans or enforce recovery/recycling/reuse (RRR) targets, once again placing greater responsibility on manufacturers to manage products at end-of-life.

All EPR will have a bearing on PDC because of the need to make design changes—in the product as well as the supply chain—to focus on the total life-cycle to reduce resource consumption and environmental impacts (Walls 2006) through the application of methods such as the 6R's (discussed earlier). Foremost to applying 6R's and innovation in the manufacturing of sustainable products by using recycled materials, remanufactured components as well as opportunities for reusing products (in primary or secondary markets).

Another shift that is needed from a sustainability point of view and one that will affect the PDC process, is moving away from selling only the product (or service) to selling of solutions, which can be entirely new value propositions that create sustainable value. Businesses will have to address this transition in stages, first moving from products to product-service systems (PSS). A PSS involves '…. shifting the business focus from designing and selling physical products only, to selling a system of products and services which are jointly capable of fulfilling "*specific customer demands*"' (Manzini and Vezzoli 2001) (italics added). A well-known example is the case of Xerox where the company transitioned from selling printers at one time to providing document services and printing solutions to their customers by managing the equipment throughout its life (Frank 2010). The co-creation of value by producers and consumers together, for example, through such PSS calls for more collaboration between the parties changing how PDC process is approached, compared to a conventional product-oriented scenario.

Also important at the strategic level of SSCM, evolving from the need to embed the total life-cycle thinking is coordinating product and supply chain design decisions (Fine 1998; Tomas and Scott 2003). PDC decisions not only affect the forward-flow (pre-manufacturing, manufacturing, use) operations but also the reverse-flow (recovery, reuse, remanufacturing, and recycling). The costs and benefits of these operations, in turn, depend on the supply chain network, partner capabilities and capacities. For example, as a result of WEEE directive requirements, electronic manufacturers are required to collect end-of-life products in the European Union (EU) region. Decisions about how to manage the reverse supply chain for these products will have strategic implications. For example, if the disassembly will be done within the EU or if they will be shipped, for example to China, will have various sustainability costs and benefits that merit consideration during PDC. Expanding the scope of PDC to consider the impact on supply chains will help companies to identify the most sustainable product design and the supply chain—existing or to be developed (Metta and Badurdeen 2009).

Given that 'sustainability is an enlarged framework through which to view the making and selling of products and services' (Badurdeen et al. 2009), metrics relevant to evaluating the sustainable PDC operations is also necessary. As discussed earlier the choice of metrics in SCM has been guided by their contribution to EVA. Product sustainability indices (PSI) can be one method approach to evaluate the SVA of the products generated through the PDC process. For example, simple yet comprehensive methods to compute PSI, such as calculating the weighted sum of environmental, societal, and economic impacts for each of the four life-cycle stages (pre-manufacturing, manufacturing, use, and post-use) (Jaffar et al. 2007) is a good point to begin evaluating PD&C processes. For example, PSI values for environmental ($\mathrm{PSI_{en}}$), societal ($\mathrm{PSI_{so}}$), or economic ($\mathrm{PSI_{ec}}$) sustainability components across all four life-cycle stages can be evaluated to compute an overall product sustainability index ($\mathrm{PSI_{TLC}}$):

$$\mathrm{PSI_{TLC}} = [\mathrm{PSI_{en}} + \mathrm{PSI_{so}} + \mathrm{PSI_{ec}}]/3$$

Each of the component PSIs above can be evaluated for the four life-cycle stages (denoted as pm, p, u and pu, respectively), by considering the relevant influencing factors (Jaffar et al. 2007). For example, $\mathrm{PSI_{en}}$ can be expanded to incorporate the environmental impact in each product life-cycle stage as:

$$\mathrm{PSI_{en}} = \mathrm{PSI_{en\_pm}} + \mathrm{PSI_{en\_m}} + \mathrm{PSI_{en\_u}} + \mathrm{PSI_{en\_ps}},$$

where the subscripts pm, m, u, and pu refer to the pre-manufacturing, manufacturing, use, and post-use stages. Similarly, the other *PSI* components, too, can be extended to capture life-cycle specific impact. These individual components, as illustrated in Fig. 5, can then be used to evaluate product sustainability. By incorporating sustainable product evaluation measures such as these during PDC, companies can evaluate strategic performance of products from a total life-cycle perspective and assess the environmental, and societal impacts as well. [Different economic, environmental and societal performance metrics must be used, as

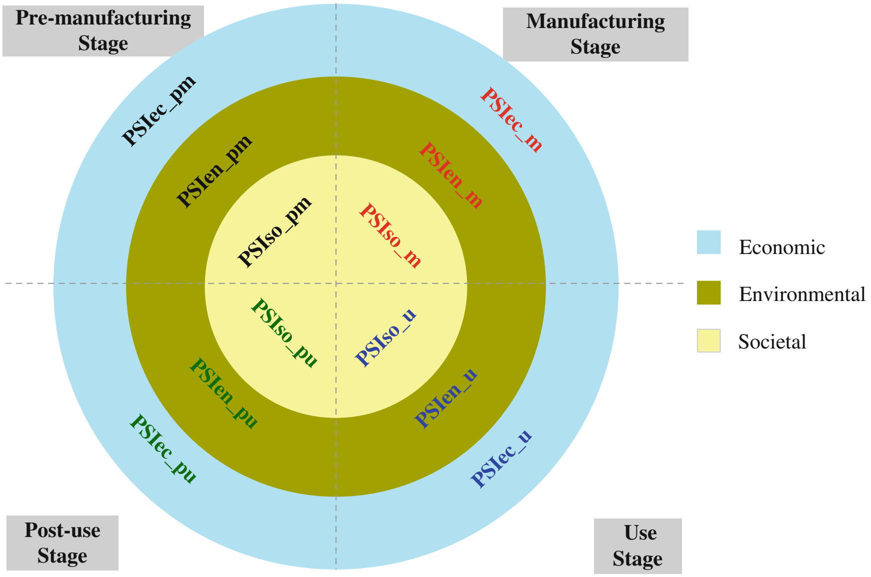

**Fig. 5** Product sustainability index representation

appropriate, to calculate $PSI_{ec}$, $PSI_{en}$, and $PSI_{so}$, respectively, for each life-cycle stage. The most pertinent metrics and their computation are beyond the scope of this chapter. The PSI concept is presented here merely as means to illustrate a tool that can be used to evaluate PD&C processes. The interested reader is referred to Jaffar et al. (2007)].

## *4.8 Returns Management*

The GSCF defines returns management as ‘that part of supply chain management that includes returns, reverse logistics, gatekeeping and avoidance’ (Lambert 2008a, b, c). The importance of minimizing the number of return requests (avoidance) and managing operations to limit the number of product returns allowed into the reverse flow (gatekeeping) to reduce returns-related costs are emphasized in this process.

Because the liberal returns policies offered by most retailers have increased product returns, companies have long focused on planning and managing operations to reduce such returns by unhappy customers (Guide et al. 2006). According to one estimate, the value of customer returns (not end-of-life) in the hi-tech industry alone has been estimated to be US $104 billion in 2004 (Infosys 2004). This value can be even higher in other industries such as seasonal fashion apparel. As a result the emphasis on the returns management process, as practiced by the majority of companies, has mostly been on effective gatekeeping, returns avoidance, and related reverse logistics (Rogers et al. 2002).

However, given the need to focus on the total life-cycle particularly to cover the post-use stage of products in sustainable supply chains may require the strategic re-scoping of the returns management process. Given this expanded scope, it becomes necessary to view the returns management process not as a 'step-child' of supply chain management but as having potential to create value for companies in the long-term (Mollenkopf and Closs 2005).

Making a strong business case for reverse logistics activities for all types of returns has been a challenge (Mollenkopf and Closs 2005). This is partly due to the short-term orientation that many companies tend to adopt in business operations. The benefits of particularly end-of-life reverse flow of products by applying the 6R's are unlikely to be derived in the short-term; they will often accrue in subsequent life-cycles of a product which, depending on the length of the product life-cycle, could be many years into the future. For example, through very successful reverse flow management Kodak has been able to reduce the material and energy consumed for later life-cycles (almost a 70 % reduction by the 5th life-cycle) of their single-use cameras (Field 2000). Therefore, evaluating the potential benefits of a returns management process re-scoped to incorporate the larger role companies have to play during product end-of-life obligates a long-term emphasis.

Different products may require varied reverse processing costs and capabilities leading to alternate network requirements (Guide et al. 2006). As discussed in the section earlier, such network selection decisions must be coordinated with product development decisions to maximize the benefits in returns management (Metta and Badurdeen 2010). For example, for Kodak's single-use cameras the reverse network was already in place; it was a matter of establishing cooperative agreements with photofinishers to collect the cameras when returned by customers to process films. For many companies this process will not be as straightforward but involve strategic (reverse) supply chain partner selection in order to mobilize effective returns flow (Guide et al. 2006; Metta and Badurdeen 2010).

The broader scope of activities involved in returns management also calls for more careful consideration of how the return products are collected after use. Proprietary collection systems, though more costly, are preferred by companies when a high degree of proprietary knowledge and specialized technology are used to make the products; in other instances, industry-wide cooperative collection systems will be more economical (Barker and Zabinsky 2010). Managing product returns under the two scenarios will involve different issues to be addressed, in coordination with product development process.

## 5 Assessing Sustainable Value

Sustainable value-added is regarded by many as the ultimate measure of sustainability success or failure. As noted by Laszlo (2008), SVA represents the simultaneous achievement of value for shareholders and other stakeholders. Further, it is depicted as occurring at the intersection of economic, environmental, and societal

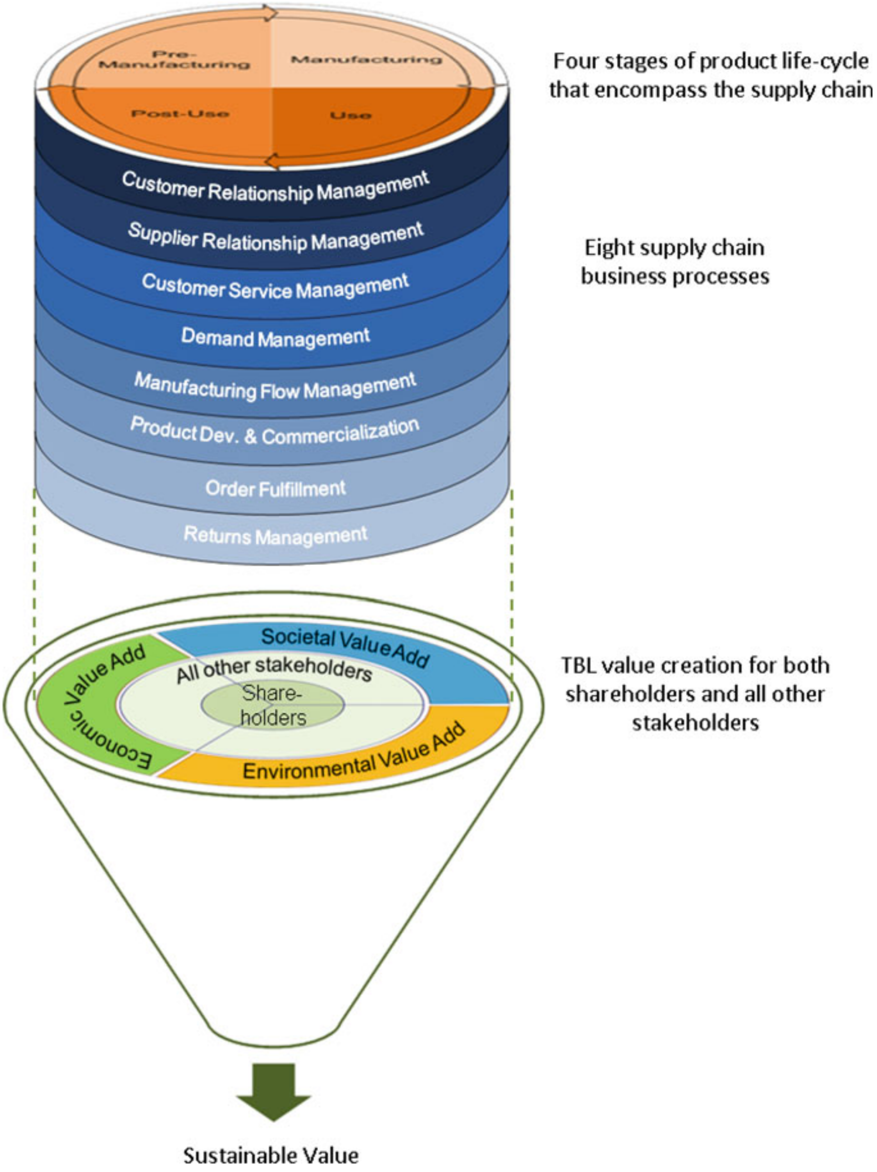

**Fig. 6** Sustainable value creation for all stakeholders in supply chain

value-added. In all of these senses, SVA is regarded as a composite outcome associated with actions that benefit the company, its shareholders, employees, fellow supply chain members, and other stakeholders without compromising the natural environment. This holistic approach to generating sustainable value across the supply chain is captured in Fig. 6.

The TBL perspective frames the proposition of sustainable action in a manner that is conceptually appealing and easy to comprehend. Further, the proposition of creating value for all parties affected by business activity—without compromising the natural environment—is attractive. Who among us would not aspire for such win–win–win outcomes? The realities associated with this pursuit are quite challenging, however. In fact, to yield circumstances in which all stakeholders find positive net results are rare—at least in the short term. Rather, the problem must be bounded in some fashion. For instance, consider the collaboration between a supplier and manufacturer that yields a unique new product that is friendly to the environment and well received in the market. Customers see benefit in the product, the manufacturer and supplier boosts sales, and the limited impact on the natural environment is a benefit to the ecology and larger society. But what might the actions of the supplier-manufacturer collaboration mean for suppliers lacking this technology or for manufacturing competitors that cannot adapt quickly and may experience declining volumes of their own? Likewise, distributors and retailers that cannot—or simply choose not to—carry the market-shaping product will exhibit a competitive disadvantage. While these eventualities may be positive for the supplier, manufacturer, and retailers that possess the technology, it is clear that not all stakeholders will be favorably affected by these actions in the short term. The net effect may be positive, yet the displaced employees at the periphery organizations would not experience benefit. It is conceivable that capacity reductions at existing suppliers may impact the focal manufacturer in the future with fewer suppliers to choose among, resulting in less innovation and less price competitiveness within the remaining supply base.

The aforementioned scenario is wholly consistent with the principles of the free market system—where only the strong survive—and is a welcomed outcome for the core stakeholders when the net effects are positive. However, the example illuminates the impracticalities associated with trying to please all stakeholders, broadly defined. Some people will be adversely affected, if only in the short term, when another succeeds. This also applies to the natural ecology, where people may be inconvenienced—perhaps only in the short term—by finding solutions that favor the environment but call for a new way of producing and/or consuming. The point is that we must rationally delimit the problem to make the pursuit of sustainable value-added attainable.

Even when approaching the bounded problem of favorably impacting a core group of stakeholders without negatively impacting the environment and society, determinations of action are not always abundantly apparent. Businesses today generally assume that environmentally and socially friendly actions require investment in some form, typically the outlay of capital toward the acquisition of new resources or development of existing resources. The payback period for such investments will vary dramatically, but there must either be a return in the form of higher economic profits or the avoidance of outlays for businesses to act on their altruistic inclinations. The matter of performance measurement must be examined more thoroughly such that the firm can reconcile the three bottom lines in way to guide decisions and actions. Laszlo (2005) quotes a Patagonia (sports equipment company) executive on their environmental performance philosophy as ‘every time you do something right, it turns out to be good for the business, too’. However, expecting such incremental and incidental benefits or even a mere focus on the TBL independently will not be enough to achieve true sustainability in business operations. There is a need for ‘intense technological, economic, social and political metamorphosis’ (Elkington 2001). In other words, for supply chains to be truly sustainable a paradigm shift to focus on all activities beginning from material extraction to end-of-life product management will be needed. This broader emphasis is mandatory in order to create sustainable value for all stakeholders. Circumstances under which all of these outcomes can be achieved are possible and should be pursued vigorously.

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