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Original Research

Multidisciplinary Life Cycle Metrics and Tools for Green Buildings

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ABSTRACT

Building sector stakeholders need compelling metrics, tools, data, and case studies to support major investments in sustainable technologies. Proponents of green building widely claim that buildings integrating sustainable technologies are cost effective, but often these claims are based on incomplete, anecdotal evidence that is difficult to reproduce and defend. The claims suffer from 2 main weaknesses: 1) buildings on which claims are based are not necessarily "green" in a science-based, life cycle assessment (LCA) sense and 2) measures of cost effectiveness often are not based on standard methods for measuring economic worth. Yet, the building industry demands compelling metrics to justify sustainable building designs. The problem is hard to solve because, until now, neither methods nor robust data supporting defensible business cases were available. The US National Institute of Standards and Technology (NIST) Building and Fire Research Laboratory is beginning to address these needs by developing metrics and tools for assessing the life cycle economic and environmental performance of buildings. Economic performance is measured with the use of standard life cycle costing methods. Environmental performance is measured by LCA methods that assess the "carbon footprint" of buildings, as well as 11 other sustainability metrics, including fossil fuel depletion, smog formation, water use, habitat alteration, indoor air quality, and effects on human health. Carbon efficiency ratios and other eco-efficiency metrics are established to yield science-based measures of the relative worth, or "business cases," for green buildings. Here, the approach is illustrated through a realistic building case study focused on different heating, ventilation, air conditioning technology energy efficiency. Additionally, the evolution of the Building for Environmental and Economic Sustainability multidisciplinary team and future plans in this area are described.

Keywords: BEES Green building Hybrid life cycle assessment Life cycle costing Buildings

INTRODUCTION

A wave of interest in sustainability gathered momentum in 1992 with the Rio Earth Summit, during which the international community agreed upon the definition of *sustainability*: "Meeting the needs of the present generation without compromising the ability of future generations to meet their own needs" (Brundtland 1987, p 51). In the context of sustainable development, needs can be thought to include the often-conflicting goals of environmental quality, economic well-being, and social justice. Although the intent of the 1992 summit was to initiate environmental and social progress, by the 2002 Johannesburg Earth Summit, it seemed to have instead brought about greater debate over the inherent conflict between sustainability and economic development.

This conflict is particularly apparent within the construction industry's sustainable building efforts. Frequently, well-intentioned environmental improvement plans are not executed for economic reasons, and economic development plans fail to materialize over concerns for environmental protection. Thus, an integrated approach to sustainable building—one that simultaneously considers both environmental and economic performance—lies at the heart of reconciling the conflict.

In this paper, we describe and illustrate, through a tall building case study, an approach that addresses the need to justify environmentally friendly, or "green," building in economic terms. It suggests a framework for quantifying the "returns" on sustainable building with the use of performance-based, science-informed thinking. Although the authors have previously addressed the economics of green building products (Lippiatt 2007), In this paper, we describe a new approach that goes beyond simple products to account for the complexities of complex industrial systems, such as buildings. By illustrating the approach through a simplistic case study, we refine and test a conceptual framework reported in an earlier paper (Sunder et al. 2008). The purpose is to demonstrate the viability of extending the approach for comparing traditional and alternative building designs.

Sustainable building metrics: A review

A limited number of comprehensive, national-scale studies have been conducted to assess the benefits and costs associated with green building. A review of the US literature finds that business cases for sustainable building typically evaluate commercial or residential buildings meeting benchmarks for green certification established by building industry stakeholders (e.g., USDOE and Federal Energy Management Program 2003, Fitzpatrick 2004, Bradshaw et al. 2005). A popular example of such a certification system is the Leadership in Energy and Environmental Design (LEED) rating system developed by the US Green Building Council (USGBC). LEED designates green buildings based on criteria that include water, materials, and energy use; siting; and indoor environmental quality (USGBC 2004). Although other US benchmarking systems have been established, LEED currently leads the way in defining guidance for green building attributes for the US building sector.

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Most published green building business cases are based on a certified green building's life cycle costs, including initial capital construction, operation and maintenance, repair, and replacement costs, which are typically collected through postoccupancy surveys. These cost data are used to determine the long-term economic merit of constructing a new building or retrofitting an existing one with green features, which usually requires higher initial construction costs. Although the use of a life cycle costing framework is common, different case studies often measure and collect these data in different ways.

The consensus among business cases is that building to environmentally friendly guidelines is financially sound in the long run. "An upfront investment of less than two percent of construction costs yields life cycle savings of over ten times the initial investment" (Kats et al. 2003, p ii). Aside from the most commonly cited benefit—reduced energy costs—increased water efficiency and property values are among the other leading financial incentives for designers, builders, and owners to build green. When "soft" economic benefits, such as productivity increases, are monetized and included in life cycle costs for office buildings, financial returns can increase significantly. The US General Services Administration (GSA) commissioned a report that demonstrates hard cost and soft cost savings from actual buildings designed to meet green building goals (GSA 2004).

Although approaches and conclusions in published business cases have been similar, their overall value is uncertain. In general, green building business cases to date are based primarily on hard cost savings, such as reduced electricity costs, but do not consider environmental costs and benefits not reflected in market prices. These studies tend to suffer from 2 major weaknesses: First, the buildings on which the cases are based are not necessarily green in a science-based, life cycle assessment (LCA) sense. Second, cost-effectiveness measures often are not based on standard methods of economic worth. A credible sustainable building metric first and foremost must be based on rigorous assessments of environmental and economic performance.

Performance-based sustainable building metrics

Environmental performance measurement—Two quantitative, science-based approaches can help determine the environmental performance of a building: process-based LCA and input–output-based LCA. Both take a similar life cycle approach, but each tackles the measurement challenge in a different way.

LCA is a holistic approach that considers the consequences of raw material, water, and energy inputs from, and releases to, the environment throughout the life cycle of an "industrial" system. An industrial system is broadly defined. For the building sector, it can be limited to individual building products, components, or systems, or it can apply to an entire building or building sector. The term "life cycle" refers to the major stages in the life of the industrial system; these stages include raw material acquisition, manufacture, transportation, installation, use, and final disposal.

As standardized by the International Organization for Standardization (ISO), LCA clearly identifies and accounts for transfers of environmental impacts from 1 environmental medium (e.g., air, land, or water) to another and from 1 life stage to the next. The ISO 14040 series of standards identify 3 steps in any LCA process—inventory compilation, impact assessment, and interpretation—which lead to measures of environmental performance (ISO 2006). During the 1st step, quantification of inputs, such as raw materials and energy, and outputs, in the form of environmental releases such as carbon dioxide and carcinogens, results in an inventory of environmental flows. During the impact assessment step, the environmental consequences of the identified inventory flows are assessed. In the 3rd step, interpretation, impact assessment results can be synthesized to facilitate comparison of environmental performance across competing industrial systems.

The process-based LCA approach has its roots in industrial ecology, which is an interdisciplinary field that focuses on the sustainable combination of environment, economy, and technology. Environmental LCA was developed from the idea of comprehensive environmental assessment of products, which was conceived in Europe and in the United States in the late 1960s and early 1970s (Hunt and Franklin 1996). The earliest forerunners of LCA were the Resource and Environmental Profile Analyses (REPAs). During that time, a series of studies were conducted by the Midwest Research Institute, and later by the consulting firm Franklin Associates, mostly for the private sector. A REPA study of different beverage packaging systems by Hunt et al. (1974) is a typical example of these LCA predecessors. Interest continued through the 1980s, with studies by Gaines (1981) and Lundholm and Sundstrom (1985) being typical of REPA studies used for policy decision making. These early studies emphasized raw material demands, energy inputs, and waste generation flows. Another early type of LCA emerged in the late 1970s in the form of net energy analysis (Boustead and Hancock 1979).

Graedel and Allenby (1995) wrote the 1st textbook in the field of industrial ecology, which counts LCA as one of its research areas. Modern LCA methodology is rooted in the development of standards through the 1990s. The Society for Environmental Toxicology and Chemistry (SETAC 1991) published "A Technical Framework for Life Cycle Assessments," which marks the 1st attempt at an international LCA standard. This outline of the components of contemporary LCA includes goal definition, inventory assessment, impact assessment, and improvement analysis. By extending LCA beyond the mere quantification of material and energy flows, this specification by SETAC paved the way for the use of LCA as a comprehensive decision tool.

Modern LCA begins by drawing system boundaries defining specific industrial processes to be included for the industrial system under study (e.g., ethylene production for input to the manufacture of the styrene–butadiene bonding agent for stucco walls). Because some of these "unit" processes involve additional, subsidiary unit processes, process-based LCAs follow system boundary–setting rules that are based on the magnitude of mass and energy contributions to the system from subsidiary unit processes. The ISO provides a detailed explanation of the scoping process associated with boundary setting in the ISO 14040 series of LCA standards (ISO 2006). Whereas compiling inventory flows for numerous industrial processes requires extensive, detailed data collection, unit process–based compilation permits analysis of virtually any building product, component, or system imaginable. For this reason, the process-based LCA can be thought of as a "bottom-up" approach. Notable building industry applications of process-based LCAs to date include NIST's Building for Environmental and Economic Sustainability (BEES) 4.0 (http://www.bfrl.nist.gov/oae/software/bees/bees.html) and

Athena's Impact Estimator (http://www.athenasmi.org/tools/impactEstimator/index.html).

By contrast, the input–output (IO)-based LCA approach is a "top-down" approach which has its origins in macroeconomics. To assess the practical issues faced by governments and firms, economists have translated general equilibrium analysis for a competitive economy into a functional form. Economic IO analysis recognizes and characterizes the interdependence of different economic sectors and represents that interdependence by national IO tables quantifying, in monetary terms, interindustry exchanges of goods and services throughout industrial supply chains. In other words, IO analysis provides a macro-level view that includes secondary- and even tertiary-level effects of consumer and producer spending decisions.

In the early 1990s, industrial ecologists began extending the IO analysis approach. They developed physical IO tables corresponding to the existing monetary IO tables that tracked environmental inputs and releases among industrial sectors. By so doing, this tracking permits environmental inventory compilation following the "metabolic structure" of an economy. Although IO-based LCA provides a straightforward and logical framework for interindustry analysis of economic and environmental exchanges, its level of resolution is limited by the specificity of industrial categories in national IO tables. The North American Industry Classification System (NAICS) used by the US Bureau of Economic Analysis to develop US economic IO tables, for example, distinguishes fewer than 1000 industries and commodities. Furthermore, IO tables are static in the sense that they represent current technology mixes and industrial practices. Thus, although IO-based LCA has a reasonable level of breadth, it is lacking in specificity and flexibility.

The respective strengths of the "bottom-up," process-based LCA and "top-down" IO-based LCA complement one another's weaknesses. Although IO tables do not provide a level of resolution permitting analyses of new technologies, their breadth provides baseline inventory data representing a range of complex industrial systems, such as buildings. IO-based LCA software tools have been developed that combine a variety of public datasets and assemble matrices for various commodity sectors. Most notable are the Missing Inventory Estimation Tool (MIET) developed by Sangwon Suh (http://www.iel.umn.edu/CEDA3_Users_Guide.pdf) and the Economic Input–Output Life Cycle Assessment tool, developed at Carnegie-Mellon University (http://www.eiolca.net/about.html).

A new hybrid approach was developed by NIST for analyzing the environmental performance of alternative building designs. By drawing on the specificity of the process-based approach and the comprehensive accounting framework of the IO approach, a meaningful comparison of traditional and alternative building designs (focused on improved operational energy efficiency in the employed heating, ventilation, and air conditioning [HVAC] systems) can be made; one that systematically and scientifically compares life cycle environmental performance at the building scale.

Economic performance measurement—Measuring the economic performance of buildings is more straightforward than measuring environmental performance. Published economic performance data are readily available, and there are well-established standard methods for conducting economic performance evaluations. The most appropriate method for measuring the economic performance of building investments is the life cycle cost (LCC) method, standardized by American Society for Testing and Materials (ASTM) International (ASTM 2005a). The Building Life Cycle Cost (BLCC) program is a NIST software tool that applies the standard LCC method to analyze the economic worth of capital investments in buildings (http://www1.eere.energy.gov/femp/information/download_blcc.html).

Economic performance is evaluated over a fixed period (known as the study period) that begins with the design of the building and ends at some point in the future. For a private investor, its length is set at the period of product or facility ownership. For society as a whole, the study period length is often set at about 25 y. Although many buildings have much longer lives, a shorter study period is selected because technological obsolescence becomes an issue, future data become too uncertain, and the farther in the future, the less important the costs.

The LCC method sums over the study period all relevant costs associated with a building. Alternative designs for the same building can then be compared on the basis of their LCCs to determine which is the least cost means of fulfilling the building function over the study period. Categories of cost typically include costs for purchase, installation, operation, maintenance, repair, and replacement.

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. Discounting accounts for the time value of money stemming from both inflation and the real earning power of money over time.

Business case measurement—By combining a building design's life cycle costs with its hybrid LCA performance measures, eco-efficiency metrics can be developed on the basis of comparisons of alternative designs. The design alternatives will include both traditional and green alternatives, resulting in eco-efficiency metrics that can be used to assess the business case for sustainable building.

Eco-efficiency analysis, like LCA, is a research area that falls under the multidisciplinary field of industrial ecology. Applied to buildings, it requires the expertise of a range of specialists—architects, engineers, owners, LCA practitioners, economists—common in the building design process. While multiple disciplines routinely contribute to building design, however, they often do so in isolation. An "integrated" design process—one in which subject area experts work together throughout the process—is being heavily promoted as key to successful green building design. The same can be said for building eco-efficiency analysis: Owners set budgets, which are adhered to by architects and engineers, whose specifications are needed by LCA practitioners and economists, who in turn inform owners of the design's eco-efficiency, and so on in an ongoing feedback loop.

PREFORMANCE-BASED SUSTAINABLE BUILDING METRICS: A BUSIBEES CASE STUDY

The NIST technique is illustrated through a "BusiBEES" case study—a "Busi"ness case extension of the popular NIST process-based LCA/LCC tool known as Building for Environmental and Economic Sustainability (BEES; Lippiatt 2007). The BusiBEES case study evaluates a tall commercial building with and without energy-saving technologies. On the basis of current US industry practice, the following prototypical

Table 1. MIET 3.0 greenhouse gas flows for baseline building

Flow	Compartment	Units	New office building construction	Refrigeration and heating equipment
Carbon dioxide	Air	kg	3.24×10^7	4.43×10^6
Methane, tetrachloro-, CFC-10	Air	kg	29.8	6.17
Methane, dichlorodifluoro-, CFC-12	Air	kg	0.786	0.133
Methane, bromotrifluoro-, Halon 1301	Air	kg	6.37×10^{-6}	6.02×10^{-7}
Methane, chlorodifluoro-, HCFC-22	Air	kg	22.3	3.61
Methane	Air	kg	1.04×10^5	1.98×10^4
Methane, bromo-, Halon 1001	Air	kg	9.20	2.77
Methane, monochloro-, R-40	Air	kg	110	21.4
Methane, dichloro-, HCC-30	Air	kg	496	73.7
Dinitrogen monoxide	Air	kg	1920	156
Ethane, 1,1,1-trichloro-, HCFC-140	Air	kg	238	31.6

design is used to represent the baseline, "business as usual," tall building (Read Construction Data 2005):

- 20-story office building
- 3-m (10-foot) story height
- 43000 m^2 (468000 $feet^2$) of floor area
- 187-m (612-foot) perimeter
- steel frame
- double glazed, heat absorbing, tinted plate glass panel exterior walls
- HVAC energy supply: oil-fired hot water
- HVAC cooling generating system: chilled water, fan coil units
- HVAC energy intensity (EIA 2003):
  - 290 $MJ \cdot m^{-2} \cdot y^{-1}$ (25.6 $kBTU \cdot foot^{-2} \cdot y^{-1}$)
  - 840 $MJ \cdot m^{-2} \cdot y^{-1}$ (74.4 $kBTU \cdot foot^{-2} \cdot y^{-1}$)

The MIET software, version 3.0, is used to apply the IO LCA approach to develop inventory data for the baseline building (CML 2004; Table 1). On the basis of US IO tables, MIET requires as input the dollar value of an industrial sector's economic activity and reports as output an inventory of resulting environmental flows throughout the US economy. Thus, the actual development of such IO LCA data is explicitly multidisciplinary—the cost data are actually input to develop the IO LCA flows in accordance with existing scientific and process-based knowledge. Two industry sectors are of interest for the BusiBEES case study: 1) new office, industrial and commercial buildings construction (US Bureau of Economic Analysis Input–Output Industry Code 110800) and 2) refrigeration and heating equipment (BEA Input–Output Industry Code 520300).

The following published costs for construction of the baseline building, and for purchase and installation of its heating and cooling system, are applied respectively to the 2 industrial sectors (Read Construction Data 2005): building construction ($43531500) and HVAC installation ($8664500).

The IO-based life cycle inventory quantifies environmental flows from the materials production life cycle stages (raw materials acquisition, manufacture, and transportation) and from the construction process. In other words, the IO inventory can be said to represent the baseline building's life cycle flows from "cradle to site."

The BEES 4.0 software currently includes performance data for more than 230 building products across a range of functional applications (Lippiatt 2007). The underlying methodology used to develop an entry to a building product was applied to HVAC systems in this study, although it has not been previously included as an analyzed product in the BEES software. Thus, the BEES tool methodology, which employs a process-based LCA approach, is used to compile inventories for the following 4 energy technology scenarios.

- Conventional heating and cooling technology (represented by the baseline building)
- 30% energy-saving HVAC technology, at a cost of $10.4 million ($10.4M)
- 50% energy-saving HVAC technology, at a cost of $13.0M
- 100% energy-saving HVAC technology (i.e., "net-zero energy" building), at a cost of $26.0M

For lack of reliable data, cost premiums for purchase and installation of the 30%, 50%, and 100% energy-saving technologies—20%, 50%, and 200%, respectively—are purely hypothetical. For the same reason, each energy-saving technology is assumed to be a higher-efficiency application of the same technology, installed in the baseline building with relatively minor changes to the overall design. Although this assumption might be realistic, at least at the 30% and 50% energy savings levels, note that the BusiBEES approach permits refinement of these data. Indeed, NIST is in the process of developing additional data and case studies permitting development of these and other interesting scenarios. Otherwise, the BusiBEES case study uses current US average data. Table 2 reports annual heating and cooling

Table 2. Annual energy consumption and costs for BusiBEES case study building design alternatives

Units[a]	Base case	30% Energy savings	50% Energy savings	100% Energy savings
MBTU/y	4.68×10^4	3.27×10^4	2.34×10^4	0.00
(MJ/y)	(4.94×10^7)	(3.45×10^7)	(2.47×10^7)	(0.00)
\$M/y	1.22	0.86	0.61	0.00

[a] MBTU/y = million BTUs per year; \$M/y = millions of US dollars per year.

energy consumption and costs for the 4 case study energy technologies on the basis of US average energy data for the baseline building design (EIA 2003; Rushing and Lippiatt 2007).

The construction-to-site, IO-based life cycle inventory is combined with each BEES inventory representing design-specific operational energy flows. Applying the BEES impact metrics to the hybrid inventory for each design in the 2nd LCA step, impact assessment, permits calculation of life cycle environmental performance for each building design.

Considering operational energy use over a 50-y study period, BEES life cycle environmental performance results are summarized in Figure 1. The figure displays weighted environmental impact category scores and their sum, the environmental performance score. The weights are based on those developed by a BEES stakeholder panel, and assign a relative importance weight of 29% to global warming (Gloria et al. 2007). The results for each environmental impact—expressed in terms of the reference flow corresponding to the impact (e.g., carbon dioxide equivalents for global warming)—have been placed on the same scale by dividing by total reference flows for that impact from all US economic activity on an annual, per capita basis.

Buildings with lower BEES scores are estimated to be greener. Over 50 y, the baseline design contributes about 900000 times as much as each American contributes annually to US environmental impacts, whereas the 50% energy-saving design contributes about 500000 times as much, yielding a reduction of 45%.

These BusiBEES case study results demonstrate a close relationship between environmental performance and operational energy savings. The explanation is straightforward: The cradle-to-site, IO-based LCA results for raw material acquisition, manufacturing, transportation, and construction of all 4 building designs—which are assumed to be similar in all respects except HVAC technology efficiency—drive a fixed amount of the BusiBEES Environmental Performance Score, leaving the rest for operational energy performance over 50 y. Given that each HVAC design uses the same fuel type, it stands to reason that environmental performance savings on a BTU-by-BTU basis (MJ-by-MJ basis) would not change, leading to building scale savings that are closely related to efficiency improvement.

Figure 1 indicates that global warming constitutes the largest share of the BusiBEES Environmental Performance Score, which prompts further analysis in this case study. As shown in Figure 2, the global warming impact from operational energy use over 50 y is a decreasing proportion of the life cycle global warming impact as energy efficiency improves. The combined impact from building materials production and building construction (labeled "Bldg Cradle-Site") constitutes the rest of the global warming impact. The global warming impact from production of the HVAC system alone is negligible.

By contrast, the relative global warming impacts for the 4 case study building designs, adjusted downward to reflect just 1 y of operational energy use, are quite different. Figure 3 clearly demonstrates the importance of the time horizon in the context of green building: The shorter the time period, the less important are future energy savings.

The same can be said for life cycle economic performance, as shown in Figures 4 and 5. Although construction costs (i.e., 1st costs) for the 4 case study buildings dominate life cycle costs when considered over just 1 y of building operation, operational energy costs (i.e., future costs) become an important share of life cycle costs over 50 y of operation. On the basis of a 3% real discount rate, US Department of Energy (USDOE) energy price projections, and LCC calculation methods prescribed by ASTM International (ASTM 2005a), 50-y operational energy costs range from \$0M (net-zero building) to \$29.1M business as usual (BAU) in present value (PV) terms for the 4 building designs.

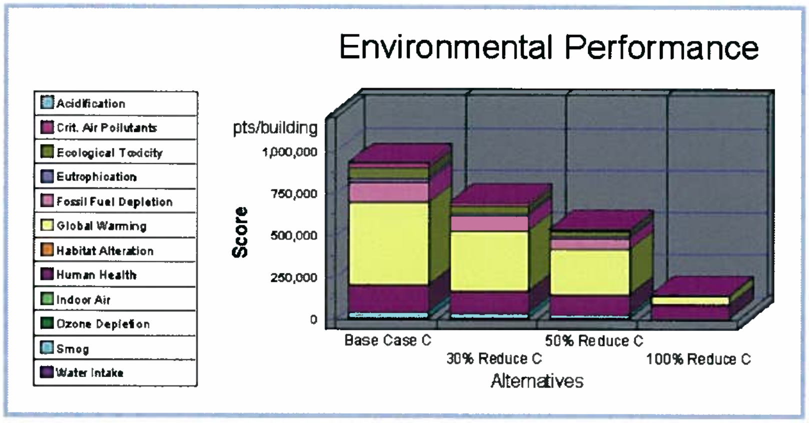

Figure 1. Life cycle environmental performance for alternative tall building designs over 50 y.

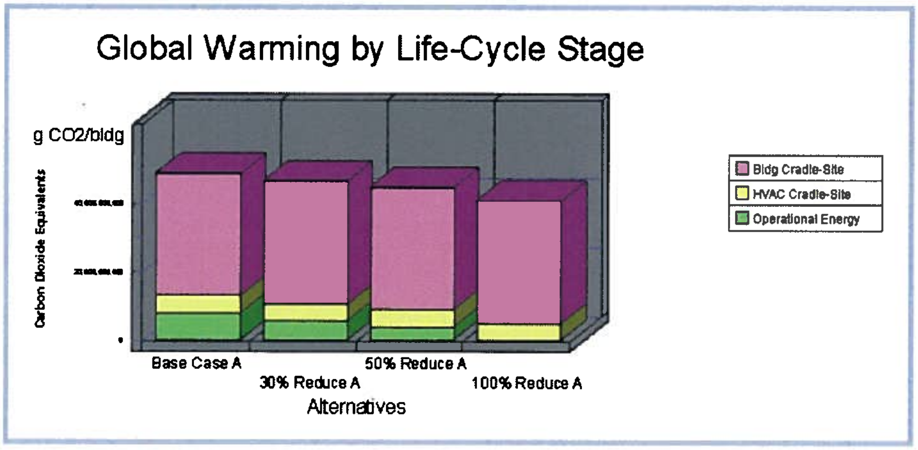

Figure 2. Global warming impact over 50 y of building operation.

With estimates of life cycle environmental and economic performance in hand, a metric quantifying business cases for the energy-saving designs can be developed. Because the global warming impact dominated all others in the BusiBEES case study, a carbon-based metric would be particularly meaningful. The metric, a carbon efficiency ratio, indicates the change in life cycle costs per metric ton of carbon saved.

As shown in Table 3, the carbon efficiency ratio ranges from a $1580/t cost increase for the 100% energy savings option over just 1 y to a $60/t cost savings for the 30% option over a 50-y time horizon. Ratios for the 2 time horizons are shown to illustrate the importance of this parameter to investment decisions; when making actual investment decisions, the time horizon will be fixed. For a private investor, its length is set at the period of building ownership. For society as a whole, the time horizon is often set at the useful life of the longest lived design alternative. However, when alternatives have very long lives, (e.g., >50 y), a shorter study period can be selected for 3 reasons: Technological obsolescence becomes an issue, data become too uncertain, and the farther in the future, the less important the costs.

In accordance with ASTM International E1185 (ASTM 2005b) guidance, BusiBEES carbon efficiency ratios are computed in a pairwise fashion. First the ratio for the lowest incremental cost alternative is evaluated with reference to the base case design alternative. If its carbon efficiency ratio is positive, then the alternative is preferred on economic grounds and it becomes the base case design alternative against which the next most expensive design alternative is evaluated. On the basis of this guidance, the ratio for the 100% energy-saving design alternative over 50 y is computed with reference to the 50%, 50-y alternative (Table 3).

CARBON FOOTPRINT METRICS

The carbon efficiency ratio developed in the BusiBEES case study is a life cycle carbon footprint metric. The carbon footprint of a building is the total amount of greenhouse gases produced directly and indirectly through its construction and operation and is usually expressed in equivalent tons of carbon dioxide (CO_2). The carbon footprint of long-lived structures, such as tall buildings that require extensive operational energy use, can be significant, as demonstrated in the case study.

The 2006 Stern Review on the Economics of Climate Change recognizes that although markets tend to deliver least cost, carbon-inefficient short-term options, they might ignore

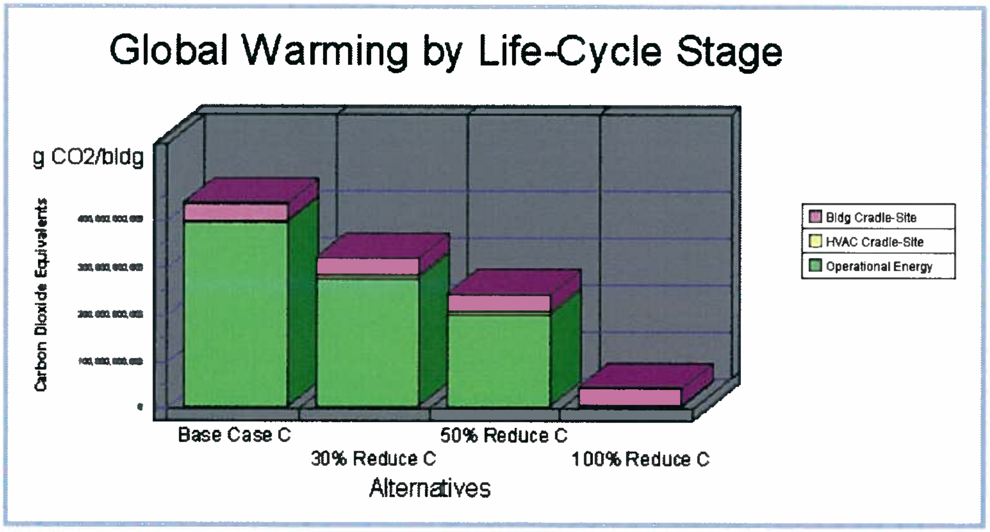

Figure 3. Global warming impact over 1 y of building operation.

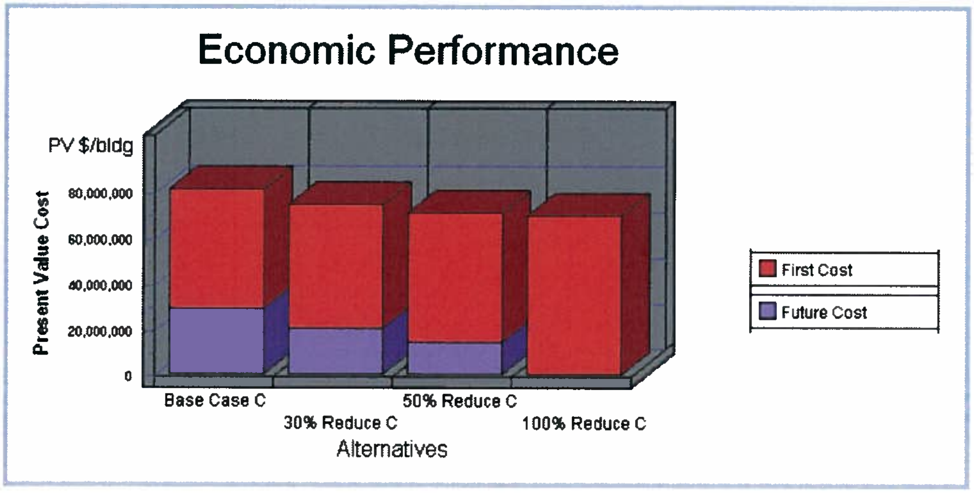

Figure 4. Life cycle costs over 50 y of building operation.

technologies that could ultimately deliver huge carbon savings in the long term. As the BusiBEES case study demonstrated, there may be alternatives with positive BusiBEES carbon efficiency ratios—those both financially superior and with reduced carbon footprints compared with conventional designs when considered over the long term. Furthermore, should carbon trading markets become widespread, even alternatives with negative ratios might become cost effective when the carbon market trades at prices above the alternative's incremental life cycle cost. Finally, designing buildings to low- and even zero-carbon footprint standards on a large scale is likely to result in economies of scale that bring to competitive levels the investment costs for technologies and innovation that help to drive down existing levels of atmospheric carbon.

CONCLUSIONS

The carbon efficiency metric described in this paper is a meaningful business indicator for investments in reduced carbon-intensive building products, components, and systems. The value of the carbon efficiency ratio lies in its use as a metric for designing and sizing cost-effective sustainable building investments, particularly those for energy-saving technologies. Although the most cost effective choice is not necessarily the investment alternative saving the most life cycle carbon, the ratio can be used to motivate investment toward measurable carbon reductions. The higher the ratio, the greater the financial gain per ton of carbon saved.

For investments geared toward less obvious environmental improvements, such as from building material selection and other major design decisions, global warming will likely not dominate all other life cycle environmental impacts. In these cases—when cradle-to-site processes are the primary drivers for environmental performance—an overall "eco-efficiency" metric should be used as the decision criterion. BEES Environmental Performance Scores could be readily substituted for carbon savings in the ratio denominator, resulting in a measure of dollars saved per unit improvement in life cycle environmental performance.

NIST is currently applying the BusiBEES protocol to about a dozen additional prototypical building types in the commercial and residential building sectors, as well as refining and developing additional data and case studies permitting variation of BusiBEES parameters that were fixed in this case study. These parameters include important variables such as fuel types for technology alternatives and US climate region–specific energy loads and costs. The NIST also plans to extend the protocol for evaluation of green retrofits to existing

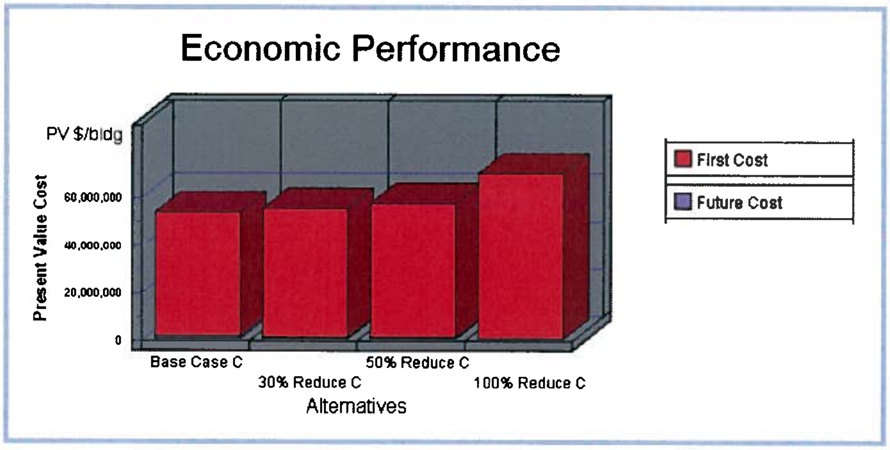

Figure 5. Life cycle costs over 1 y of building operation.

Table 3. BusiBEES case study savings and carbon efficiency ratios, by time horizon[a]

Time horizon (y)	Building design alternative (energy savings)	Incremental life cycle cost savings ($PV)	Incremental carbon savings (t)	Incremental carbon efficiency ratio (=$PV/t)
1	30%	−1380000	2300	−590
	50%	−2360000	3900	−600
	100%	−12410000	7800	−1580
50	30%	6990000	117500	60
	50%	3220000	78300	40
	100%	1550000	195800	10

[a] $PV = present value in US dollars.

buildings. Its applicability to existing buildings can be tested through verification of results with known building outcomes, such as those reported in the High Performance Buildings Database sponsored by the USDOE (http://www.eere.energy.gov/buildings/database/). An effort is also underway to better harmonize the MIET and BEES life cycle inventory databases.

The NIST BusiBEES approach combines a hybrid LCA performance metric with standard measures of economic worth. It enables calculation of carbon- and eco-efficiency ratios comparing the business value of alternative sustainable building investments. Building industry decision makers from a range of disciplines routinely make investment decisions with potentially significant impacts on the environment. By supporting their decisions with life cycle, science-based metrics, represented by a single value expressed in the monetary terms they are accustomed to using, they can better allocate scarce global and financial resources to investments having reduced long-term negative consequences on our environment.

DISCUSSION AND FUTURE DIRECTIONS

In the LCA field, there is a meaningful place for interdisciplinary connections to be made; this has been true throughout the development of LCA processes and will continue to increase in scope as we approach more complex systems, which could wed various LCA methods. The building sector, discussed through the case study presented in this paper, is an extreme example of the complexity of a true systems approach. A number of disciplines and viewpoints are considered in the development of process-based LCA and IO-based LCA separately. Thus, when the 2 LCA approaches are utilized in a hybrid fashion, there are multiple levels of interdisciplinary stratification, as noted in the *Performance-based sustainable building metrics* section. The integration of the same field of study (e.g., engineering or economics) varies between each LCA method in isolation, thus it is key to develop a balanced approach, unique to the hybrid LCA viewpoint that addresses various stakeholder needs. To this point, the NIST BusiBEES approach used environmental impact weightings developed through the multi-attribute decision analysis method (ASTM 2005c).

Multi-stakeholder life cycle considerations are significant in the development of a comprehensive understanding of the environmental, economic, and social impacts of whole–building system processes. These 3 elements constitute the triple bottom line, which is a primary concern in sustainable development research and public projects (Parkin 2000). In response to concerns of objectivity loss through the implementations of social aspects, Longino (1990, p 210) states that "a [scientific] methodology powerful enough to account for theories of any scope and depth is incapable of ruling out the influence of social and cultural values in the very structuring of knowledge." Such social knowledge can be incorporated into LCAs by directly accounting for societal ethics and concerns through stakeholder meetings as well as the careful differentiation of life cycle input data based on characteristics of the population dealing with the social issue. For instance, Cicas et al. (2007) have begun to implement localized economic and environmental characteristics within IO LCA models to address potential social impacts, such as employment division: They use Gross State Product multipliers to indicate proportions of national annual production of NAICS-coded industries occurring in different US regions. Although the BusiBEES approach encompasses the environmental and economic prongs of the triple bottom line, social impacts and values are only indirectly, and incompletely, addressed in the weighting methodology used to combine environmental impacts in the model. Other means of addressing social aspects should be explored.

As LCA continues to grow and is further established as a staple process in disciplines addressing environmental issues, there is a growing necessity for clear LCA frameworks and proper applications. As mentioned previously, the ISO LCA standards provide LCA practitioners general guidance within the process; however, the results of various LCA views can vary widely. For instance, we opted to utilize an attributional LCA view, which aims to describe the environmental consequences of changes within a life cycle and its subsystems in relative isolation, whereas some view the cognitive framework of a consequential LCA, which estimates the effects of changes within the life cycle on parts of the economy through use of the economics technique known as partial equilibrium analysis, to be superior because decision makers need to be informed about the consequences of decisions. Partial equilibrium analysis considers a market in equilibrium in isolation from other product or input markets. Consequential LCAs can provide sweeping macro-level sector predictions that are reasonable approximations of general effects only if the linkages between economic sectors are very weak. If linkages are strong, these LCAs can be misleading. For example, a consequential LCA for BusiBEES might predict changes in world oil prices if all US buildings were designed and renovated to green standards, with no consideration for the interplay of the US construction and energy sectors. Because US buildings account for 40% of US energy consumption, however, a consequential LCA in this case is ill advised. Thus, although attributional LCAs could be of limited use in a macroeconomic sense, they avoid the documented limitations of consequential LCAs: completeness, accuracy, and relevance (Ibenholt 2002).

Sustainability performance metrics and standards based on rigorous measurement science are needed to evaluate the cost effectiveness of building alternatives in an LCA sense. The BusiBEES approach is one that seeks to aggressively address these needs through the interdisciplinary lens. Additional analyses of prototypical building types, and more extensive datasets linking technology costs, operational energy savings, and building design features, will help refine and establish the approach and lay the groundwork for widespread green buildings analyses. We will only get to this point by continued strength in team formation and knowledge-sharing efforts between discipline-focused experts from each life cycle stage of the building process and its stakeholders.

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