NIST Metrics and Tools for Tall and Green Buildings

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Abstract

Tall building stakeholders need compelling metrics, tools, data, and case studies supporting major investments in sustainable building technologies. Proponents of green building widely claim these buildings to be cost-effective, but often these claims are based on incomplete, anecdotal evidence that is difficult to reproduce and defend. The claims suffer from two main weaknesses: (1) buildings 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. Yet the tall building industry needs 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 NIST Building and Fire Research Laboratory is beginning to address these needs by developing rigorous metrics and tools for assessing the life-cycle economic and environmental performance of tall buildings. Economic performance is measured using standard life-cycle costing methods. Environmental performance is measured using LCA methods that assess the "carbon footprint" of tall buildings as well as 11 other sustainability metrics including fossil fuel depletion, smog, water use, habitat alteration, indoor air quality, and human health. The paper further describes NIST activities and plans in this area.

Keywords: BEES, green building, hybrid life cycle assessment, life-cycle costing, tall buildings.

Introduction

A wave of interest in sustainability gathered momentum in 1992 with the Rio Earth Summit, during which *sustainability* was agreed to mean "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs." 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. While 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.

This paper describes and illustrates 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 using performance-based, science-informed thinking.

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 U.S. literature finds that business cases for sustainable building typically evaluate commercial or residential buildings meeting benchmarks for green certification established by building industry stakeholders. A popular example of such a certification system is the Leadership in Energy and Environmental Design (LEED) rating system, developed by the U.S. Green Building Council (USGBC). LEED designates green buildings based on criteria including water, materials, and energy use, siting, and indoor environmental quality.[1] While other U.S. benchmarking systems have been established, LEED currently leads the way in defining green building

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[1] USGBC, *LEED: Leadership in Energy and Environmental Design*, U.S. Green Building Council Web Site: http://www.usgbc.org, 2004.

attributes for the U.S. building sector.[2]

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 typically collected through post-occupancy 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. While 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. 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 tenfold.

While approaches and conclusions in published business cases have been similar, their overall value is uncertain. These studies suffer from two major weaknesses: First, the buildings upon which these cases are based are not necessarily "green" in a science-based, life-cycle assessment (LCA) sense. Secondly, 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 building 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 life-cycle assessment (LCA) and input-output-based LCA. Both take a similar life-cycle approach, but each tackles the measurement challenge in a radically different way.

LCA is a holistic approach which 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 over the last decade by the International Standardisation Organization (ISO), LCA clearly identifies and accounts for transfers of environmental impacts from one environmental medium (e.g., air, land, or water) to another and from one life-stage to the next. The ISO 14040 series of standards identify three steps in any LCA process: (1) *inventory compilation*, (2) *impact assessment*, and (3) *interpretation,* which lead to measures of environmental performance.[3] During the first 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 third step, *interpretation*, impact assessment results may be synthesized to facilitate comparison of environmental performance across competing industrial systems.

A *Process-based 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). Since some of these "unit" processes involve additional, subsidiary unit processes, process-based LCAs follow system boundary-setting rules based on the magnitude of mass and energy contributions to the system from subsidiary unit processes. While compiling inventory flows for numerous industrial processes requires extensive, detailed data collection, the 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.

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

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[2] These include the Green Building Initiative's *Green Globes* system, the joint U.S. Environmental Protection Agency/U.S. Department of Energy *Energy Star Homes* system, and the National Association of Homebuilders *Model Green Home Building Guidelines.* (Bradshaw et al., *The Costs & Benefits of Green Affordable Housing*, New Ecology, Inc., 2005).

[3] International Organization for Standardization (ISO), *Environmental Management – Life-Cycle Assessment – Principles and Framework,* International Standard 14040, 2006.

national IO tables quantifying, in monetary terms, inter-industry 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. While IO-based LCA provides a straightforward and logical framework for inter-industry 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 U.S. Bureau of Economic Analysis to develop U.S. economic IO tables, for example, distinguishes fewer than 1,000 industries and commodities. Furthermore, IO tables are static in the sense that they represent current technology mixes and industrial practices. Thus, while 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. While IO tables do not provide a level of resolution permitting analyses of new technologies, their breadth readily provides baseline inventory data representing complex industrial systems, such as buildings.

The U.S. National Institute of Standards and Technology (NIST) has developed a new "hybrid" approach 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 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 buildings is the life-cycle cost (LCC) method, standardized for building investment analyses by ASTM, International.[4]

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 years. While 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 measures, eco-efficiency metrics can be developed based on comparisons of alternate designs and investor time horizons. 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.

Performance-Based Sustainable Building Metrics: A Case Study

The NIST technique is illustrated through a case study comparing a tall commercial building with and without energy-saving technologies. Based on current industry practice, the following prototypical design is used to represent the baseline, "business as usual," tall building:[5]

- 20-story office building
- 10 ft (3 m) story height
- 468,000 ft^2 (43,000 m^2) of floor area

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[4] E917-05 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems ASTM International, *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,* ASTM Designation E917-05, West Conshohocken, PA, 2005.

[5] RS Means, *2006 RSMeans Square Foot Costs*, 27th annual edition, Kingston, MA, 2005.

- 612 ft (187 m) perimeter
- steel frame
- double glazed, heat absorbing, tinted plate glass panel exterior walls
- heating, ventilation, air conditioning (HVAC) energy supply: oil fired hot water
- HVAC cooling generating system: chilled water, fan coil units
- HVAC energy intensity:[6]
    - 185.6 kBtu/ft^2/yr (2,100 MJ/m^2/yr) district heat
    - 194.5 kBtu/ft^2/yr (2,200 MJ/m^2/yr) district chilled water

The Missing Inventory Estimation Tool (MIET), version 3.0, is used to apply the IO LCA approach to develop inventory data for the baseline building.[7] Based on U.S. 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 U.S. economy. Two industry sectors are of interest for the case study: (1) New office, industrial and commercial buildings construction (U.S. 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 two industrial sectors:[8]

- Building Construction: $4,565,150
- HVAC Installation: $654,450

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."

Next, the NIST Building for Environmental and Economic Sustainability (BEES) tool, which employs a process-based LCA approach, is used to compile inventories for the following three energy technology scenarios:[9]

- Conventional heating and cooling technology (represented by the baseline building)
- Energy-saving heating and cooling technology using 20 % less operational energy than the baseline building, at a cost of $1.5 million ($1.5M)
- Energy-saving heating and cooling technology using 50 % less operational energy than the baseline building, at a cost of $4.0M.

For the case study, each energy-saving technology is assumed to be installed in the baseline building with relatively minor changes to the overall design. Table 1 reports annual energy consumption and costs for each of these energy technologies, based on U.S. average energy data for the baseline building design.[10,11]

Table 1 Annual energy consumption and costs for three case study building alternatives

Units	**Base Case**	**20% Energy Savings**	**50% Energy Savings**
MBtu/yr (MJ/yr)	1.80E+5 (1.90E+8)	1.44E+5 (1.52E+8)	8.99E+4 (9.49E+7)
$M/yr	3.9	3.1	2.0

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 second LCA step, impact assessment, permits calculation of life-cycle environmental performance for each building design.

Considering operational energy use over a 25-year 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.[12] The results for each environmental

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[6] Energy Information Administration, *2003 Commercial Building Energy Consumption Survey: Consumption and Expenditure Tables,* Table C11.

[7] CML, *Missing Inventory Estimation Tool (MIET) Version 3.0*, Leiden University, The Netherlands.

[8] RS Means, 2005.

[9] Lippiatt, B. *BEES 4.0: Building for Environmental and Economic Sustainability-- Technical Manual and User Guide*, NISTIR 7423, National Institute of Standards and Technology, May 2007.

[10] *2003 Commercial Building Energy Consumption Survey: Consumption and Expenditure Tables.*

[11] Rushing and Lippiatt, *2007 Energy Prices and Discount Factors for Life-Cycle Cost Analysis,* National Institute of Standards and Technology, April 2007.

[12] Weights based on BEES Stakeholder Panel weight set reported in Gloria, Lippiatt, and Cooper, "Impact Weights Supporting Environmentally Preferable Purchasing in the United States," *Environmental Science and Technology,* October 2007. The weight set assigns a relative importance weight of 29 % to global warming.

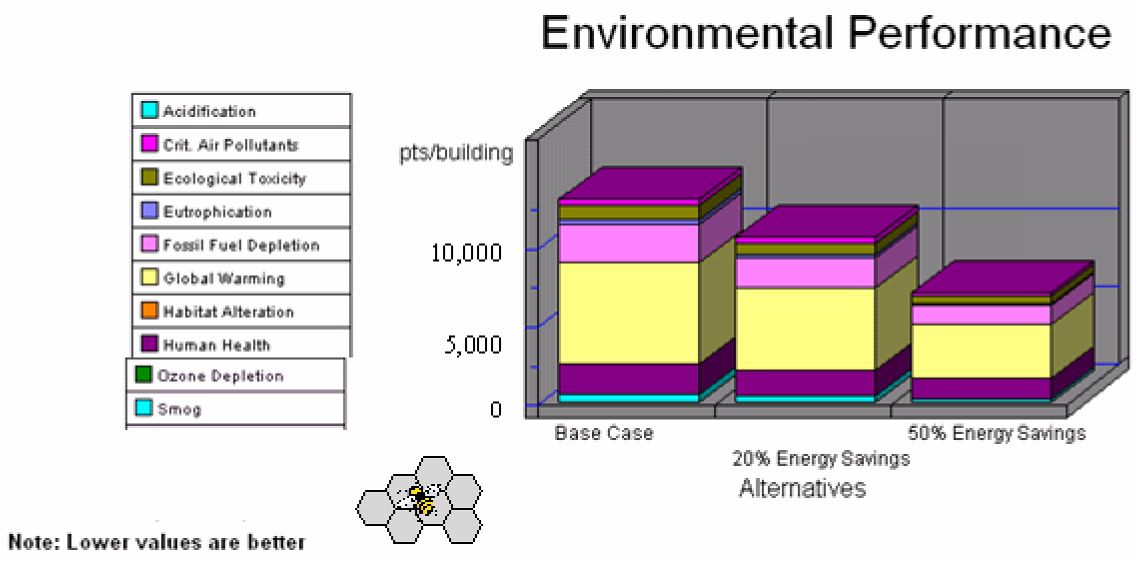

Figure 1 Life-cycle environmental performance for alternative tall building designs over 25 years

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 U.S. economic activity on an annual, per-capita basis.

Buildings with lower BEES scores are greener. Over 25 years, the baseline design contributes about 13,000 times as much as each American contributes annually to U.S. environmental impacts, while the 50 % energy-saving design contributes about 7,000 times as much.

These case study results show that environmental performance over a 25-year study period is virtually proportional to energy savings. Focusing on the impact with the largest contribution, global warming, explains why. As shown in figure 2, the global warming impact from operational energy use far exceeds the combined impact from building materials production and building construction (labeled “Bldg Cradle-Site”). The impact from production of the HVAC system alone is negligible.

By contrast, the relative global warming impacts for the same three building designs, adjusted downward to reflect just one year 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. Construction costs for the three case study buildings pale in comparison when considering operational energy costs over 25 years. Based on a 3 % real discount rate, U.S. Department of Energy energy price projections, and LCC calculation methods prescribed by ASTM, International,[13] 25-year operational energy costs range from \$34M to \$68M in present value (PV) terms for the three building designs, compared with just up to \$9M in total construction costs.

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

As shown in Table 2, the carbon efficiency ratio ranges from a \$1.31/t cost increase for the 50 % energy saving option, over just 1 year, to a \$1.20/t savings for the 20 % option over a 25-year time horizon.

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[13] ASTM International, *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,* ASTM Designation E 917-05, West Conshohocken, PA, 2005.

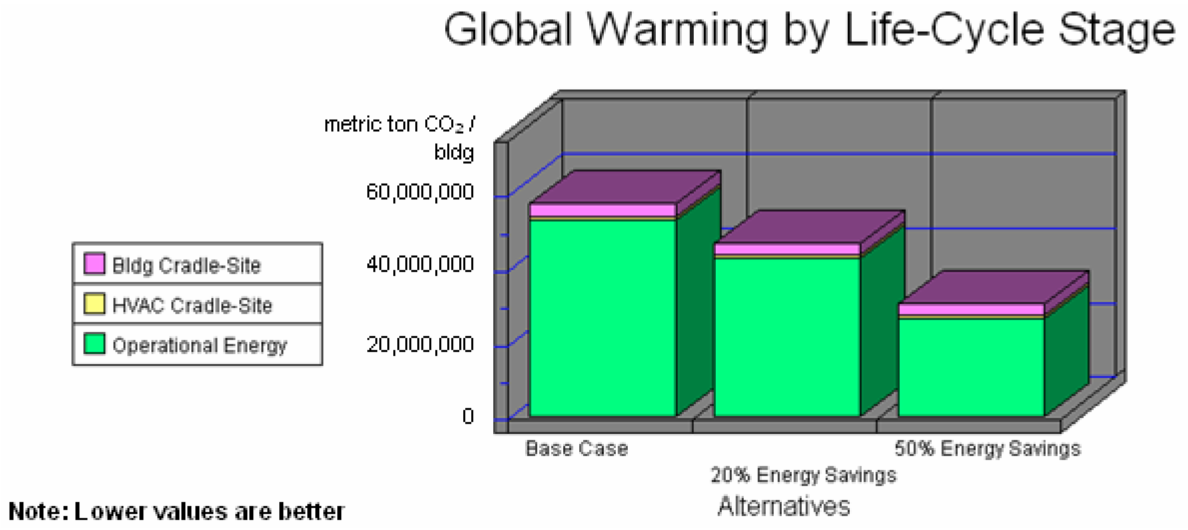

Figure 2 Global warming impact over 25 years of building operation

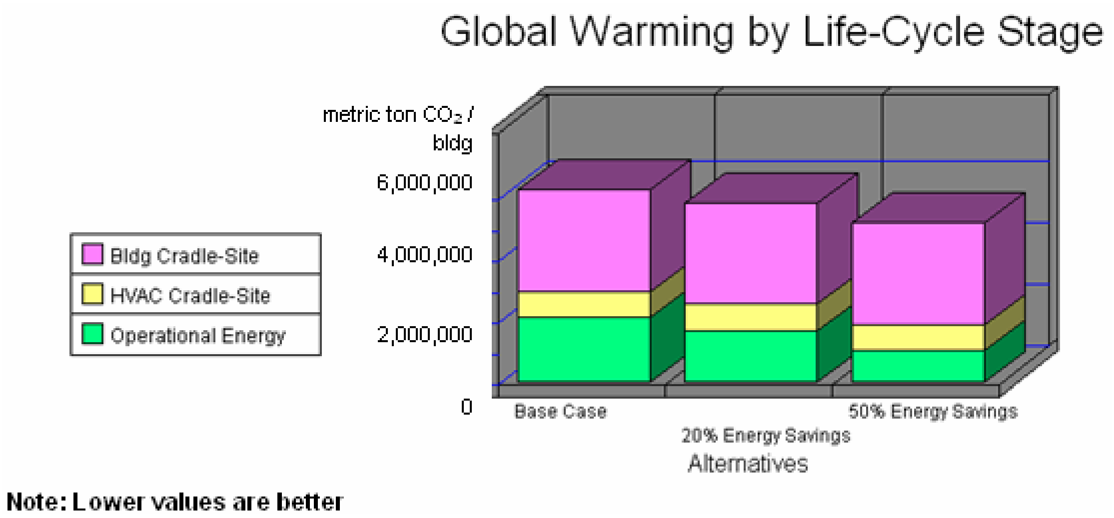

Figure 3 Global warming impact over 1 year of building operation

Table 2 Case study savings and carbon efficiency ratios, by time horizon

Time Horizon	**Building Design Alternative**	**Life-Cycle Cost Savings ($PV)**	**Carbon Savings (t)**	**Carbon Efficiency Ratio (=$PV/t)**
1 year	20 % energy savings	-65,405	424,863	-0.15
	50 % energy savings	-1,395,192	1,062,157	-1.31
25 years	20 % energy savings	12,762,931	10,621,559	1.20
	50 % energy savings	30,675,653	26,553,898	1.16

Carbon Footprint Metrics

The carbon efficiency ratio developed in the 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 which require extensive operational energy use, can be significant as demonstrated in the case study. Indeed, the 2006 *Stern Review* on the Economics of Climate Change recognizes that while markets tend to deliver least-cost short-term options, they may ignore technologies that could ultimately deliver huge cost savings in the long term. Yet high first-cost, long term options may not be the whole story. A thorough study and application of life-cycle carbon footprinting may reveal financially superior alternatives with reduced carbon footprints in comparison to the business-as-usual case. Designing tall buildings to low and even zero-carbon footprint standards on a large scale may even promote cost-effective technologies and innovation which help to drive down existing levels of atmospheric carbon.

Conclusion

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 identifying *cost-effective sustainable building investments*, particularly those for energy-saving technologies. While the most cost-effective choice is not necessarily the design 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.

While not illustrated in this case study, the carbon efficiency ratio is also valuable as a *sustainable construction portfolio selection* metric. That is, ratios for non mutually-exclusive carbon saving investments—not only for different building types but for different civil infrastructure types (e.g., roadways, bridges, dams)—can be compared to determine where governments can best invest in sustainable public resources. The sustainable investment portfolio should consist of investments selected in descending order of carbon efficiency ratios until the investment budget is exhausted.

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 may 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.

The NIST Building and Fire Research Laboratory approach, though still in the conceptual stage, is a hybrid LCA approach combined with standard economic analysis. It allows calculation of carbon- and eco-efficiency ratios comparing the business value of alternative sustainable building investments. Building industry decision makers 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 consequences on our environment.

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