AN ANALYSIS OF VARIATION IN THE ENERGY-RELATED ENVIRONMENTAL IMPACTS OF LEED CERTIFIED BUILDINGS

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ABSTRACT

The US Green Building Council's (USGBC) LEED guidelines have become the dominant third-party certification program for "green" buildings in the US. Given that buildings use 37% of all energy and 68% of all electricity while contributing substantially to air emission, waste generation, and water consumption issues in the US, one of LEED's purposes is to address the environmental impacts of energy use in buildings. This research analyzes (1) how well the LEED guidelines measure these impacts and (2) which parameters create the most variation among these impacts. Environmental impacts here refer to emissions of carbon dioxide, nitrogen oxides, sulfur dioxide, mercury, and particulate matter (PM_{10}); solid waste; nuclear waste; and water consumption. Using data from the US Department of Energy, the National Renewable Energy Laboratory, the US EPA Energy Star program, and the USGBC, among others, models using Monte Carlo analysis were created to simulate the range of impacts of LEED-certified buildings. Various metrics and statistics were calculated to highlight the significance of variation in these impacts. Future research needs and implications of the results for LEED version 3.0 are also discussed.

KEY WORDS

LEED, USGBC, green building, Monte Carlo analysis, energy, environmental impacts, carbon dioxide, particulate matter, nitrogen oxides, sulfur dioxides, mercury, nuclear waste, solid waste, water consumption

INTRODUCTION

The Environmental Impacts of Buildings

The 4.8 million commercial buildings and 116 million residential buildings in the US have substantial environmental impacts (US Department of Commerce 2000; US Energy Information Administration 2003a). Research indicates that building construction, operation, and demolition account for 15% to 45% of all environmental impacts in the US (Levin *et al.* 1995; US Environmental Protection Agency 2001). Moreover, these impacts will become more significant as the number of buildings increases, and a number of sources estimate that the built environment may double by the year 2030 (Rees 1999; Cortese 2003; Nelson 2004).

Estimated building impacts include 55% of timber consumption, 27% of plastics use, 12% of iron and steel applications, 30% of raw material consumption, 40% of atmospheric pollution, 25% of solid waste, 24% of all water use, 20% of effluent, substantial indoor air quality issues, 37% of all energy, and 68% of all electricity use (Lenssen and Roodman 1995; Newton *et al.* 2001). Moreover, as of 2004, power plants—the main source of energy for buildings—were responsible for 69% of the nation's sulfur emissions, 22% of the nitrogen oxides, 33% of stationary mercury emissions, and 39% of all carbon dioxide (Goodman and Walker 2006). Mazria (2003) estimates that the built environment may be responsible for as much as 48% of US carbon dioxide emissions.

To meet these electricity demands, water is also withdrawn and consumed. In 2000, the US Geological Service estimated that 52% of all surface water withdrawals and 39% of total fresh water withdrawals were used for thermoelectric power generation (US Geological Service 2000). Water consumption resulting from energy use, while a smaller percentage than actual water withdrawals, is estimated at over

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six billion gallons of water per day (US National Energy Technology Laboratory 2007). Given estimates that 40 states are expected to experience water shortages by 2050, these are not insignificant data (US House Committee on Transportation and Infrastructure 2003).

Among all building-related environmental impacts, those related to building energy use are the focus of this research for a number of reasons. First, energy-related environmental impacts are very much on the minds of the general public, decision makers, and the investment community alike (Adler 2006; The New York Times 2006; Ceres 2007). Accordingly, progress on these issues should be accurately represented with the LEED label. For example, the Carbon Disclosure Project has organized 284 institutional investors, with assets over $41 trillion, in an effort to ask the world's largest 2400 companies what they are doing about their greenhouse gas emissions (Carbon Disclosure Project 2007). Other examples include the prominent AIA 2030 Challenge and the adoption of the US Mayors Climate Protection Agreement by over 600 mayors (Mayors Climate Protection Center 2007). Second, it can be argued that energy impacts merit more attention than other building impact categories when one considers 1) their relative contribution to environmental problems, 2) the severity of the impacts, 3) the scale of the impact in space and time, and 4) the number of environmental problems to which energy use is related. Third, energy impacts, with fairly well established emissions factors, are relatively easy to quantify. Lastly, the Energy & Atmosphere section of LEED has more points than other categories, and points in other categories also create to overall building energy use.

For the purposes of this study, energy-related environmental impacts refer to power plant and/or on-site combustion-related air emission, waste generation, and water consumption attributable to building energy use. These focus on operational energy use (e.g., for heating and cooling) not embodied energy consumption (e.g., upstream energy consumption in material extraction and transportation of products) because the latter constitutes a relatively small percentage of a building's life cycle energy use (Lazarus 2003; International Energy Agency 2004). Impacts here should be thought of as environmental loadings (e.g., CO_2 emissions) rather than subsequent effects (e.g., an increase in global temperatures). Dispersion modeling to and within media, assimilation into the environment (e.g., biochemical transformation), as well as organismal uptake and corresponding health effects (i.e., risk assessment) are outside the scope of this research. Moreover, the focus is on regional and global impacts rather than site-related energy use impacts (e.g., carbon monoxide).

The Importance of LEED

The US Green Building Council (USGBC), with more than 10,000 member organizations, and its LEED green building rating program were designed to reduce the environmental and health impacts of buildings by stimulating market change. LEED saw significant growth between 2001 and 2005—on average the number of LEED buildings increased by over 50% each year. As of February 2007, over 800 million square feet of new buildings had been certified or registered in 50 US states and 13 countries. In the US, at least 17 federal agencies, 18 state agencies, and 59 cities encourage developers to construct LEED buildings with legislative mandates or various incentive packages (US Green Building Council 2007). To expand the USGBC's influence, other green building programs now on the market include LEED for Commercial Interiors, LEED for Homes, LEED for Core and Shell, LEED for Existing Buildings, and LEED for Schools. The LEED for Neighborhood Development is also in pilot phase. With a presence in more than 13 countries, market adoption of these programs is likely to magnify the opportunities for LEED to influence a growing portion of the $5 trillion global construction industry.

The major owners and developers of buildings listed previously are using the LEED green building rating program as a benchmark. As such, LEED has become a tool for public policies affecting billions of dollars in current and future construction. Part of the decision to use LEED is based on a presumption that a LEED-certified building is a building with reduced energy use and lower corresponding environmental impacts. That is, these institutions are either implicitly or explicitly using LEED as an environmental management tool, not just as a brand in the market as it was originally intended.

For example, the City of Seattle's Sustainable Building Policy, a part of the City's Environmental

Management Program, specifies the use of LEED as a way to gauge progress towards a City goal of improved environmental performance (City of Seattle 2007). The Director of Sustainable Design at the US GSA—perhaps the largest public owner of real estate in the US—has stated that LEED "is used as a measure of [the GSA's] accomplishment towards [the GSA's] sustainability goals" (Bowen 2005). Accordingly, it is increasingly important that the LEED label have accuracy and precision, and attention must be paid to the variability which exists in environmental impacts—in this case, from energy use—caused by these buildings.

Variability in Environmental Impacts Due to LEED Building Energy Use

Select sources of variation in energy-related environmental impacts from LEED buildings include:

1. the fuel mix at power plants and on electrical grids,
2. the general level of efficiency and pollution control at power plant electricity generation and on-site furnace/boiler efficiency,
3. the specific LEED credits obtained (or high performance design features included),
4. the difference in modeled versus actual energy use,
5. the type of renewable energies used on site or purchased from off-site sources,
6. the use of energy costs, instead of British Thermal Units (BTU's), as the unit for calculating energy efficiency improvements in LEED,
7. building type,
8. climate,
9. the use of the American Society for Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) standard 90.1 as the benchmark for measuring energy efficiency improvements, and
10. transportation-related emissions.

Parameters #1 to #8 will be addressed either explicitly or implicitly in this research. Consider below a few examples of variation in these parameters.

For #1 and #2, the *Benchmarking Air Emissions* report (Goodman and Walker 2006) shows that sulfur dioxide emissions from power plants can vary from 0 to 16 lbs per MWh (megawatt-hour), nitrogen oxides from 0 to 7 lbs per MWh, and carbon dioxide from 0 to 2370 lbs per MWh. Similarly, the US EPA's Power Profiler illustrates how fuel mixes vary considerably by grid; for example, the coal portion of overall energy sources ranges from 17% in Massachusetts to 53% in North Carolina to 91% in Kentucky (US EPA 2006). In addition, 15% of nitrogen oxides and 65% of sulfur dioxides in fossil fuel power plants does not undergo pollution control (Goodman and Walker 2006).

For #3, the differences in type and number of LEED credits obtained for LEED-certified buildings leads to variation in impacts, i.e., not all LEED buildings obtain the same LEED points. For example, when looking at the USGBC's LEED point tally—a national database of 390 LEED-certified buildings as of June 2006—only 7.7% of those projects obtained Energy and Atmosphere (EA) credit 2.3, which requires a building to obtain 15% of its energy from renewable sources. Similarly, only 41% of these buildings earned EA credit 6, which requires a building to offset more than 50% of its electricity with green energy purchases, a.k.a., Renewable Energy Credits or REC's (USGBC 2006).

For #4, it is important to note that the variation between modeled and actual energy use can vary considerably. A study of 21 first-generation LEED buildings showed that the actual energy use divided by modeled energy use varied by 18% to 225%, even though the mean was 99% (Diamond 2006). As of February 2007, the New Buildings Institute is completing a much more detailed analysis of this relationship in LEED buildings (Frankel 2007). This variation can be caused by varying occupancy behavior, imprecision in energy modeling, and the data used to determine the typical meteorological year (TMY) in an energy model (e.g., airport versus downtown locations for weather monitoring stations and the impact of the urban heat island effect).

For #5, consider that environmental impacts from renewable energy sources, even those certified by the Center for Resource Solution's Green-e program to meet LEED's requirements are not all equal (Power Scorecard 2006). In addition, the timing of conventional energy offsets from renewable energy generation has also been found to be important (Stauffer 2004). More broadly, the time of year, time of day, and general level of subscription in a region contribute to variations in emissions away from the average for a state or a given grid. However, these types of variables are not addressed in this research largely because of the lack of widespread data for this level of detail.

For #6, note that the use of energy costs as the unit for calculating energy efficiency in LEED can also cause confusion. While the cost of energy is more important to many building owners than the kilowatt-hours (kWh) or BTU's consumed, its use in calculating energy efficiency gains in baseline versus LEED buildings results in misrepresentations of the actual environmental impacts of these buildings. This can be attributed to variations in energy costs by fuel type and by region (Scheuer and Keoleian 2002). Using data from NREL research on select high performance buildings, it can be shown that a building's energy cost savings divided by a building's reduction in energy use can vary from 65%–200% (Torcellini *et al.* 2006).

Finally, regarding #7 and #8, the importance of climate and building type in affecting energy use is fairly well known, if not always apparent to all parties interested in a building's environmental footprint. In terms of impacts due to climate, Energy Star and the US Energy Information Administration's Commercial Building Energy Consumption Survey (CBECS) data demonstrate that an average restaurant in climate zone 2 (e.g., Idaho) will use approximately 250 kBTU per square foot per year compared to 134 kBTU per square foot per year in climate zone 4 (e.g., North Carolina). As for the impact of a building type, consider a health care facility using 270 kBTU per square foot per year compared to 93 per square foot per year for an office and 77 kBTU per square foot per year for a school, though all are in the same climate zone—in this case, climate zone 1 (e.g., Maine) (US Energy Information Administration 2003b).

The issues raised above suggest that there may be significant variation in the energy-related environmental impacts from buildings that all fall within the same LEED certification level—Certified, Silver, Gold, or Platinum. While this may be assumed to be the case, it has never been well quantified, and a high degree of variation may be deemed unacceptable by stakeholders. For example, would it be acceptable if these sources of variation caused a LEED Certified building with superior energy efficiency to result in lower carbon or mercury emissions than a LEED Platinum building which focused little on energy improvements?

There is little doubt that LEED has stimulated significant market change towards a growing number of buildings with lower environmental impacts. However, while LEED was not designed to serve as a scientific assessment of the environmental impacts of buildings, due to a lack of other standards and easy-to-use tools, it functions as such by default. LEED has likely accomplished the goal of reducing some of the variability in the impacts of green buildings by providing more standard definitions. It is also probable that the environmental impacts of buildings are closely related to LEED certification levels. However, it is unclear to what degree these are related. If the LEED system is designed properly, there should be 1) minimal variation among impacts from buildings of the same type (e.g., educational) within each LEED certification level—i.e., low "within group variation," and 2) minimum overlap of environmental impact distributions (i.e., probability distribution functions) from buildings among the four different LEED certification levels—high "between group variation."

POINT OF DEPARTURE

Literature

There are many green building rating systems in addition to LEED, but few have been evaluated as to their ability to truly differentiate between the environmental impacts of different buildings. Other such programs or initiatives which have been developed and/or are in current use include Building Environmental Performance Assessment Criteria (BEPAC) in Canada; the US EPA Energy Star Program; Building Research Establishment Environmental Assessment Method (BREEAM) in the UK; the internationally oriented Green Building Challenge (GBC) and its GBTool; EcoProfile in Norway; HQE in France; Eco-Effect in Sweden; Green Globes in Canada, the UK, and the US; and CASBEE in Japan, in addition to many regional programs such as Earthcraft and Built Green. It is likely that all of these programs could benefit from the type of analysis conducted in this research to ensure that program stakeholders get the benefits (e.g., reduction in environmental impacts) that many expect through certification.

Assessments of these programs to date have focused on the goals, intended users, and building life cycle phases (Bosch *et al.* 2003). Crawley and Aho (1999), Todd *et al.* (2001), Cole (2005), and Boecker *et al.*, (2006) provide similar comparisons of the more popular green building programs, though several have matured since this comparison. More rigorous evaluations of these types of programs are rare and needed (Bosch *et al.,* 2003). Quantitative analyses of LEED typically focus on cost, and these have provided the beginnings of much needed data to aid decision-makers on investment and policy questions related to green building (Kats 2003; Matthiessen 2004; Stegall 2004; Steven Winter Associates 2004). Others have criticized LEED, noting the drastic cost differences for obtaining points (Stein and Reiss 2004; Frangos 2005), the ease of obtaining LEED certification and its high costs (Frangos 2005), its slow adoption and the limitations of ASHRAE as an energy benchmark (Eley 2001; Udall and Schendler 2005), the tendency for LEED to encourage point-chasing over integrated design for the most cost-effective high performance buildings (Eijadi *et al.* 2002; Stein and Reiss 2004), and the importance of regional context in determining the benefits from certain designs, such as "cool roofs" (Akbari *et al.* 1998; Eijadi *et al.* 2002).

Other literature has focused on the relationship between modeled and actual energy use in LEED and related high performance buildings (Pless and Torcellini 2004; Scofield 2004; Diamond *et al.* 2006), the stringency of energy requirements in LEED (Eley 2001), the level of effort required to achieve various LEED points (Eijadi *et al.* 2002), the need for weighting of LEED points with respect to environmental benefits (Eijadi *et al.* 2002), the effectiveness of energy strategies to earn LEED points (Werthan and Navvab 2006), the potential inadvertent environmental consequences of relying on LEED (Bray and Natasha 2006), the relationship between a building's ENERGY STAR Score and its level of electricity savings compared to code (Johnson 2002), and decision support for selecting building energy strategies (Chalifoux 2006; Pulaski *et al.* 2006).

However, very little research has been conducted on the relationship between a LEED certification and a building's environmental impact. Other programs and tools address regional variances and select building-related emissions (typically just carbon dioxide), though these programs are more focused on research rather than certifying new buildings, and the ease of use of the resulting tools has also been questioned (Cole 1998; Crawley and Aho 1999). The Green Building Challenge Tool makes an important step in this direction by suggesting the use of certain indicators of impacts from a green building, such as normalized greenhouse gas emissions, total material consumption, and overall potable water use (Lindsey 2007). UK's BREEAM program also awards projects which reduce their contributions to global carbon dioxide emissions. Related research has been conducted on the importance of regional fuel mix in affecting greenhouse gas emissions in Canadian homes (Sheltair Group 1999); the effects of grid fuel mix and hourly generation from PV panels in determining the level of avoided emissions (Stauffer 2004); the use of life cycle analysis (LCA) to assess environmental impacts from a LEED building (Scheuer and Keoleian 2002); the cost-effectiveness of LEED energy and water credits in LEED (Azerbegi 2000); and the impact of various building designs on air emissions, design costs, life-cycle costs and grid reliance for energy supply (BNIM Architects *et al.* 2002).

The Current Study

LEED currently measures an energy strategy (e.g., energy efficiency) rather than an energy goal (e.g., a quantitative measure of reduced emissions). A focus on environmental loadings—that is, air emissions, waste generation and water consumption—in the current analysis is a major deviation from and proposed revision to the current LEED program. We suggest that these loadings may serve as a factor for weighting and aggregating impacts resulting from the built environment instead of cost per point as is frequently suggested. This paper will focus on a broader array of impacts than those typically considered in related studies. For example, a 500-Megawatt, coal-fired power plant produces an average of 318,000 tons of fly ash and scrubber slurry each year, and 75% of this is landfilled (Union of Concerned Scientists 2005). These impacts do not normally receive the same attention as a plant's air emissions. Or consider the argument in favor of nuclear energy in a world of increasing concern about global climate change, which may neglect the significance of high and low level nuclear waste generated. Furthermore, the impact estimations in this research rely on the most up-to-date emission factor data for buildings (Deru and Torcellini 2006). In addition, to understand the magnification effect of potentially inaccurate representations of the environmental footprint of high performance buildings created by the policies of a single decision-making body (e.g., a state, city, governmental agency, or campus) which mandates or provides incentives to developers and owners to use LEED, the simulated impacts will also be summed across a larger portfolio of buildings. Lastly, to quantify these impacts, this research applies a methodology rarely used in this field—Monte Carlo analysis and probabilistic modeling.

METHODS

To quantify the environmental impacts from energy use in buildings, it would have been best to take actual measurements from many buildings in many regions of the country. However, this was not feasible for the current study. Instead, probabilistic models were created to simulate the energy-related environmental impacts of LEED buildings based on the LEED points received by those buildings. It is not suggested that probabilistic simulation be used to model or measure individual building energy use—for these, approved energy modeling software and actual measurements are the preferred methods.

Monte Carlo analysis, performed with the Crystal Ball software package, was used to simulate these impacts. Monte Carlo analysis is a probabilistic analytical method frequently used in risk assessment, cost-benefit analysis, and other fields where decisions based on uncertain variables are involved. The advantage of analyses run in a stochastic manner such as this versus those created in a deterministic model is the ability to produce a picture of the variation in environmental impacts across different buildings in a category instead of simply a discrete, average value. This is possible because Monte Carlo simulations allow a user to represent variables in a model or algorithm with ranges rather than point estimate or average values (e.g., the variation in solid waste generated by buildings lies between 0.3 and 430 pounds per MWh of electricity used per year with an average of 210 pounds per MWh per year). In addition, a stochastic analysis allows for 1) an analysis of the variability distributions underlying predictions (e.g., based on 1,000 scenarios, there is a 90% chance that the particulate matter emissions caused by a specific 20,000-square foot building's energy use is 70 pounds per year or less), 2) sensitivity analysis (e.g., variation in the emissions factor for sulfur dioxides is responsible for ~60% of the variability among the sulfur dioxide emissions of LEED office buildings), and 3) simulation comparison (e.g., distributions of impacts from 1,000 modeled LEED Silver buildings can be laid over similar distributions for 1,000 simulated LEED Gold buildings on the same axis to see whether these distributions overlap or are significantly different).

Normal, triangular, gamma, beta and other distributions were used for each building parameter, depending on the availability of data points for each. For example, a triangular distribution was used for the average energy use intensity (EUI), i.e., kBTU per square foot per year, for education buildings because the mean, minimum, and maximum values were the only reliable data obtainable, primarily through the US Energy Information Administration's CBECS database. Where more detailed data were available for a parameter, more detailed variability distributions were developed.

See Table 1 for a summary of model types. These three building categories represent the buildings which most commonly use LEED. In terms of total energy consumption by building type in the US, these building types are all in the top five (US Energy Information Administration 2003c).

Additional model variations addressed the difference between modeled and actual energy use; fixed versus variable air emission, waste generation, and water consumption factors; the relevance of green energy purchases in reducing emissions; and the importance of scale, that is, how the small variations in impacts on a per square foot basis are magnified when cities or campuses make policies based on LEED. In total, over 180,000 simulated environmental impacts for buildings were generated and analyzed.

Each probabilistic model consists of algorithms that convert building data and features to estimates of environmental impact. Figure 1 summarizes these relationships. Each simulated impact is based on different model parameter inputs taken from the distributions for energy efficiency, renewable energy, and emissions factors, among other variables. These impacts are calculated on a "per square foot per year" basis. The models used here incorporate 14 of the total 64 categorical total LEED points or approximately 22% of all credits. The 14 points reflected in

TABLE 1. Characteristics of models used to simulate environmental impacts.

Building Type	Sample Size of Actual LEED Buildings	LEED Certification Levels Modeled *	# of Environmental Impacts Modeled **	# of Simulated LEED buldings Per Model	# of Simulated Impacts Per Model
All buildings	390	Base case, Certified, Silver, Gold, Platinum	9	1,000	45,000
Only educational buildings	33	Base case, Certified, Silver, Gold	9	1,000	45,000
Only office and institutional buildings	235	Base case, Certified, Silver, Gold, Platinum	9	1,000	45,000
Only residential buildings	17	Base case, Certified	9	1,000	45,000

* Models were not created when the sample size was too small.
** These will be explained later.

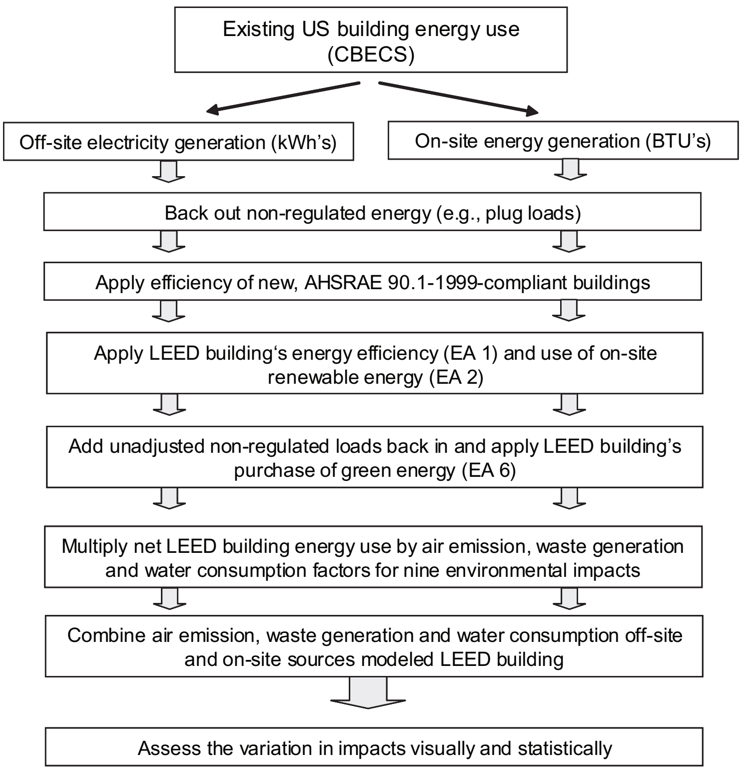


FIGURE 1. Simplistic representation of model algorithms.

the current study are EA credit 1 "Optimize Energy Performance" worth 10 points, EA credit 2 "Renewable Energy" worth 3 points, and EA credit 6 "Green Power" worth 1 point. (Note that in LEED calculation methods, the on-site renewable energy component is counted in EA credit 1 to represent a reduction in grid energy use.) Empirical data on the percentage of LEED buildings which obtain each credit were drawn from the USGBC's point tally, the national database of LEED-certified buildings.

More detail on these algorithms is highlighted in the series below. Note that most numerical entries are included as distributions rather than discrete or average values (example distributional characteristics are shown in parentheses).

1. Each model is defined by specifying the following elements:
   a. The building category (e.g., educational buildings)
   b. The EUI for these buildings in the existing building stock (e.g., 61–103 kBTU/square foot/year with a mean of 81 kBTU/square foot/year)
   c. The percent of electricity (i.e., versus natural gas) for these buildings (e.g., 25%–87% with a mean of 54%)
   d. The kWh-based plug loads for these buildings (e.g., 8%–23%, with a mean of 18%)
   e. The BTU-based plug loads for these buildings (e.g., 4%–10%, with a mean of 6%)
   f. The energy efficiency, or reduction in energy use, for these buildings compared to existing buildings from 1.b. above (e.g., 4%–13% with a mean of 8.6%)
   g. The LEED certification level
   h. The frequency with which these buildings have historically obtained the following LEED credits:
      i. EA credits 1 and 2
      ii. EA credit 6
2. Using 1.b and 1.c, energy use in each simulated building was broken into electricity (kWh) and non-electricity (BTU) uses for an existing building.
3. Using 1.d and 1.e, the energy use not regulated by ASHRAE 90.1-1999 (e.g., plug loads) was subtracted from the kWh and BTU values above.
4. Using 1.f, the baseline energy for kWh and BTU per square foot per year was calculated from the value above to arrive at the estimate for a new ASHRAE 90.1-1999 compliant building.
5. Using 1.h.i, values for energy efficiency and on-site renewable energy were subtracted from the value above.
6. Using 1.d and 1.e, the kWh's and BTU's non-regulated energy use were added back in.
7. Using 1.h.ii, the total kWh's were reduced because of green energy purchases.
8. The resulting kWh's and BTU's per square foot per year were multiplied by the air emission, waste generation, and water consumption factors.
9. The sub-total environmental impacts were combined for kWh's and BTU's.
10. This simulation was run 1,000 times for each model to produce a variability distribution of the magnitude of these impacts.

Model results were verified by ensuring that the mean, minimum, and maximum EUI for the simulated LEED and base case, non-LEED buildings were comparable to those based on CBECS data and a small number of actual LEED buildings documented in sufficient detail on the USGBC website of completed projects.

Model assumptions

EUI values used as the starting point for calculations were drawn from the minimum and maximum EUI by census region and building type found in the US Energy Information Administration (EIA) 2003 CBECS database (US Energy Information Administration 2003d), which represents the entire US building stock. Energy Star estimates provided for average, minimum, and maximum "percent electricity" values (Jurovics 2007). Off-site electricity and on-site energy impacts were handled separately because the environmental impact of each varies considerably (e.g., transmission inefficiency). Non-regulated loads for off-site electricity use (kWh's) and on-site energy use (BTU's) were estimated by building type using 1995 and 1999 CBECS data on fuel consumption by end use. The average plug load as a percentage of total building energy use was approximately 22% with a range of 12%–29%, which includes an estimated 10% increase in plug loads from 1999 to 2003 (US Energy Information Administration 1995, 1999a, 1999b). Out of this total, plug loads from electricity use (as compared to plug loads from on-site natural gas) represented approximately 76% of total plug loads.

In order to make the baseline CBECS energy use comparable to energy use in new LEED buildings compliant with ASHRAE 90.1-1999, 2.4%–14.8% of energy use was subtracted. This was based on a study comparing the efficiency of buildings compliant with ASHRAE 90.1-1999 versus ASHRAE 90.1-1989 (US Building Energy Codes Program 2002).

This is further supported by CBECS data highlighted in the 2007 Buildings Energy Data Book, showing that 1) buildings built between 2000 and 2003 and 2) the entire building stock used 81.6 and 91 kBTU per square foot per year, respectively. It was assumed that an ASHRAE 90.1-1989 compliant building is a reasonably good proxy for CBECS energy use data, where the average EUI for all existing buildings is 91 kBTU per square foot per year and buildings built between 1990-2000 (i.e., when many buildings were following ASHRAE 90.1-1989) averaged 90.3 kBTU per square foot per year. The assumption follows that the higher energy use by buildings not built to ASHRAE 90.1-1989 standards in the 1990's is offset by renovations and equipment replacement in that same time period to bring these older buildings up to this standard or beyond.

While approximately 41% of all LEED buildings earn EA credit 6, the actual percentage for a given building varies. For example, the value averaged 34% for LEED Certified office buildings and 67% for LEED Platinum office buildings. This variability was incorporated into the models for this study through the use of a random number generating function. For example, if the random number, which falls between 0 and 1, produced in the model for LEED Platinum office buildings was less than 0.67, then the reduction in environmental impacts would be equal to approximately 50% of the amount of electricity consumed (because that is the percentage of the building's electricity likely to be supplied by green power purchased because this is the level set by LEED) multiplied by 0.86 (explained in the following paragraph) and then by the air emission, waste generation, and water consumption factors (Table 2).

It is normally assumed that these green energy purchases result in zero environmental impacts and, therefore, a reduction by 50% of the negative impacts of using conventional energy for a building, recent work suggests otherwise. The Power Scorecard—a collaboration among Environmental Defense and Natural Resources Defense Council among others—makes an effort to quantify the level of such air, land, and water impacts of various energy sources (Power Scorecard 2006). In this analysis, scores ranged from 0 to 12, where 12 denoted the highest impacts from an energy source. For example, distributed solar power scored a 0.0, biomass with no nitrogen oxide controls earned a 4.1, coal corresponded to 8.5, and nuclear scored 11.8. The equation below illustrates how the value of 0.86 was derived to suggest that Green-e power does not translate into a 100% reduction in conventional energy impacts. "%" values correspond to relative abundance of conventional (numerator) and Green-e renewable (denominator) energy sources and "Impact Score" refers to the value that each energy source received in its Power Scorecard rating.

$$\frac{A-B}{A} = \frac{8.97-1.25}{8.97} = 0.86 \times 100 = 86\% \text{, } \textit{where}$$

"A" = weighted average score for conventional energy:
$(\%_{Coal} * \textit{Impact Score}_{Coal}) + (\%_{Gas} * \textit{Impact Score}_{Gas}) + \ldots$

"B" = weighted average score for Green-e renewable energy:
$(\%_{Solar} * \textit{Impact Score}_{Solar}) + (\%_{Wind} * \textit{Impact Score}_{Wind}) + \ldots$

When model simulations were run, values were not drawn independently from each distribution because sometimes there were correlations between two variables. Correlations between a number of variables, e.g., between census region and emission factors, were considered, but no others were found to be present except between 1) EA credit 1 and EA credit 2, which addresses energy efficiency and on-site renewable energy, and 2) EA credit 6, which deals with green energy purchases. Correlation coefficients for each building category were calculated by first converting the energy efficiency percentage (0%–60%) for EA credits 1 and 2 to a binary value of 1 or 0 to match the binary values for EA credit 6. For EA credits 1 and 2, a value of 0 meant that the building was used the same amount of energy as the ASHRAE baseline building (which served as the standard used for the vast majority of buildings in the LEED point tally), while a value of 1 meant that the building used less grid energy than this standard. For EA credit 6, a value of 0 indicated that green energy purchases did not pass LEED's threshold, and a value of 1 denoted that the green energy purchase contracts exceeded 50% of total electricity use for a term of more than two years. Next, tetrachoric correlation coefficients, which allow for the estimation of correlation coefficients for binary data sets, were calculated in SAS (SAS 2007). Resulting correlation coefficients were found to be relatively insignificant and varied from 0.04 to 0.16 depending on the building category.

Air emission, waste generation, and water consumption factors

Table 2 summarizes these factors. The National Renewable Energy Laboratory (NREL) provides total emission factors for the air emissions as well as estimates for the generation of solid waste. These are based on source, not site, energy and, therefore, include combustion and pre-combustion pollution per kWh of delivered electricity, such as the impacts involved with "extracting, processing, and delivering the primary fuels to the point of conversion in the electrical power plants or directly in the buildings" (Deru and Torcellini 2006). Water consumption estimates are also derived from NREL research (Torcellini et al. 2003), though the water consumption factors used in this research have been reduced compared to those from the NREL study. The NREL estimates are conservative and are based on available data; these assume that water lost through evaporation from reservoirs is due entirely to the need for electricity generation, and is, therefore, caused by hydroelectricity generation. However, our models assume that this water loss is also attributable to at least three other uses of dams, which may include recreation, flood control, irrigation, or municipal water supply. As such, we use estimates of water consumption per kWh of electricity equal to one-third of the NREL estimates. The US DOE's Office of Nuclear Energy (2006) provides estimates for nuclear waste generation.

Assessment of simulation results

These results were then analyzed using F values, R-square values, two impact ratios, and various overlays of the probability distribution functions of sets of 1,000 simulated impacts by LEED certification level. The F value and R-square values were calculated using SAS (SAS 2007). Each was used to compare "between-group" variability (i.e., discrete means for the impact distributions from buildings with different LEED certification levels would be ideal) and "within group" variability (i.e., smaller standard deviations within the impact distributions from buildings in each LEED certification level would indicate an acceptable rating system). A null hypothesis and F-test were not used because it was assumed that there is a

TABLE 2. State-level source air emission, waste generation, and water consumption factors.*

Impact	Units	Mean	Minimum*	Maximum*	Coefficient of Variability**
Off-site (Indirect Impacts)					
Carbon dioxide	Lbs/MWh/yr	1.7E+03	1.8E+01	2.7E+03	0.41
High level nuclear waste	Lbs/MWh/yr	1.2E-03	0.0E+00	4.5E-03	—
Low level nuclear waste	Cf/MWh/yr	6.2E-04	0.0E+00	2.3E-03	—
Mercury	Lbs/MWh/yr	3.8E-05	1.0E-06	1.7E-04	0.82
Nitrogen oxides	Lbs/MWh/yr	3.0E+00	1.4E-01	5.0E+00	0.45
Particulate matter	Lbs/MWh/yr	1.4E-01	7.7E-03	3.0E-01	0.54
Solid waste	Lbs/MWh/yr	2.1E+02	2.8E-01	4.3E+02	0.55
Sulfur dioxides	Lbs/MWh/yr	8.1E+00	1.1E-01	1.5E+01	0.47
Water	Gallons/MWh/yr	2.3E+03	7.4E+01	2.4E+04	2.25
On-site (Direct Impacts)					
Carbon dioxide	Lbs/BTU/yr	2.0E-04	1.2E-04	3.3E-04	—
Mercury	Lbs/BTU/yr	3.9E-11	8.1E-16	9.3E-11	—
Nitrogen oxides	Lbs/BTU/yr	3.4E-07	4.6E-08	9.2E-07	—
Particulate matter	Lbs/BTU/yr	5.3E-08	5.3E-09	1.7E-07	—
Sulfur dioxides	Lbs/BTU/yr	1.1E-07	6.1E-10	2.8E-07	—

* Only data on average emissions, consumption, and waste generation from net energy-exporting states was used for off-site impacts, as these are more reliable than data from energy-importing states. Data for HLNW and LLNW are based on grid fuel mixes.

** The coefficient of variability represents the standard deviation divided by the mean, it is used because units and scale vary among the emission, consumption, and waste generation factors. "—" denotes an instance where the coefficient could not be calculated due to small sample size and less reliable standard deviations.

difference between the means of different LEED certification levels.

The first impact ratio, referred to as "Rank Order Phase Shift," was calculated by first rank ordering the results of the 1,000 simulated impacts from a building's energy use. The resulting number is an expression of the percentage difference in impacts which occurs as different categories of building certification are considered, from non-LEED base case buildings through LEED Platinum buildings. An example calculation is shown below for one set of particulate matter emissions, though all 1,000 such ratios were also combined in an average Rank Order Phase Shift:

$$\left(\frac{\text{PM Emissions}_{\textit{LEED Certified}}}{\text{PM Emissions}_{\textit{LEED Silver}}}\right) - 1 \times 100 = \text{Rank Order Phase Shift}$$

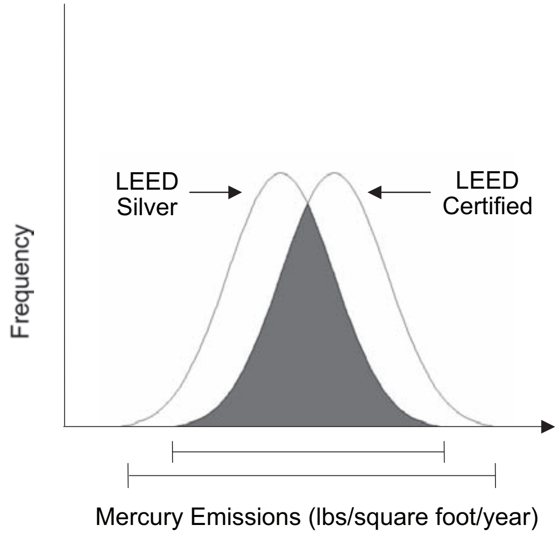
The second impact ratio, referred to as "Percent Distribution Overlap," quantifies the degree of overlap in comparisons of probability distribution functions of these sets of 1,000 simulated impacts. This ratio ignores the issue of frequency in the simulations and represents the possibility that individual buildings certified at different levels of LEED could have the same level of environmental impact. Figure 2 depicts how this formula is calculated using simple probability distribution functions for the simulated mercury (Hg) emissions for 1,000 LEED Silver buildings and 1,000 LEED Certified buildings as an example. The range represented by the upper, shorter line was divided by the range estimated the lower, longer line to arrive at the Percent Distribution Overlap. Consider the formula below for an example calculation of this overlap for carbon dioxide emissions:

$$\frac{\text{Maximum Hg Emissions}_{\text{LEED Silver}} - \text{Minimum Hg Emissions}_{\text{LEED Certified}}}{\text{Maximum Hg Emissions}_{\text{LEED Certified}} - \text{Minimum Hg Emissions}_{\text{LEED Silver}}}$$

$$= \text{Percent Distribution Overlap}$$

Finally, the probability distribution functions characteristic of Figure 2 allow for a visual representation of the overlap of actual simulated impacts (Figure 3 and 4). The relative level of kurtosis and degree of separation among each distribution can be seen in these graphs. Because the derivation of base case building energy use is not based on actual or modeled energy use and is, therefore, less than perfect, it is worth stressing that actual energy use and impact predictions in this research are less important than the degree of variation in said impacts.

FIGURE 2. Visual representation of the calculation of Percent Distribution Overlap using two probability distribution functions for hypothetical mercury emissions resulting from building energy use.



FINDINGS

EUI values for *simulated* LEED and non-LEED, base case buildings were comparable to EUI data for *actual* LEED buildings and non-LEED, base case buildings (though the availability of energy use data on completed LEED buildings is sparse and the range of EUI is also high). In analyzing the results presented here, it is important to understand that the environmental impacts represented are not cumulative. That is, a building responsible for a very high level of nuclear waste generation would not likely be the same building shown in the probability distribution functions that is responsible for a very high level of carbon dioxide emissions. These buildings would likely be located on grids with substantially different fuel mixes.

Figures 3 and 4 show the variation in two of the nine impacts studied here: carbon dioxide and particulate matter emissions. Variation in the other seven impacts looks very similar. The results suggest that on average there is a distinction among the emissions of buildings with different LEED certification levels. That said, there is considerable overlap in these impacts, and when making comparisons of individual buildings, the variation can become problematic. For example, the results indicate that it is possible for the

FIGURE 3. Probability distribution functions for carbon dioxide emissions for models analyzing office buildings with different levels of LEED certification (or lack thereof).

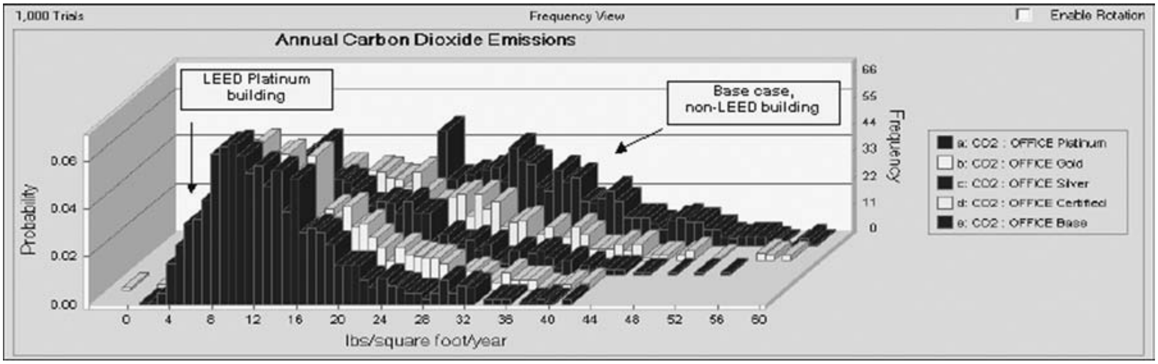
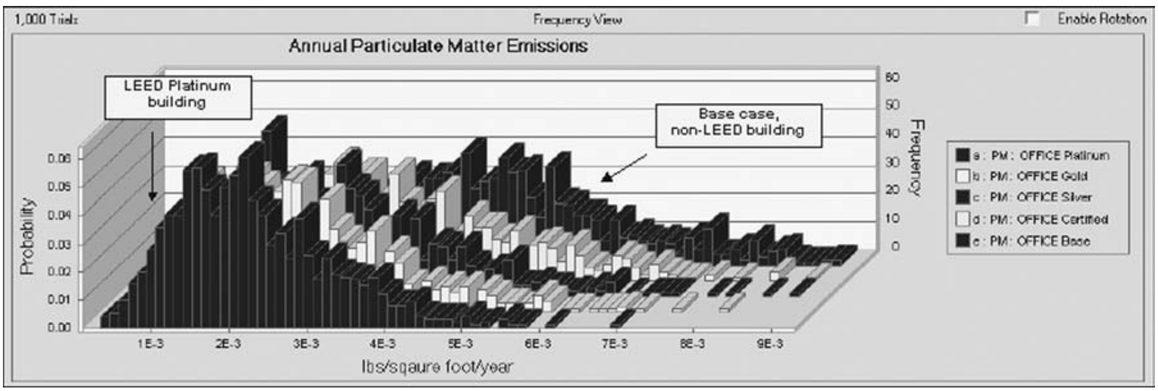


FIGURE 4. Probability distribution functions for particulate matter emissions for models analyzing office buildings with different levels of LEED certification (or lack thereof).



energy-related environmental impacts of a LEED Certified or Silver building to be lower than those of a LEED Platinum or Gold building.

The majority of results presented here are based on office buildings because 1) LEED was primarily designed to serve this product type, 2) these buildings constitute the largest portion of the empirical data from the USGBC's point tally, and 3) the results based on other building types analyzed are similar in pattern and scale to those from office buildings. The study yielded a separate figure for each of the nine environmental impacts for all four building categories—all buildings combined as well as educational, office, and residential buildings. All were combined in the same manner as in Figures 2 and 3.

F values were calculated for each of the four building categories and for all nine impacts, for a total of 36 values. All F values had corresponding probability values less than 0.001, which suggests that there are statistically significant differences among the mean impacts of buildings with different LEED certifications, even if the variability distributions overlap to a high degree. These high F values are caused in part by the large sample size—2,000 to 5,000 data points for each of the 36 analyses for F values and R-square values (i.e., 1,000 simulated impacts for nine impacts across four different buildings categories with varying levels of LEED certification levels). As the number of actual LEED-certified buildings reaches the thousands, the implications of these F values become more noteworthy.

The R-square values, which are not influenced by the sample size, show a slightly different picture. These values capture more of the variation represented by the high Percent Distribution Overlap values (described next) and probability distribution functions shown previously in Figures 3 and 4. R-square values ranged from 0.06–0.32 with a mean of 0.18. Given the large intra-group variation, this suggests that a non-trivial portion of overall variation lies between the groups, i.e., between any set of simulated impacts from buildings with different LEED certification levels.

The two impact ratios also produced mixed results. The first, the Rank Order Phase Shift, was calculated for all four building categories. These values were similar across building categories. For office buildings, the mean value was 58% when comparing the all nine impacts between a non-LEED, base case building and a LEED Certified building. This implies that on average (given 1,000 buildings of each type) a non-LEED, base case building would be expected to generate 58% more air emissions, waste products, or water waste than a LEED Certified building. Side-by-side comparisons of LEED buildings with different LEED certification levels showed a mean Rank Order Phase Shift value of 18%. For example, on average a LEED Gold office building would have approximately 20% more nitrogen oxide emissions due to its energy use compared to similar indirect emissions from a LEED Platinum office building. Table 3 summarizes these comparisons for LEED among all four building categories. Note that "Base case/Certified" percentages are similar across building categories. "Gold/Platinum" percentages are also consistently higher than other side-by-side comparisons of impacts from LEED-certified buildings. "Base case/Certified" percentages for residential buildings are higher than those for other building categories because these LEED Certified buildings tend to have higher values for EA credit 1 and 2 as well as EA credit 6 than LEED Certified buildings in other categories.

However, the second impact ratio, the Percent Distribution Overlap, averaged 90%, which represents considerable commonality of environmental impacts in side-by-side comparisons of LEED buildings (Figure 2). In theory, this percentage would be much lower and represent more separate impact distributions, as one might expect, among buildings with different LEED certification levels.

With respect to the sensitivity analysis performed, the parameters shown in Table 4 are responsible for

TABLE 3. Percentage differences in environmental impacts in the four building categories based on LEED certification level.

	All Buildings				Educational Buildings		Office Buildings				Residential Buildings
Impact	Base case/ Certified	Certified/ Silver	Silver/ Gold	Gold/ Platinum	Base case/ Certified	Certified/ Silver	Base case/ Certified	Certified/ Silver	Silver/ Gold	Gold/ Platinum	Base case/ Certified
Carbon dioxide	51%	11%	17%	20%	46%	22%	44%	21%	13%	22%	65%
High level nuclear waste	67%	13%	15%	18%	58%	26%	53%	23%	15%	20%	85%
Low level nuclear waste	67%	13%	16%	18%	59%	25%	51%	23%	15%	22%	86%
Mercury	46%	8%	15%	20%	58%	24%	39%	16%	12%	18%	55%
Nitrogen oxides	56%	9%	12%	21%	48%	21%	50%	16%	16%	20%	64%
Particulate matter	48%	8%	13%	23%	37%	20%	40%	16%	12%	20%	53%
Solid waste	62%	15%	15%	20%	60%	27%	61%	23%	16%	21%	77%
Sulfur dioxides	61%	11%	21%	15%	52%	29%	53%	22%	19%	21%	87%
Water	53%	21%	10%	22%	58%	26%	60%	15%	12%	32%	78%
Average	57%	12%	15%	20%	53%	24%	50%	19%	14%	22%	72%

TABLE 4. Sensitivity analysis showing the five most important parameters in creating variation in the nine energy-related environmental impacts of LEED buildings.

		All Buildings		Educational Buildings		Office Buildings		Residential Buildings	
		Ranking as the Most Significant Sources of Variation							
Overall Rank	Parameter	No.1	Top 3	No.1	Top 3	No.1	Top 3	No.1	Top 3
1	Air emission, waste generation, and water consumption factors	78%	78%	78%	78%	78%	78%	78%	78%
2	LEED EA credits 1 and 2	0%	56%	0%	100%	0%	78%	0%	78%
3	% electricity versus natural gas/fuel oil	0%	56%	0%	44%	0%	56%	0%	56%
4	Building energy use	0%	56%	0%	22%	0%	44%	0%	67%
5	Nuclear as % of grid energy	22%	22%	22%	22%	22%	22%	22%	22%

creating most of the variation in impacts, and, as such, should receive the most attention when thinking about alterations to the current LEED framework to better incorporate environmental metrics. For example, consider that for office buildings, the sensitivity analysis showed that "LEED EA credits 1 and 2" ranked in the "Top 3" of all parameters when seven of the nine environmental impacts (78%) were analyzed. It is worth noting that some of these parameters are somewhat outside of the control of many building owners and developers, i.e., many are location-dependent. However, this should not imply that these impacts are ignored in a green building scoring system. It could suggest, for example, that the awarding of LEED points might need to be made location-dependent.

Table 5 shows the effects of an imprecise green building certification program on the environmental footprint of a city, state, federal agency, or campus which uses LEED as policy. It is unlikely that the dozens of such organizations who rely on LEED for gauging their innovation, forward thinking, and environmental performance would expect this much variability resulting from their policies and codes. It considers the possible range of environmental impacts created by 2,000,000 square feet of new buildings affected by an institutional policy mandating or providing incentives to developers to build LEED Silver office buildings. To make this variation more tangible using the conversion factor of one pound of carbon dioxide produced per mile driven in an automobile, consider that the difference between the minimum and maximum carbon dioxide emissions from these 2,000,000 square feet of buildings is equivalent to taking approximately 8,300 cars off the road per year (US Environmental Protection Agency 2007).

While the majority of models used in this research assume that modeled energy use is equal to actual energy use, since this is the premise under which LEED operates, Table 6 shows the increase in the variability of impacts that occurs when the ratio of actual versus modeled energy use is included in the model. This change increases the variability of impacts from LEED Silver buildings by 10%–38%. Similarly, LEED's use of energy cost versus actual energy consumption as the metric to estimate reduction in conventional grid energy use also can also lead to variation in the impacts from LEED buildings. When this factor was added to the basic model, increases in variability were found to be similar to those shown in Table 5. Again, the coefficient of variability—the standard deviation divided by the mean—is used to represent this increase in variation because it allows comparison across the nine different impacts regardless of scale and units.

Finally, two other versions of the basic model were considered. The first involved ignoring the reduction in impacts that could occur due to the purchase of green energy offsets. Because the market for REC's is a relatively young, voluntary market in the US, some question the real meaning of REC's, despite the third-party verification by the Center for Resource Solution and its Green-e program. Green energy supported through the purchase of REC's is often located on a different grid with different fuel mixes than the building for which they are purchased, which makes emis-

TABLE 5. Variations in energy-related environmental impacts from LEED Silver office buildings as the scale reaches 2,000,000 new square feet of construction

Impact	Units	Minimum	Maximum	Maximum/Minimum
Carbon dioxide	Lbs/year	3,300,000	104,000,000	32
High level nuclear waste	Lbs/year	0	153	—
Low level nuclear waste	Cf/year	0	80	—
Mercury	Lbs/year	0.3	9	30
Nitrogen oxides	Lbs/year	10,100	214,000	21
Particulate matter	Lbs/year	740	16,000	22
Solid waste	Lbs/year	130,000	14,000,000	108
Sulfur dioxides	Lbs/year	12,000	540,000	45
Water	Gallons/year	960,000	603,000,000	628

TABLE 6. The influence of actual versus modeled energy use on variation in the energy-related environmental impacts of LEED Silver office buildings

	Coefficient of Variability		
Impact	Before*	After**	% Increase in Impacts
Carbon dioxide	0.45	0.58	29%
High level nuclear waste	0.69	0.82	19%
Low level nuclear waste	0.70	0.83	19%
Mercury	0.46	0.60	30%
Nitrogen oxides	0.43	0.56	30%
Particulate matter	0.42	0.58	38%
Solid waste	0.61	0.74	21%
Sulfur dioxides	0.57	0.70	23%
Water	1.00	1.11	11%

* As in LEED, this model scenario assumes that designed energy use equals actual energy use.
** This model scenario assumes that designed energy use does not equal actual energy use.

sion reduction calculations complicated. Plus, the assurance of "additionality" is uncertain—i.e., it is difficult to ascertain whether a new wind farm would have been developed without the financial support generated through REC's. Most of the simulations in this research assume that the purchase of green energy supports renewable energy generation that would not have occurred otherwise and that the environmental impacts avoided through the purchase of REC's correspond to those impacts that would have been caused by a building's location in its own particular electrical grid. However, when these offsets are eliminated for LEED Silver office buildings, mean environmental impacts increase by 15%–42% with an average increase of 28%. Table 7 illustrates increases for specific impacts.

TABLE 7. The percentage increases in energy-related environmental impacts for LEED Silver office buildings when green energy purchases are ignored

Impact	% Increase in Impacts
Carbon dioxide	29%
High level nuclear waste	30%
Low level nuclear waste	29%
Mercury	15%
Nitrogen oxides	27%
Particulate matter	15%
Sulfur dioxides	33%
Solid waste	33%
Water	42%

The last model variation involved fixing the air emission, waste generation, and water consumption factors at national averages—as often happens now when the environmental impacts of a building are estimated—rather than as distributions varying by geography and corresponding grid, as was done for the models in this study. This reduced variability by 29%–58%, with an average reduction of 36%. Accordingly, these results suggest that using average air emission, waste generation, and water consumption factors substantially misrepresents the variation in the environmental impacts caused by buildings.

DISCUSSION AND CONCLUSION

The results suggest a considerable amount of between-building variation in the nine selected environmental impacts of LEED buildings. For an individual building category, the variation appears to be greater than that which most people would consider desirable for a green building certification system. On the other hand, when looking at the variation among the means for thousands of simulated LEED buildings, the variation suggests an acceptable degree of difference between at least the mean values of the impacts for LEED and non-LEED buildings and among buildings with different levels of LEED certification.

The significance of these results, showing wide overlap in the variability distributions for different levels of LEED certification, might be lessened by arguing that LEED was intended to be an instrument for market change, not a scientific tool for assessing the environmental impacts of buildings. While that may be true, in the absence of widely accepted methods for assessing building-related impacts, many building professionals, owners, and other stakeholders look to LEED to serve this more quantitative purpose. Accordingly, it is worth considering whether it serves this purpose in light of the results presented here. Moreover, given other categories of concern in LEED, such as site selection, indoor environmental quality, water efficiency, and materials and resources, it would be a mistake to quickly generalize the results of this research to the entirety of LEED.

One important source of energy-related impacts that was not addressed in this research is the required transportation to and from buildings. Preliminary calculations from Jonathan Rose Companies (2006), a developer of infill and mixed-use projects suggests that—depending on building location, building type, and building energy efficiency—transportation energy use can account for 20%–60% of combined building and transportation energy use. In addition, the emission profiles vary between power plant and automobile combustion engine. Future work should take these emissions into consideration, despite the significant number of assumptions required to arrive at these estimates of environmental impacts. In fact, this lack of attention to transportation and site-related impacts has been a major criticism of LEED for New Construction, which has been overcome to a degree with the development of LEED for Neighborhood Development.

In addition, it could be argued that improving the ability of LEED to measure environmental impacts without considering the costs for LEED buildings is problematic because owners, developers, and tenants are more concerned about costs than environmental impacts. While cost-effective green design is important, its economics were deemed to be outside the scope of this work and have been addressed in numerous studies mentioned previously. Furthermore, in addition to green design, many other factors affect construction cost and calculations of green premiums, such as the use of additional consultants or reliance on the conventional development team, the time required to finish a project, financing options, fee increases to account for risk and uncertainty, capital structure, and the varying cost and choice of materials.

Similarly, efforts to improve the accuracy and precision of LEED will not necessarily lead to an increased rate of adoption of green building in the market. In fact, a wide variety of other factors ultimately affect the increased abundance of buildings with lower environmental impacts, such as media attention, market demand, government incentives, and the costs of green products and systems as they reach scale. More importantly, to the degree that any suggested changes to LEED improve its scientific basis but add to its complexity or diminish the ease with which it is understood, these changes could decrease the adoption of LEED. Despite this concern, improvements seem to merit attention in order that LEED certification—notably certification with LEED version 3.0 currently being created—is more meaningful and comparable across buildings in terms of environmental impacts.

The authors' next phase of research will build on this current study and will focus on such alterations to LEED. This will include a focus on 1) revisions to the LEED scoring system so that it better incorporates environmental metrics and reduces the variability of said impacts by LEED certification level and 2) the creation of user-friendly methods for allowing a comparison of the environmental impacts from LEED buildings with similar parameters (e.g., building type and grid fuel mix). Since this research began in mid-2006, the USGBC itself has already begun to take steps in this direction by requiring buildings to now 1) obtain at least two EA credit 1 points above ASHRAE 90.1-2004 and 2) reduce building emissions by 50% compared to current levels.

Other research should focus the variability in LEED buildings' environmental impacts in other LEED categories (e.g., Water Efficiency, Materials & Resources). Investigations should also aim to understand how to weight the relative importance of each environmental impact, which will facilitate the estimation of an aggregate environmental impact from buildings across many impacts such as the nine discussed here. A variety of work has been done on this topic to date (Levin 1997; Goedkoop *et al.* 1993, 1995) and a number of methods are available to determine weightings based on expert input (Barzilai and Golany 1990; Saaty 1980; Linstone and Turoff 2002). The weighting criteria to arrive at weightings, for example, could be based on the spatial scale of the impact, the severity of the hazard, the degree of exposure, the penalty for being wrong, and the status of affected sinks (Levin 1997; US Environmental Protection Agency 1990).

In conclusion, it is worth reiterating the success of the USGBC's LEED program in contributing significantly to the growing transformation of the US construction industry towards healthier, more environmentally responsible buildings. In the 2006 white paper entitled, Green Buildings and the Bottom Line, Building Design + Construction states it this way: "What started out as a charismatic environmental crusade has matured into an established sector of the U.S. construction industry" (Building Design + Construction 2006). Given the increasingly influential role that LEED is playing, it seems clear that the rating program should be as robust and meaningful as possible. While careful not to negate the good in favor of the perfect, the authors hope that this research contributes to the constant improvement which characterizes much needed programs like LEED.

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REFERENCES

Adler, J. (2006, July 17). "The new greening of America." *Newsweek*, 42-52.

Akbari, H., Gartland, L.M., and Konopacki, S.J. (1998). "Measured Energy Savings of Light-colored Roofs: Results from Three California1 Demonstration Sites." *Proceedings of the 1998 American Council of Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings*, Asilomar, CA.

Azerbegi, R.J. (2000). "Quantifying Green: An Economic and Environmental Analysis of the Leadership in Energy and Environmental Design 2.0 Green Building Rating System." Master's thesis, University of Colorado at Boulder.

Barzilai J., and Golany, B. (1990). "Deriving weights from pairwise comparison matrices: the additive case." *Operations Research Letters,* 9, 407-410.

BNIM Architects, Keen Engineering, Holland Design Associates, Oppenheim Lewis, Hawley Peterson Snyder Associates, and Packard Foundation Facilities Steering Committee. (2002). *Sustainability Report: The David and Lucille Packard Foundation Los Altos Project*. The David and Lucille Packard Foundation, October 2002.

Boecker, J., Todd, J.A., Reed, B., Malin, N., and Lindsey, G. (2006). "Seeing beyond metrics: lessons learned about rating systems from GBTool and other international systems." June 28, 2006 draft. Unpublished.

Bosch, S.J., and Pearce, A.R. (2003). "Sustainability in public facilities: analysis of guidance documents." *Journal of Performance of Constructed Facilities*, 17(1), 9-18.

Bowen, T.S. (2005, October 26). "Construction criticism." *Grist*. http://www.grist.org/news/maindish/2005/10/26/leed/index.html

Bray, J., and McCurry, N. (2006). "Unintended consequences: how the use of LEED can inadvertently fail to benefit the environment." *Journal of Green Building*, 1(4), 152-165.
Building Design + Construction. (2003). *White Paper on Sustainability: A Report on the Green Building Movement*. Supplement to Building Design + Construction, November.
Building Design + Construction. (2006). *Green Buildings and the Bottom Line*. Supplement to Building Design + Construction, November.
Carbon Disclosure Project. (2007). http://www.cdproject.net/aboutus.asp
Ceres. Coalition of Environmentally Responsible Economies. (2007). http://www.ceres.org/.
Chalifoux, A. (2006). "Using life cycle costing and sensitivity analysis to 'sell' green building features." *Journal of Green Building,* 1(2), 39-48.
City of Seattle. (2007). City Green Building. http://www.seattle.gov/dpd/GreenBuilding/OurProgram/Resources/FAQs/default.asp#LEED.
Cole, R.J. (1998). "Emerging trends in building environmental assessment methods." *Building Research and Information,* 26(1), 3-16.
Cole, R.J. (2005). "Building environmental assessment methods: redefining intentions and roles."
Building Research and Information, 33(5), 455-467.
Cortese, A.D. (2003). "The critical role of higher education in creating a sustainable future." *Planning for Higher Education*, 31(3), 15-22.
Crawley, D., and Aho, I. (1999). "Building environmental assessment methods: applications and development trends." *Building Information & Research,* 27(4/5), 300-308.
Deru, M. and Torcellini, P. (2006). *Source Energy Use and Emission Factors for Energy Use in Buildings.* (Revised January 2007). Report by the National Renewable Energy Laboratory. NREL/TP-550-38617.
Diamond, R., Opitz, M., Hicks, T., Vonneida, B., and Herrera, S. (2006). "Evaluating the site energy performance of the first generation of LEED-certified commercial buildings," published in the *Proceedings of the 2006 Summer Study on Energy Efficiency in Buildings*, American Council for an Energy Efficient Economy, Washington DC, August. LBNL-59853.
Eijadi, D., Vaidya, P., Reinertsen, R., and Kumar, S. (2002). "Introducing comparative analysis to the LEED system: A case for rational and regional application." A collaboration between The Weidt Group and Lawrence Berkeley National Laboratory. Submitted for publication at ACEEE 2002 Summer Study on Energy Efficiency in Buildings. http://www.osti.gov/energycitations/servlets/purl/894554-BtWSb0/894554.PDF
Eley, C. (2001, January 30). "A question of stringency." *Environmental Design + Construction*. http://www.edcmag.com/CDA/Archives/30d36bd288697010VgnVCM100000f932a8c0____
Frankel, M. (2007, January 25). New Buildings Institute. Personal communication.
Frangos, A. (2005, October 21). "'Green' buildings are trendy, but do they save energy?" *Wall Street Journal Online*. http://www.realestatejournal.com/propertyreport/architecture/20051021-frangos.html.
Goedkoop, M.J., Demmers, M., and Collignon, M.X. (1993). *The Eco-indicator 95, Phase One, Methodology.* National Reuse of Waste Research Programme (NOH) report 9407. PRé Consultants.
Goedkoop, M.J., Demmers, M., Collignon, M.X. (1995). *The Eco-indicator 95, Final Report.* National Reuse of Waste Research Programme (NOH) report 9523. PRé Consultants.
Goodman, S., and Walker, M. (2006). *Benchmarking Air Emissions.* Produced by E^3 Ventures, Natural Resources Defense Council, Ceres, and PSEG. www.nrdc.org/air/pollution/benchmarking/default.asp
International Energy Association. (2004). *Annex 31: Energy-related Environmental Impact of Buildings*. http://www.greenbuilding.ca/annex31/index.html
Johnson, J. (2002). "Is what they want what they get? Examining field evidence for links between design intent and as-built Energy performance of commercial buildings." *Proceedings of the 2002 American Council of Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.*
Jonathan Rose Companies, LLC. (2006). "BTU analysis for office location and green building." July 3 Memorandum.
Jurovics, Steve. (2007, March 21). Cadmus Group (Contractor to US EPA ENERGY STAR). Personal communication.
Kats, G. (2003). *The Costs and Financial Benefits of Green Building*. Capital E, Washington, D.C. https://www.usgbc.org/ShowFile.aspx?DocumentID=1992
Lazarus, N. (2003). *Beddington Zero (Fossil) Energy Development Construction Materials Report Toolkit for Carbon Neutral Developments—Part 1.* BioRegional Development Group.
Lenssen, N., and Roodman, D.M. (1995). "Worldwatch Paper 124: A Building Revolution: How Ecology and Health Concerns are Transforming Construction." Worldwatch Institute.
Levin, H., Boestra, A., and Ray, S. (1995). "Scoping U.S. Building Inventory Flows and Environmental Impacts in Life Cycle Assessment." Paper presented to the *World Congress of the Society for Environmental Toxicology and Chemistry (SETAC)*. November. Vancouver, BC.
Levin, H. (1997). "Systematic Evaluation and Assessment for Building Environmental Performance (SEABEP)." Submitted for presentation at *Buildings and Environment Conference*, Paris, June 9-12.
Lindsey. G. (2007, January 17). Member, US Team for International Green Building Challenge 2000. Personal communication. http://www.iiSBE.org
Linstone, H.A., and Turoff, M. *(*2002). "The Delphi Method: Techniques and Applications." New Jersey Institute of Technology, Information Systems Department. http://www.is.njit.edu/pubs/delphibook/
Matthiessen, L.F., Morris, P. (2004). *Costing Green: A Comprehensive Cost Database and Costing Methodology*. http://www.davislangdon.com/upload/images/publications/USA/2004%20Costing%20Green%20Comprehensive%20Cost%20Database.pdf
Mayors Climate Protection Center. (2007). http://www.usmayors.org/climateprotection/

Mazria, E. (2003). "It's the Architecture, Stupid!" *Solar Today,* May/June, 48-51.

Nelson, A.C. (2004). *Toward a new metropolis: the opportunity to rebuild America*. Brookings Institution, Washington, DC.

Newton, P.W., Baum, S., Bhatia, K., Brown, S.K., Cameron, A.S., Foran, B., Grant, T., Mak, S.L., Memmott, P.C., Mitchell, V.G., Neate, K.L., Pears, A., Smith, N., Stimson, R.J., Tucker, S.N., and Yencken, D. (2001). *Human Settlements: Australia State of the Environment Report 2001*. CSIRO Publishing. Canberra, Australia.

Pless, S.D., and Torcellini, P.A. (2004). *Energy Performance Evaluation of an Educational Facility: The Adam Joseph Lewis Center for Environmental Studies, Oberlin College, Oberlin, Ohio.* Report by the National Renewable Energy Laboratory. NREL/TP-550-33180.

Power Scorecard. (2006). http://www.powerscorecard.org/

Pulaski, M.H., Horman, M.J., and Chandra, M.J. (2006). "Case study validation and the continuous value enhancement proces." *Journal of Green Building,* 1(3), 169-182.

Rees, W.E. (1999). "The built environment and the ecosphere: a global perspective." *Building Information & Research*, 27(4/5), 206-220.

Saaty, T. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill, New York, New York.

SAS. 2007. SAS 9.1. http://www.sas.com/.

Scheuer, C.W., Keoleian, G.A. (2002). *Evaluation of LEED Using Life Cycle Assessment Methods.* Report to National Institute of Standards and Technology (NIST). NIST GCR 02-836. Department of Commerce. Washington, DC.

Scofield, J.H. (2002). "Early energy-performance for a green academic building." *ASHRAE Transaction,* 108(2), 1214-1230.

Sheltair Group. (1999). *Residential Sector Climate Change Foundation Paper*. Report for the National Climate Change Secretariat of Canada.

Scientific America. (2005). Scientific American 50. http://www.sciam.com/article.cfm?articleID=0008F6E7-3C92-137E-BC9283414B7F0000 &pageNumber=13&catID=9

Stauffer, N. (2004, April 8). "MIT studies impact of solar energy on emissions reductions." MIT News Office. http://web.mit.edu/newsoffice/2004/renewables.html

Stegall, N. (2004). "Cost implications of LEED Silver certification for New House residence hall at Carnegie Mellon University." Senior Honors Research Project, CIT, Carnegie Mellon University. http://www.cmu.edu/greenpractices/green_initiatives/new_house_images/newhouse_report.pdf

Steven Winter Associates. (2004). *GSA LEED Cost Study*. Report to the US General Services Administration. October 2004. Contract No. GS–11P–99–MAD–0565.

Stein, J., Reiss, R. (2004). "Ensuring the sustainability of sustainable design: what designers need to know about LEED." *E Source*. Paper AED-04-01 September.

The New York Times. (2006, May 17). "The business of green." pp. E1, 1-12.

Todd, J.A., Crawley, D., Geissler, S., and Lindsey, G. (2001). "Comparative assessment of enviornmental performance tools and the role of the Green Building Challenge." *Building Research & Information,* 29(5), 324-335.

Torcellini, P. Pless, S., Deru, M., Griffith, B., Long, N., and Judkoff, R. (2006). *Lessons learned from case studies of six high-performance buildings.* Report by the National Renewable Energy Laboratory. NREL/TP-550-37542.

Udall, R., Schendler, A. (2005, October 26). "LEED is Broken; Let's Fix It." *Grist.* http://www.grist.org/comments/soapbox/2005/10/26/leed/index1.html

Union of Concerned Scientists. (2005). "How coal works." http://www.ucsusa.org/clean_energy/fossil_fuels/offmen-how-coal-works.html

US Building Energy Codes Program. (2002). Commercial Code Determination. Quantitative analysis of the estimated differences between the 1989 and 1999 editions of ASHRAE Standard 90.1. http://www.energycodes.gov/implement/determinations_com.stm

US Department of Commerce. (2000). General Housing Characteristics. Census Bureau.

US Department of Energy. (2006, November 20). Office of Nuclear Energy. Personal communication.

US Office of Energy Efficiency and Renewable Energy. (2006). *2006 Buildings Energy Data Book*. http://buildingsdatabook.eren.doe.gov/

US Energy Information Administration. (1995). Commercial Building Energy Consumption Survey. Sum of Major Fuel Consumption by End Use. http://www.eia.doe.gov/emeu/cbecs/cbec-eu3.html

US Energy Information Administration. (1999a). Commercial Building Energy Consumption Survey. Comparison of 1999 End-Use Estimates with Previous CBECS. http://www.eia.doe.gov/emeu/cbecs/enduse_consumption/compare.html

US Energy Information Administration. (1999b). Commercial Building Energy Consumption Survey. End-Use Consumption for Natural Gas, Electricity, and Fuel Oil (Preliminary Estimates). http://www.eia.doe.gov/emeu/cbecs/enduse_consumption/intro.html

US Energy Information Administration. (2003a). Commercial Building Energy Consumption Survey.
2003 Commercial Buildings Energy Consumption Survey: Sample Design.
http://www.eia.doe.gov/emeu/cbecs/2003sample.html

US Energy Information Administration. (2003b). Commercial Building Energy Consumption Survey. Consumption and Gross Energy Intensity by Climate Zone for Sum of Major Fuels.
http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

US Energy Information Administration. (2003c). Commercial Building Energy Consumption Survey. Total Energy Consumption by Major Fuel. http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

US Energy Information Administration. (2003d). Commercial Building Energy Consumption Survey. Consumption and Gross Energy Intensity by Census Division for Sum of Major Fuels. http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

US Environmental Protection Agency. (1990). *Reducing Risks: Setting Priorities and Strategies for Environmental Protection.* Report SAB-EC-90-021 and 021a. U.S. Environmental Protection Agency. Washington, DC.

US Environmental Protection Agency. (2001). *The Greening Curve: Lessons Learned in the Design of the New EPA in North Carolina.* U.S. Environmental Protection Agency. Washington, DC.

US Environmental Protection Agency. (2007). Green Vehicle Guide. http://epa.gov/emissweb/about.htm

US Geological Service. (2000). *Estimated Use of Water in the United States in 2000.* USGS Circular 1268.

US Green Building Council. (2007). LEED Initiatives in Government by Type. https://www.usgbc.org/ShowFile.aspx? DocumentID=1741

US House Committee on Transportation and Infrastructure. (2003). "Water Officials Urge Congress to Implement Improvements in Water Supply Management." In Tinker, A., Kreuter, U., Burt, R., and Bame, S. 2006. Green construction: contractor motivation and trends in Austin, Texas. *Journal of Green Building,* 1(2), 118-130.

US National Energy Technology Laboratory. (2007). Energy &Water Resources - Water-Energy Interface: Power Plant Water Management. http://www.netl.doe.gov/technologies/coalpower/ewr/ water/power-gen.html

Werthan, A.K., and Navvab, M. (2006). "Building design strategies and their contribution to energy performance for LEED certification." *Journal of Green Building,* 1(4), 67-87.