Environmental Impacts of Technologies for Sustainable Buildings

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***Summary**: There are many consequences of measures taken to move toward sustainability in the creation of healthy buildings. Technologies aimed at improving indoor environmental quality must be evaluated in terms of their total environmental impacts: indoor, local, regional, and global. Increasing ventilation to improve workplace productivity may yield net economic benefits. However, increased energy use adversely affects local and regional air pollution and increases emissions of greenhouse gases. Other indoor environmental quality control technologies also can adversely affect air or water quality or other environmental areas of concern. Certain environmental impacts might be deemed unacceptable at any cost. Holistic assessment methods and metrics are needed to properly assess building technologies.*

***Keywords:** Sustainability, Ventilation, Indoor Air Quality, Productivity, Environmental Impacts*

1 Introduction

The environmental impacts of buildings are substantial, perhaps 15-45% of the total anthropogenic burden [1][2]. Urban, regional, and global environmental problems have increased since industrialization, and, despite improvements in some areas, global conditions have worsened at an accelerating rate during recent decades [3].

Biodiversity Loss and Habitat Destruction

Species extinction rates have increased from a long-term average based on the fossil record of ~0.1% of species per year that has increased 1000x to a current rate of ~100 species/y and is expected to reach 1000/y by the end of the present century [3].

More land was converted to cropland in the 30 y after 1950 than in the 150 y between 1700 and 1850. Cultivated systems - areas where at least 30% of the landscape is in croplands, shifting cultivation, confined livestock production or freshwater aquaculture - now cover ¼ of Earth's terrestrial surface. Roughly 20% of the world's coral reefs were lost and an additional 20% degraded in the last decades of the 20th century [3].

Greenhouse gas emissions and climate change

Since 1750, the atmospheric concentration of carbon dioxide (CO_2) has increased by about 32% (from about 280 ppm to 376 ppm in 2003) primarily due to the combustion of fossil fuels and land use changes. Approximately 60% of that increase (60 ppm) has taken place since 1959. During the same time period the global average temperature has increased significantly [3]. In nearly every year since 1990, the global average temperature has been the highest on record. Even the targets set by the Kyoto Protocol fall far short of limiting carbon emissions to a sustainable level. [4]

Water resources

The amount of water impounded behind dams has quadrupled since 1960; reservoirs now hold between 3 and 6 times as much water as natural rivers. Water withdrawals from rivers and lakes have doubled since 1960. Most water use (70% worldwide) is for agriculture. [3]

Nitrogen

Since 1960, flows of reactive (biologically available) nitrogen in terrestrial ecosystems have doubled and flows of phosphorus have tripled. [3]

Other major impact categories

In addition to the categories listed above, other major environmental problems that must be addressed include stratospheric ozone depletion, urban air pollution, groundwater and surface water contamination, soil erosion, and natural and mineral resource consumption. [1]

Need for building environmental performance metrics

Buildings in the U.S. consume roughly 10% of all energy consumed on earth. Concern about human impacts on the indoor and general environment motivates the development of tools to assess buildings' environmental performance. Such tools usually focus on one or a limited number of aspects of building performance and environmental impacts – most commonly, energy consumption. Examples related to the indoor environment include thermal comfort, indoor air quality, acoustics, and lighting. Models like those for thermal comfort have influenced more than a generation of architects, engineers, researchers, and building standards writers. Some models also include energy consumption associated with different indoor environmental control approaches and levels. Perhaps more accurately, many building energy models are based on assumptions primarily about thermal control and illumination. Only in recent years has attention been focused on indoor air quality. Yet fully integrated models of the indoor environment and energy do not exist.

In the past ten years, tools to assess buildings impacts on the general environment have emerged. These include rating systems, life cycle assessments, life cycle impact analysis, input-output analysis, and environmental footprint analysis, among others. Rating systems assign points to certain building features deemed environmentally preferable and the total number of points is added for an overall score. Points are assigned by the developers of these tools based on their knowledge of the environmental effects and their personal values, implicit or explicit. Life cycle assessments (LCA) determine buildings' resource consumption and pollution emissions inventories or total environmental loads for established categories of environmental concern. The results are based on available science and highly dependent on data availability; the design trade-offs still need to be made by decision-makers. Life cycle environmental impact assessments use LCA-based inventories, but the trade-offs among the impacts are still in the hands of the decision makers – designers, developers, or others, and dependent on the values. Input-output analysis uses standardized economic data to evaluate building impacts, not entirely unlike LCAs, but with different (often less direct) types of data sources. Environmental footprint analysis translates data on the environmental resources consumed to standardized or normalized comparisons based on equivalent land area requirements for total environmental resources required to support a project or design.

Results of building environmental performance assessments are often compared to typical or average performance of similar buildings or to "best current practice." Performance is reported as percentage improvement. Thus building performance is not assessed against targets related to a scientific construct of sustainability.

In this paper, we discuss some recent investigations into the impacts of improved indoor environmental quality (IEQ) on building occupants. The increased energy use to improve IEQ, occupant comfort, health, and productivity justified on the basis of direct economic cost and benefits is discussed. It is proposed that the broader economic and environmental costs of increased energy consumption must be considered due to increasing evidence of human impacts on greenhouse gas concentrations and climate change. Finally, the case of carbon emissions is used to illustrate the development of building-specific targets for environmental performance based on the best available scientific information regarding sustainable levels of anthropogenic environmental impacts. Such a target can be used to compare performance of different designs for a specific building or to compare the performance of various buildings against their own targets. Targets can also be developed for other environmental pollution loading or resource consumption following the same process. This was illustrated by the 1992 Dutch report "Ecocapacity as a Challenge to Technological Development" [5]. We propose that such targets be developed for all major categories of building environmental impacts and used to evaluate building environmental performance.

2. Technologies to improve indoor environmental quality

Many technologies are used to improve IEQ including ventilation, pollution source control, thermal control, illumination, and acoustic control. Relatively recent interest in indoor air quality (IAQ) has raised awareness of ventilation's importance. Energy costs have led many building owners and operators to reduce energy consumption by reducing outdoor air ventilation. But during the past 10 years or more, arguments have been made that improved worker productivity or student learning justified on cost grounds alone significant increases in ventilation.

Ventilation and productivity

For more than twenty-five years there have been studies and recommendations regarding improving IEQ in order to improve comfort, health, satisfaction, task performance, and productivity [6-13]. Recently there have been several studies designed to elucidate the relationships between ventilation and task performance or learning, often collectively labeled "productivity." The vast majority of IEQ-productivity studies suggest that improvements in environmental quality can favorably affect work performance [10-11]. Seppänen and Fisk [10] reviewed a wide range of data from numerous studies using a sophisticated model to aggregate the data from diverse studies. They found that "…typically a 1–3% improvement in average performance per 10 l/s-person increase in outdoor air ventilation rate. The performance increase per unit increase in ventilation was bigger with ventilation rates below 20 l/s-person and almost negligible with ventilation rates over 45 l/s-person. The performance increase was statistically significant with increased ventilation rates up to 15 l/s-person with 95% CI [confidence interval] and up to 17 l/s-person with 90% CI."[10]. Figure 1 from their report shows the greater impact at the lower end of the ventilation rate range. That could be expected since strong pollution sources and inadequate ventilation are potentially the most critical IAQ conditions. Contaminant levels from indoor sources are very roughly inversely proportional to outdoor air change rates. Also, the most relevant data are at the lower end of the range since future efforts to reduce energy use will likely lead to more careful control of energy-related ventilation.

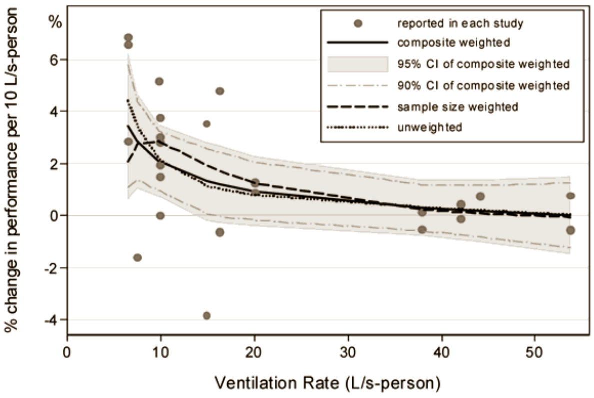

Figure 1. Change in Normalized Adjusted Performance (Delta P%) per 10 L/s-person versus average ventilation rate, estimated by fractional polynomial regression models. [10]

Visual inspection of Figure 1 reveals a substantial scatter in performance at the lower ventilation rates in the range of 7 to 20 L/s-person – the range specified in most ventlation standards and building codes and in most building designs. Looking at the data points alone while ignoring the curves drawn in the figure does not reveal an obvious relationship between ventilation rate and performance. It may be more valuable to determine the source of the scatter at any given ventilation rate; addressing differences in building conditions that cause poor performance could actually obviate the need for increased ventilation while resulting in the improved work performance and reduced C emissions.

Advocates of increased ventilation to improve IEQ in offices or schools justify on economic grounds increased energy expense for outdoor air ventilation to improve occupant task performance [9,11]. They estimate that productivity improvements yield economic benefits that could justify a doubling of the expense of increased outdoor air ventilation [11]. Similar arguments are made for improved thermal conditions or illumination. It is argued that since energy comprises only 1 or 2% of total building operational costs including workers salaries, the improvement in IEQ by doubling the energy cost will easily be paid for by the “productivity” benefit. More recently, authors of a detailed review of the relevant literature concluded that there is a high level of uncertainty in the data used in many of the studies they analyzed [10]. Authors who have analyzed ventilation and sick building syndrome also argue that more ventilation is, on average, better.

Lacking from these analyses is consideration of the overall impacts of increased energy consumption on the indoor environment, the immediate outdoor environment, and the regional and global environment. Increasing ventilation by mechanical means, especially with air conditioning, often produces negative indoor environmental effects [14]. It appears that ventilation system hygiene and off-gassing from components can degrade air quality and increase occupant reported symptoms and discomfort. Increased energy consumption can also increase regional air pollution. Thus deteriorated air quality is used for the ventilation itself. Ventilation air polluted by ozone, a common downstream product of fossil fuel based energy production, reacts with common indoor chemical pollutants to produce far more harmful air pollutants. Finally, increased fossil energy consumption results in higher atmospheric CO_2 concentrations with significant potential impacts on global climate.

Each of the four main categories of IEQ – thermal conditions, acoustics, illumination, and IAQ – have significant implications for energy and other resource consumption and associated pollutant releases. No solution to IEQ problems can be evaluated in terms of sustainability without consideration of these implications. This requires modeling for the entire life cycle of a building and comparing various alternative design, construction, and operational options in a comprehensive framework. In the end, there will inevitably be trade-offs among environmental goals.[15]

For example, increasing electric illumination or dilution ventilation and close regulation of thermal conditions by mechanical means will require more energy consumption with all the associated environmental impacts. Increasing illumination increases heat loads, thus requiring more cooling in large commercial buildings where cooling loads dominate throughout most of the year. Increasing outdoor air ventilation in humid climates can increase energy requirements for removing excess moisture in order to control humidity within acceptable limits for comfort and to avoid mold growth. In dry climates, increasing ventilation can result in indoor air that is too dry resulting in occupants’ symptoms and complaints related to dry eyes and mucus membranes.[15]

Reducing entry of noise from outdoors may require reducing natural or passive ventilation and result in increased levels of pollutants from, indoor sources while natural ventilation can result in elevated levels of pollutants with outdoor sources such as combustion products from motor vehicles or electric power plants. Increasing daylight illumination using windows or skylights can increase thermal loads requiring more energy to provide comfortable and productive conditions for occupants. Each indoor environmental control technology should be analyzed at both indoor and general environmental problem levels according to the list in Table 1, Reference [15]. Furthermore, each aspect must be analyzed in terms of the collective impact of the total building design and performance.[15]

3. Environmental impacts

Greenhouse gas emissions are among the many environmental impacts of increased fossil energy consumption. Stabilizing atmospheric CO_2 at 450 to 550 ppm during the present century is hoped to limit global temperature increase to 2 ºC and requires that human release of fossil carbon must be reduced substantially, rather than increasing, as projected under business-as-usual scenarios.

A recent European Environment Agency report estimates that even at 450 ppm CO_2, there is still a chance that average global temperature over current temperatures will exceed the target 2ºC increase. At 550 ppm, it is estimated that there is a strong probability that warming will exceed 2ºC. [4]. The magnitude of the environmental impacts related to such warming, although only projected, are substantial [3]. Thus, even the ambitious targets that have been established may not prevent large impacts with consequences for both human and non-human species and long-term sustainability [4].

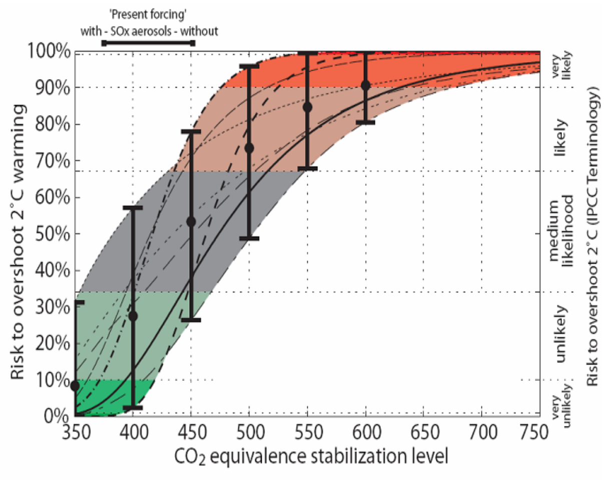

Figure 2. The probability of overshooting the 2ºC target.

Thus, the increased use of energy to improve "productivity" in offices or educational performance in schools cannot be accepted without more careful examination of its impacts and of the alternatives. These alternatives include use of cleaner energy sources, passive ventilation and thermal conditioning, improved efficiency of mechanically-supplied ventilation and comfort control, reduced pollutant source strengths leading to lowered ventilation requirements, and non-carbon-emitting sources of energy. [16]

Urban and regional air pollution created by fossil fuel combustion can also result in decrements to outdoor air quality and reduce the overall benefit of outdoor air ventilation for removing indoor-source pollutants from buildings. All energy supply and transformation systems have adverse impacts. Hydroelectric production adversely impacts aquatic ecosystems. Nuclear power produces radioactive wastes requiring long-term storage for which widely accepted means have not been devised. Even wind turbines and solar photovoltaic panels have associated environmental impacts albeit nearly negligible carbon emissions.

4. Metrics for Sustainable Buildings

A grand challenge that we face in transforming our current systems into more sustainable ones is to develop metrics and methods that can properly evaluate the many benefits and adverse impacts of current practices and proposed alternatives. These must be useful to designers and policy-makers as well as building owners and developers.

IEQ has not often been addressed in life cycle assessments. Its evaluation in "green building" rating systems is limited to incomplete, imprecise indicators of potential indoor pollution and its effects. Since LCAs use equivalencies for various pollutants that contribute to (cause or exacerbate) an environmental problem. Indoor pollutants can be treated in a similar manner using a risk-based approach to evaluation of various products' contributions to indoor pollution. The permissible contribution of any source of any given type of pollutant in an indoor environment must be determined in the context of all other sources of that pollutant in the particular building in question.

Background of proposed metric

An example of the proposed method is the calculation of fossil carbon emissions, an indicator of carbon equivalents that are believed important for climate change. The method for deriving environmentally-sustainable budgets for buildings involves use of scientists' calculations of the capacity of the earth's atmosphere to balance the heat coming in and the heat coming out of it as a result of all forces including but not limited to human activities [2-4, 16]. A critical factor in climate change is thought to be the anthropogenic contribution to global CO_2 concentrations. Climate scientists think we should attempt to stabilize the concentration between 450 and 550 ppm by the year 2100 in order to limit global average temperature to a warming of 2 ºC above current levels. The increasing science devoted to the impacts of such warming suggest rather significant consequences that are hoped to be tolerable [3, 4].

The prudent approach is to reduce anthropogenic carbon emissions as much as possible as quickly as possible – probably considerably faster than contemplated under the Kyoto Protocol and the most advanced current planning in Europe. Some argue that we can't wait until 2100 and that we should shoot for 2050 or sooner to stabilize atmospheric CO_2 [19]. From a practical perspective, that is probably not achievable. The developing countries -- like the U.S. -- are not current signatories to the Kyoto Protocol, and rapid population growth and diffusion of technology among these nations suggests that all nations will have to radically alter their current path. But until developed nations set an example and develop the technology and the policy instruments necessary to effectuate the necessary changes, it is difficult for the leaders of these countries to request developing countries curtail their growth in the distribution of higher standards of living through appliances, cars, and other energy intensive consumption.

5. Defining building environmental performance targets

The approach proposed here involves a number of assumptions that are subject to revision as new and better data are obtained in the coming decades. It also involves choices that beg for further discussion and revision to improve their fairness (environmental justice) to all affected parties as well as their social feasibility. The background for this approach was first described in the 1992 report, Ecocapacity as a Challenge to Technological Development [5]. A recent paper by the Americans Graedel and Klee [17] used the same approach without referencing the earlier Dutch work; the authors may have arrived at the approach independently. In both of these instances, environmental performance targets were derived based on the best available scientific understanding and some basic assumptions about distribution of environmental resources and pollution "rights" – collectively termed "ecocapacity" or "ecospace" by the Dutch [5].

There are five simple steps in the process as follows.

A. Define the capacity of the resource or sink in question.

In the case of fossil carbon emissions, this is based on the best available models of the impact of carbon emissions on global climate and uses the assumption of a 450 to 550 ppm global average CO_2 concentration target.

B. Translate the total emissions that are believed "sustainable" into a per capita budget

In the case of carbon emissions, this is on the order of one kg of carbon per day (kg C/d) per person in the year 2100 with an expected population of about $8.5*10^9$ people. Of course various sources of energy have different carbon emissions implications, with electricity from coal being far higher than that derived from natural gas. Hydropower is closer to carbon neutral, although there are emissions related to development and maintenance of hydropower electricity sources. Solar photovoltaic can also be close to zero on a life cycle basis. Using a maximum atmospheric CO_2 target of 450 ppm by 2100, and assuming a total population of $8.5*10^9$, a global per capita target of 1 kg C/d is established [16]. Current U.S. emissions average about 15 kg C/d while for the Swiss it's about 5.5 kg C/d per person [17]. Swiss energy use is more efficient, although much of it is generated by nuclear power plants. Coal-fired power plants produce ~270g C/kWh while overall average U.S. power plants produce about 170 g C/kWh.

Table 1: U.S. Primary Energy Use by Sector[17]

	Res	Com	Bldgs Total	Indtry	Trans
1980	20%	14%	34%	41%	25%
2000	21%	17%	38%	35%	27%
2003	22%	18%	40%	33%	28%

C. Calculate the portion of total emissions attributable to buildings

Using the U.S. Department of Energy data on the distribution of energy consumption by sector and our own data on the components of building-related energy attributed to industry, transportation, and agriculture, we estimated that building related energy consumption (including "plug loads") >40% of total energy consumption [18].

Dividing total per capita carbon emissions based on buildings' current share of total primary energy use, each individual is allocated 0.4 kg C/ day as a "sustainable" emission budget. This estimate could be refined but is not likely to change more than about 5% in the short term. It includes construction, use, operation, maintenance, renovation, and demolition or recycling of buildings.

D. Determine the portion of total building use attributable to each building type

Again, based on DOE data on the portions of total primary energy used by each building type, we used the present share of each building type and allocated it to each. Since residential and commercial use was 22% and 18% respectively in 2003, we allocate 22% to residential and divide the 18% of commercial use among the various building types and their 2003 primary energy use as shown in Table 2. This approach would result in offices being allocated 22% of 18% or ~4% of total carbon emissions, or $4*10^{-2}$ kg C/d per person for office buildings.

This allocation could be refined by analysis of the degree of conservation and efficiency already applied, the amount of further reductions deemed reasonably feasible and achievable, and by the base demand for the type of use associated with each space type. For example, laboratories or health care facilities may have some baseline needs that cannot be reduced as much as office or warehouse uses..

E. Derive target for a specific building by applying users' budgets

For example, for a school, divide the number of students, teachers, and staff who study or work at the school by the total number at all schools at the same grade levels in the country. For offices, the value could be based on workers or work stations, for a library it could be based on daily average users, for a retail establishment on the number of customers or customer hours, etc. So, if an office had 100 occupants, its budget would be 100($4*10^{-2}$) kg C/d (4 kg/d).

Table 2. Primary energy consumption by space type in the U.S. for 1999.[17]

Space Type	***Total Floorspace***	***Primary Energy Use***
Office	18%	22%
Warehouse/Storage	16%	8%
Mercantile	15%	15%
Education	13%	10%
Public Assembly	7%	6%
Lodging	7%	7%
Service	5%	6%
Health Care	4%	8%
Food Service	3%	7%
Public Order/Safety	2%	1%
Food Sales	1%	4%
Vacant	8%	2%
Other	2%	3%
	100%	100%

Conclusion

We propose that modeling data for building designs or monitoring data from built structures be compared with the specific targets. We have shown the example of carbon emission budget targets in order to determine their "sustainability" with respect to atmospheric CO_2. Similar budgets can be prepared, for consumption of renewable and non-renewable resources as well as for pollution emissions and land encroachment. Targets can be set for biodiversity loss, ozone depletion, copper consumption, cadmium releases, etc. Once these targets are established, building design and performance can be evaluated against more science-based, data-driven targets and performance can be determined with respect to sustainability. This will allow more comprehensive evaluation of the costs and benefits of increasing energy consumption to improve indoor environmental quality.

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