Habitat International 37 (2013) 22–32

Contents lists available at SciVerse ScienceDirect

Habitat International

journal homepage: www.elsevier.com/locate/habitatint

Using carrying capacity as a baseline for building sustainability assessment

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Keywords:
Sustainability
Carbon footprint
Ecological footprint
Ecosystem services
Green building
Urban design

ABSTRACT

Building sustainability assessments are driving greater market demand for sustainable buildings in the developed world. However, do such assessments actually demonstrate building sustainability? Some critics of building sustainability assessment argue that the methods should evolve toward an "absolute" assessment of building sustainability. That is, rather than assessing a building relative to a average like-type building as is typically done, the assessment should be made to whatever is deemed sustainable using a credible science. One possible form of absolute assessment is using the indicator of sustainability known as carrying capacity. After discussing the opportunities with a carrying-capacity-based assessment of buildings, this paper proposes a computational model that provides such an assessment.

There are four main components to the presented computational model. The first is the amount of carbon (C) stored on the building site in its native state. This native-site carbon storage is defined as the baseline carbon storage and represents the carrying capacity of the building project. The second is land use change, which accounts for the removal or addition of vegetation and other carbon storing elements to the project site. The third and fourth carbon emissions sources in the model are building construction and operation.

A building is considered sustainable in the model if by the end of its expected lifetime the total amount of carbon emissions are completely offset. Building designers and their clients can use this model to more comprehensively account for carbon emissions and identify options for reducing and offsetting them. To drive greater adoption, the model has been developed into an online resource, Green Footstep (www.greenfootstep.org).

To demonstrate the usefulness of the model, this paper presents a case study of an institutional building in Lake Placid, Florida, USA. The case study shows that the design team used the model to better understand what it means to have a "low-carbon" goal. The model showed them that over one hundred years, the building project must reduce and offset carbon emissions at a rate of 16 tonnes C per year.

Introduction

Building sustainability assessment methods influence both the design process as well as the building product. The introduction of the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK in 1990 marked the beginning of building sustainability assessment. Since then several different assessment methods have emerged around the world. Academic and non-academic discourse, including a major initiative to develop a single tool for international use, known as the Green Building Challenge, has clarified the intent and content of these methods (Cole, 2005; Cole & Larsson, 1999; Kaatz, Root David, Bowen Paul, & Hill Richard, 2006).

Public and private sector significance

Sustainability assessment methods "were initially conceived, and still largely function, as voluntary, market place mechanisms by which owners striving for improved performance would have a credible and objective basis for communicating their efforts" (Cole, 2005: 458). Ultimately, it is often stated, these methods were meant to transform the market place to expect and demand greater building environmental performance (Cole, 2005).

The methods create a sense of competition between building stakeholders by comparing the assessed building with standard practice. It is assumed that with the leadership of one group in environmental responsibility, others will follow to achieve the

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0197-3975/$ – see front matter
doi:10.1016/j.habitatint.2011.12.021

same recognition (Cole, 1999). To a certain extent this assumption is proving itself true as the number of certified buildings grows internationally.

Building sustainability assessment methods are increasingly used as documentation for corporate sustainability. The methods are used within frameworks such as corporate social responsibility (CSR) and socially responsible investment (SRI); ethical and social reporting guidelines as published by the Global Reporting Initiative and the Institute of Social AccountAbility; and the Dow Jones Sustainability Index and FTSE4 Good Index Series. These frameworks have been identified as ways for corporations and other institutions to demonstrate to investors they contribute to sustainability (Lützkendorf & Lorenz, 2006).

Property professionals are increasingly interested in identifying correlations between a building's market value and its sustainability performance. European lenders have already adopted a new property and market rating system that includes a section on sustainability (Lützkendorf & Lorenz, 2006). The US Department of Energy is developing a voluntary national Asset Rating Program for Commercial Buildings, in which energy efficiency is taken into account. Muldavin (2010) has presented a framework for underwriting sustainable properties, noting:

> "Significantly, existing green building certifications like LEED®, BREEAM, GreenStar, CASBEE, or LEED India measure environmental outcomes, not financial outcomes, and thus cannot be the sole basis for underwriting from a financial perspective. For example, environmental certifications focus on energy, water, and materials design, performance or practices, but not on how the market responds to such performance. Accordingly, environmental certifications are an important building performance indicator, but are a few steps away from offering financial insights." (Muldavin, 2010: 16)

Assessment methods are also fulfilling a role in government. More municipalities in the US are setting mandatory building performance targets for government buildings (USGBC, 2008). The US State of Colorado now offers incentives to school districts to agree to Leadership in Energy and Environmental Design (LEED) certification. In addition, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan is promoted by a nation-wide government action plan (Endo, 2008).

Assessment criteria

Most building sustainability assessment methods have a list of criteria for which points are awarded. The points are tallied and the building achieves a rating such as certified, gold, or platinum. These criteria typically fall under resource use, ecological loading, and indoor health and comfort (Cole, 2005). Energy assessment is typically made in regard to expected building operational energy consumption and the embodied energy; however, for the great majority of methods, only operational energy is directly quantified (IEA, 2009).

For assessment of operational energy consumption, credit is given in two ways. One is on a performance basis, that is, energy consumed as evidenced by a building energy model or measured performance. The other is on a prescriptive basis, that is, using a particular strategy to mitigate energy use, such as ongoing commissioning, access to mass transit, and daylight autonomy. Regarding the former, in most methods the expected energy use of the assessed building is compared to standard performance. One method, the Living Building Challenge from Cascadia Green Building Council, requires the building to be net zero site energy.

The same performance versus prescriptive distinction is found in the assessment of embodied energy, or the energy required to produce the building (everything from raw material extraction to on-site assembly of the manufactured materials). Most methods award assessment points for following prescriptive guidelines around recycled content, delivery distance, and building reuse. Only two assessment methods—Green Globes and CASBEE—require quantification of the embodied energy, which is done using life cycle assessment (LCA), in order to assess material performance. While there are at least twenty-one LCA tools for buildings around the world, including sixteen in Europe, that can directly quantify the embodied energy of materials and other aspects of buildings, LCAs are not common in industry because they require a lot of time and data. Makers of Green Globes and CASBEE simplified the LCA process for their users by providing aggregate data, making the LCA less time-intensive and costly but sacrificing accuracy.

Striving for an absolute measure

A major criticism of building sustainability assessment methods that dates back to the nascent period of building environmental assessment has been a lack of objectivity, especially in the energy assessment. Effort has been made to benchmark energy assessment values across different systems (Lee & Burnett, 2008), but the assessment is still made relative to typical buildings rather than an absolute measure of the sustainable amount of energy consumption. There has been made a distinction between "green" and "sustainable" assessments, the latter being ideally based on absolute measures (Cole, 1999). A measure produced by an established science is considered in Cole (1999) and in this paper an absolute measure.[1] Thus far, two absolute measures have been presented and used for building sustainability assessment: (1) the Ecological Footprint method and (2) net zero energy assessment. One additional method could be developed using data from the Intergovernmental Panel on Climate Change (IPCC). Each of these three potential methods is evaluated below.

Approach #1: ecological footprint

In 2004, Olgyay and Herdt presented an assessment method to determine the ecosystem services attributable to a building project and the stress on those services. Using the global average ecosystem productivity of 100 GJ per hectare-year, as determined by Wackernagel and Rees (1996), a carrying capacity was established in units of energy per year based on the size of the building project site. This carrying capacity was then compared to the embodied and operational energy consumption of the building. If the building uses more energy than is currently being produced on site, then, according to the method, it is not sustainable. In this way, an "absolute" measure based on the ecological footprint method was created for building sustainability assessment.

Another unique aspect of the Olgyay and Herdt (2004) method was an assessment with regard to time. It was identified that net zero energy buildings and energy producing buildings all would fit well within the carrying capacity of the site. Yet, when the embodied energy is measured, the environmental effect of the building extends well beyond what is produced on site. So even a net zero energy building is truly not sustainable due to the impact of the embodied energy. The embodied energy, therefore, can be

[1] There is strong objection to the statement that science can produce absolute truth, in at least philosophy as well as science, technology, and society (STS) studies. For instance, Heidegger (1982: 155–82) describes how science creates truth only in the sphere of science. The *No-Nonsense Guide to Science* (Ravetz, 2007) describes how science tends to impose its truth structure on the rest of society.

thought of as an "ecological debt" that only a "regenerative" building can earn back through energy produced on site or increased land productivity (Olgyay & Herdt, 2004). Fig. 1

While providing an innovative framework for future building assessment, the method of Olgyay and Herdt (2004) can be criticized for the assumption that ecological debt can be repaid. See Fig. 2 below for the different categories identified as part of the ecological footprint model. Olgyay and Herdt (2004) assume that, for example, a 1000-GJ debt in timber consumption can be repaid using a source of 1000 GJ of productivity outside of forests, such as fisheries. It is not easy to believe that fishery productivity could replace what comes out of forests.

Moreover, in ecological footprint theory, if the rate at which energy is converted into useful energy (i.e., net ecosystem productivity) is smaller than the rate at which we consume, we are tapping into the stored productivity on the planet. This can be seen in deforestation, depletion of fisheries, and removal of fossil fuels. While calculation of this debt can be conceptualized (see Fig. 3), the ecological footprint method does not offer any way to repay the ecological debt due to the inherent complexity of identifying clear and credible repayments. The ecological footprint framework was not meant to quantity ecological debt or identify repayments, rather, only to provide a snapshot of the state of our society and the general direction and magnitude we need to move (Ewing et al., 2008).

Approach #2: Net Zero Energy

Net Zero Energy Buildings, or NZEBs, are a very well known target for building design in at lease the US. The Architecture 2030 Challenge is a US-based initiative to design all new and renovated buildings to zero site energy by 2030. The US American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) has recently begun an initiative to "provide to its members by 2020 the tools necessary to design, construct, and operate NZEBs" (ASHRAE, 2008: 3). In addition, the Cascadia Green Building Council's Living Building Challenge rating system requires buildings to be net zero site energy.

However, little effort has been made to identify the significance with regard to sustainability of using net zero energy as a measure of building performance. Studies from Architecture 2030 are more about the effect buildings now have on climate change rather than the outcomes of all buildings shifting to net zero energy. Much effort has been made on defining the NZEB measure itself, yet the justification for the chosen definition was based on practical concerns such as data availability (ASHRAE, 2008). No one has yet described an overarching vision of sustainability or identified a science of sustainability that NZEBs fit into. Numerous questions and concerns about NZEBs could be raised, such as: How will all the distributed energy production from NZEBs affect the electrical grid and its operation? Is it okay to leave embodied energy out of the assessment?

Since the general magnitude and direction of the "NZEB vector" is likely true—i.e., building energy consumption needs to decrease dramatically in order to reach a level of consumption that is within the limits of sustainability—it is no small surprise that neither Architecture 2030 nor any other body that supports NZEBs have looked in detail at the bigger picture outcomes that NZEBs produce. However, until those societal studies begin showing that NZEB is a good goal, the goal is more an exercise in mathematics (energy in = energy out) than a significant goal founded on an established science and is truly an absolute measure of "sustainability."

Approach #3: reports from the Intergovernmental Panel on Climate Change

Another way to define an absolute measure for a building could be based on reports from the IPCC. This United Nations panel has used various scientific data sources regarding the carbon cycle and the greenhouse effect to estimate that the developed nations in the world must cut 1990-level carbon emissions by 80% by 2050 in order to avoid catastrophic effects of climate change (IPCC, 2007). Translating this goal to building projects could be relatively straightforward if we assume a certain rate of new and major renovation building projects between now and 2050, identify the carbon emissions associated with each project if they were built in 1990, and calculate the percent reduction in these emissions required in order to reach the overall 80% reduction by 2050. See for example the analysis done by Amory Lovins and Rocky Mountain Institute in Reinventing Fire (2011: 238–39). As part of a coordinated effort in transportation, industry, and buildings sectors, the authors propose that the US can cut carbon emissions by 80% by 2050 from year 2000 levels—a total of 5.5 gigatonnes carbon dioxide equivalent annual emissions, with the buildings sector being responsible for 2.1 gigatonnes—to save US$5 trillion (over a business-as-usual scenario) and to support a 158% bigger US economy.

While the Reinventing Fire analysis provides a good macro-level buildings target (i.e. the buildings sector can profitably reduce carbon emissions by 38% to help meet the 80% reduction societal goal) it provides little guidance on an individual building or group

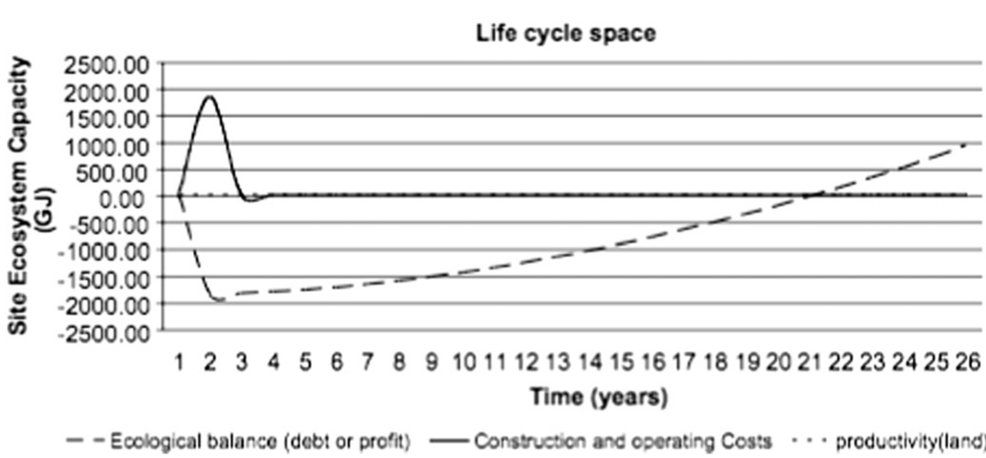

Fig. 1. The concept of earning back an ecological debt incurred with building construction.

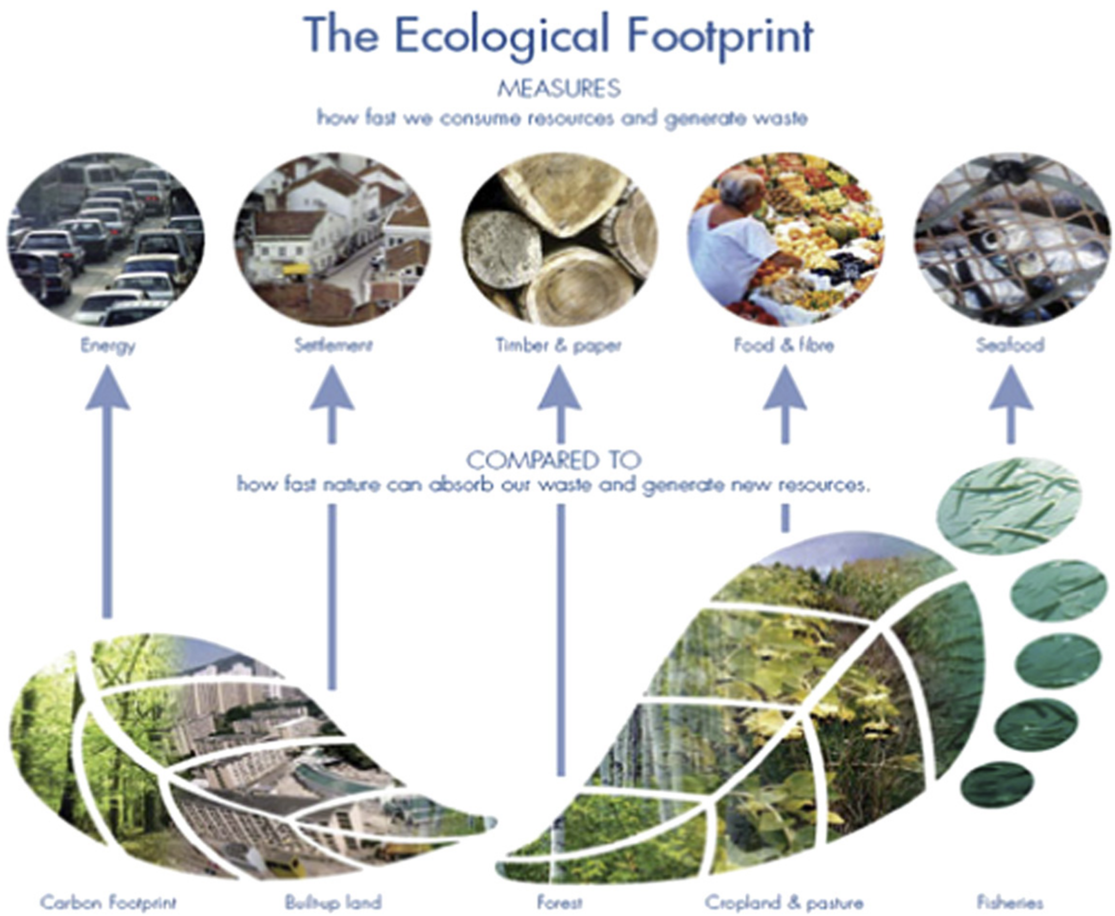

Fig. 2. The ecological footprint method divides societal consumption into five different categories. (www.footprintnetwork.org).

of buildings level. Thus, future work could be to identify rational micro-level targets for an individual or group of buildings. One major challenge, among others, in doing so will be determining "average" values from 1990 (or year 2000), especially when there is little information about the building (or the building type). Obvious benefits in using the IPCC approach is that it can be considered a direct measure of the effect of buildings on climate change, is based in oceanic and atmospheric science, and can be considered an "absolute" measure.

Overview of ecological carrying capacity method

Building sustainability assessment methods have come to define the progress of many nations toward sustainability. As the

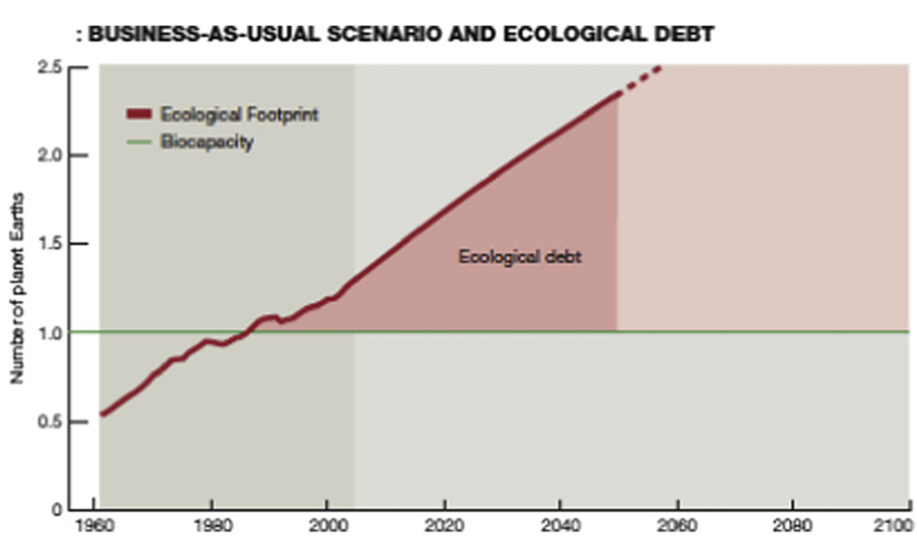

Fig. 3. Conceptual account of ecological debt (2008 living planet report).

methods become more infused to societal and economic processes, they take on greater responsibility to not only transform the market but to transform the built environment. Now, more than ever, it is necessary to know how assessment methodology should improve. The remainder of this paper introduces a method that could make such assessment more appropriate to sustainable development, and demonstrates the method's functionality through a case study.

We have developed an ecological carrying capacity method that estimates net carbon flow from the earth to the atmosphere, or vice versa, as a result of a building project. The analysis period extends from initial construction (or major renovation) through a user-specified number of years of building operation. The method assesses the building project with regard to carrying capacity, a concept used by biologists to describe how many animals a given habitat could support but, in contrast, used in the method to denote the amount of carbon stored on the building project site in its native state. By the end of the project analysis period, the net amount of carbon stored on the building project site must be equal to or greater than the native amount in order for the project to be considered sustainable with regard to carbon emissions, or "carbon neutral."

In order to avoid the problems identified in the Olgyay and Herdt (2004) method regarding like-for-like ecological debt repayments, the carrying capacity concept is applied to carbon emissions only. Other elements of sustainability, such as water and waste, are obviously important to account for in any assessment of building sustainability but we have chosen not to address those aspects in this method. We acknowledge that any true assessment of sustainability would take these other factors into account, as well as other ecosystem services (such as biodiversity) that had once been valued at US$ 33 trillion (Costanza et al., 1998)—indeed, we may be closer than we think to being able to quantify ecosystem services for urban planning purposes as tools are currently being developed by the Natural Capital Project (www.naturalcapitalproject.org). Hence, the proposed carbon model is meant to be an absolute measure that falls within a broader assessment of sustainability. It is not meant to be the definitive statement or rating of building sustainability. It represents a step toward a more absolute building sustainability assessment.

Why use our proposed definition of carbon neutrality as opposed to the IPCC approach of 80% carbon emissions reduction by 2050? If we think back to a time when there were no buildings, the amount of carbon stored in the native vegetation and soil on the current building sites helped to maintain a global carbon balance between the earth and atmosphere. Any vegetation that is removed from the site or any carbon emissions that are emitted from the site (such as to operate a building) creates an increase in atmospheric carbon. Our method is in concert with the approach of climate scientists, in that they first attempt to understand the historical carbon storage on the Earth and the atmospheric carbon dioxide equivalent (CO_2e) concentration, and then estimate a net change in these values (Barker et al., 2007). The difference is that the carrying capacity method proposed in this paper is based on a longer timeframe, beyond 2050, in which anthropogenic emissions should be nearly zero. The other major difference is the boundary of analysis, which is narrowed from the entire Earth to the project site.

The ecological carrying capacity method accounts for the carbon emissions (also known as carbon dioxide equivalent, CO_2e, and greenhouse gas, GHG) from three aspects: site development, construction, and operation. "Site development" accounts for the removal or addition of vegetation and other carbon storing elements to the project site. "Construction" accounts for the carbon emissions from the raw material extraction, manufacture, transport and on-site assembly of building materials. "Operation" accounts for the GHG Protocol Scope 1 and 2 carbon emissions resulting from consumption of electricity, natural gas, fuel oil and other fuels used on site. Users can also account for other (Scope 3) emissions sources such as commuter transport in the Operation category. We have excluded from the analysis building disposal and recycling due to a lack of data.

Fig. 4 below is a representation of the "Overview Chart" that the method generates. As illustrated, the emissions from site development and building construction occur during only the first year of the building project. Fig. 4 also illustrates three separate scenarios for the operation phase of the building. The scenario represented by the red line shows how the building continues to emit carbon and goes into greater carbon "debt" (if we continue with the ecological mortgage analogy used by Olgyay and Herdt). The orange line represents a net zero operational carbon emissions scenario and the blue line represents a building that has negative operational carbon emissions. The dips in the lines represent possible retrofits that would each carry an amount of embodied carbon emissions.

As shown in Fig. 5 below, the carbon model shows whether or not the building project is contributing to a net increase or decrease in atmospheric concentration of carbon based on the location of the end point. Above the dotted line indicates a net decrease in concentration and vice versa.

The formula behind the Overview Chart is as follows:

$$CS(t) = NSCS - SD - C - O(t) \quad (1)$$

Where

CS = Carbon storage on the building site (kg CO_2e)
t = Time (years)
NSCS = Native-site carbon storage (kg CO_2e)
SD = Emissions from site development (kg CO_2e)
C = Emissions from building construction (kg CO_2e)
O = Emissions from building operation (kg CO_2e/year)

Estimating the native-site carbon storage

The IPCC has gathered several studies of carbon storage specific to land types including forests and grassland, as shown in Table 1. New studies continued to be conducted (Alexis et al., 2006; Powell et al., 2006), but unfortunately there is no available data for land types other than forest or grassland. In addition, the studies do not account for underground biomass, which can be as high as 80% of the total biomass (Swain, 2008). Hence, the uncertainty in these values is at least 80%.

$$NSCS = CI \times SA \quad (2)$$

Where

NSCS = native-site carbon storage (kg CO_2e)
CI = Carbon intensity of the native ecological zone (kg CO_2e/sq ft)
SA = Site area (ft^2)

Estimating the carbon emissions from site development

Site development is perhaps most well known as forest depletion, which represents nearly 20% of global carbon emissions. Using the same method developed by the IPCC to account for this

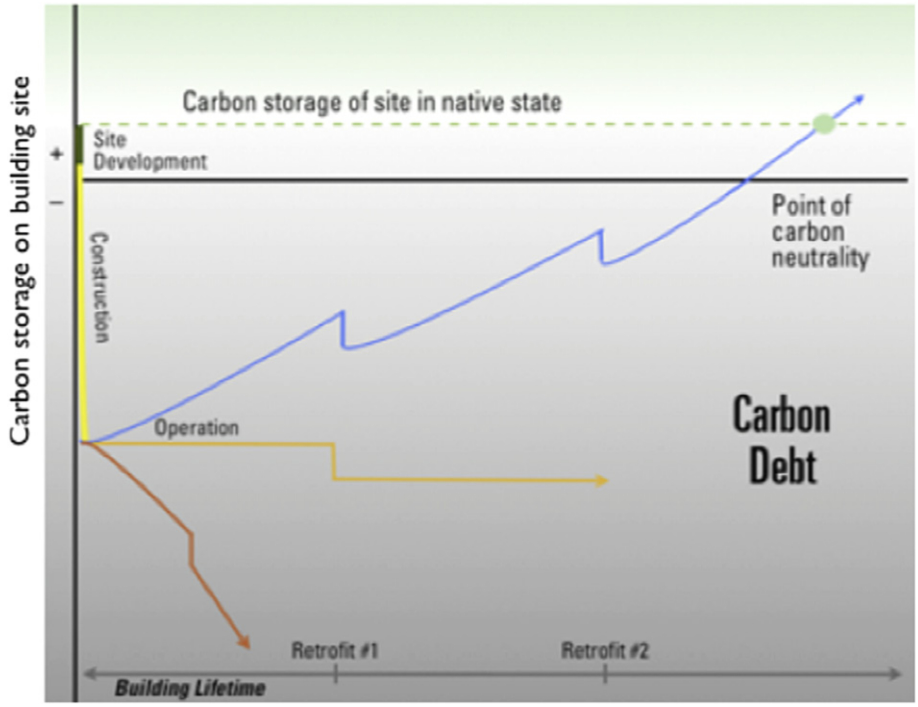

Fig. 4. Overview Chart. The carbon stored on the building site (*y*-axis) goes up or down with the threes aspects of the building project: Site development, construction, and operation. If during the operation phase a building can reach back up to the amount of carbon stored on the site in the native state, the building project is considered "carbon neutral."

depletion in carbon storage and resultant carbon emissions, it is possible to calculate the emissions associated with land or site development for buildings and urbanization (IPCC, 2006).

The amount of emissions from site development is calculated by comparing the design-case carbon storage with the native-state carbon storage, as shown in Eq. (3). The design-case carbon storage may include some percentage of the site that has native vegetation, in which case that percentage should be multiplied with the native-state carbon storage. On areas with no native vegetation the number of trees can be estimated, and converted to stored carbon using Table 2. The method's carbon storage value per tree is based on an average tree growth rate over

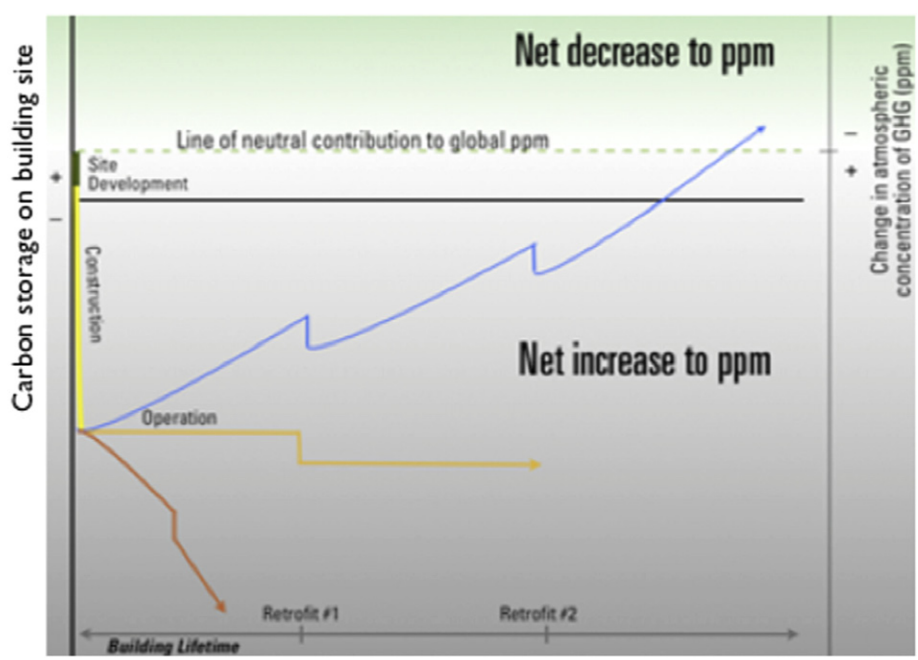

Fig. 5. Atmospheric concentration of GHGs. The method shows a net increase or decrease to parts-per-million (ppm) of carbon in the atmosphere. If the carbon storage on the building site increases to a point above the native-site carbon storage, or the "line of neutral contribution to global ppm," the project will result in a net decrease in concentration of greenhouse gasses.

Table 1
Biomass of various ecological zones. The IPCC recommends multiplying the biomass by a carbon fraction of 0.5 to obtain the carbon (C) content, which will then have to be multiplied by a factor 44/12 to obtain CO_2 mass. See Bendewald and Olgyay (2011) for the complete list of stored carbon values for different land types from the IPCC.

Above-ground biomass in forests			
Domain	Ecological zone	Continent	Above-ground biomass (tones d.m. ha^{-1})
Temperate	Temperate oceanic forest	Europe	120
		North America	660 (80–1200)
		New Zealand	360 (210–430)
		South America	180 (90–310)
	Temperate continental forest	Asia, Europe (≤20 y)	20
		Asia, Europe (>20 y)	120 (20–320)
		North and South America (≤20 y)	60 (10–130)
		North and South America (>20 y)	130 (50–200)
	Temperate mountain systems	Asia, Europe (≤20 y)	100 (20–180)
		Asia, Europe (>20 y)	130 (20–600)
		North and South America (≤20 y)	50 (20–110)
		North and South America (>20 y)	130 (40–280)

20 years, or a total of 0.2 metric tons (t) of carbon (or 0.73 t CO_2e[2]) per tree.

$$SD = NSCS - (\%\,Native \times NSCS) - (Trees \times CR \times Yrs) \tag{3}$$

Where

SD = Emissions from site development (kg CO_2e)
NSCS = Native site carbon storage (kg CO_2e)
% Native = Percent of building site that will have native vegetation in its design state
Trees = Number of trees expected on the site in non-native areas
CR = Rate at which the trees sequester carbon during growth period (kg CO_2e/yr)
Yrs = Length of trees growth period (yr)

The uncertainty associated with the calculated emissions from site development can be over 100%. This is due to the 80% uncertainty associated with the carbon storage in a certain ecosystem and uncertainty associated with estimating carbon storage of individual trees. Other major sources of uncertainty includes whether or not planted vegetation thrives, which can be mitigated with thorough analysis of plant species and soil conditions.[3] Reducing other sources of uncertainty will require generation of more accurate native-site carbon storage data, such as what is being developed as part of the Welikia Project (http://welikia.org/) in New York.

Estimating carbon emissions from building construction

The emissions from the building construction include all site work (earth moving, assembling, etc.) and the embodied carbon emissions of materials (from the extraction of raw materials through transportation to site). Since assessment of carbon emissions from these sources for building projects is a relatively nascent practice and several methods and tools exist, the method enables

[2] The mass of C (carbon) is converted to CO_2e (carbon dioxide equivalent) by multiply by 44, the molecular weight of carbon dioxide, and dividing by 12, the molecular weight of Carbon.

[3] A tool for determining which plant species will likely succeed on a site can be found free for public use at http://nativespec.com/nativebrowser/.

Table 2
Annual carbon accumulation per tree per year (developed from IPCC 2006).

Species	Annual carbon accumulation per tree (*t* C/yr)
Aspen	0.0096
Soft Maple	0.0118
Mixed Hardwood	0.0100
Hardwood Maple	0.0142
Juniper	0.0033
Cedar/Larch	0.0072
Douglas Fir	0.0122
Pine	0.0087
Spruce	0.0092
Average Carbon Stored per Tree per Year	0.01

users to enter their own estimate. Perhaps the easiest tool to use is Carnegie Mellon University's Economic Input Output (EIO LCA) calculator.

The EIO LCA approach produces a macro-level, economy-wide estimate of carbon emissions that has only one or two significant figures (Hendrickson, Chris, Lave, & Scott Mathews, 2006). If greater certainty is desired, a process-based LCA (using a tool such as Athena Institute's EcoCalculator) can be used and entered as the UserValue variable. The uncertainty associated with process-based LCA (also known as ISO 14040 LCA), which is a micro-level estimate, tends to be much less than EIO LCA; however, the respective weaknesses and strengths of the two methods have not been extensively studied in a quantitative matter (Majeau-Bettez, Hammer Strømman, & Hertwich, 2011).

User option for estimating construction emissions:

$$C = UserValue \tag{4a}$$

Where

C = Emissions from building construction (kg CO_2e)
UserValue = Value entered by user

Carnegie Mellon University EIO LCA option for estimating construction emissions:

$$C = EIOLCA \tag{4b}$$

Where

C = Emissions from building construction (kg CO_2e)
EIOLCA = The total carbon emissions from building construction based on EIO LCA carbon intensity values (kg CO_2e)

The EIO LCA option for estimating construction emissions

The EIOLCA variable used in Eq. (4b) can be determined in two ways. One approach is valid for both new and renovation construction and the other works for new construction only. This section will describe both approaches.

Approach #1: new and renovation construction

Approach #1 for determining the EIOLCA variable is to use data that comes directly from the Carnegie Mellon EIO LCA calculator, the 1997 National Purchaser Price model.[4] The data from this model is the amount of carbon emissions per 1997 US dollar of

[4] For building construction sectors, there is no difference between the Producer and Purchaser price models.

construction activity in a particular construction sector of the US economy, as shown below in Table 3. Users simply enter the amount of dollars in the project budget (adjusting for inflation to convert to 1997 dollars) to determine the amount of emitted carbon.

Approach #2: new construction only

Approach #2 for determining the EIOLCA variable is to use the data in Table 2 above converted to the amount of carbon emissions per square feet of new construction. Users simply enter the amount of square feet of new construction in order to determine the amount of emitted carbon. This section will describe how the carbon per square foot data was derived.

First, the total amount of carbon emitted in 1997 was determined for each of the building sectors in Table 2. Second, the total square feet of construction starts in 1997 was determined. Finally, the total carbon emitted was divided by the total square feet of constructions starts in order to determine the carbon emissions per square feet of new construction.

In order to calculate the total amount of carbon emissions in 1997 for each of the building types, the total economic outputs of each construction sector were multiplied by the appropriate carbon emissions coefficients in Table 2. The total economic outputs were determined from the BEA's 1997 Benchmark IO Item Output table and are listed in Table 3 below.

Construction starts in 1997 were provided by the McGraw-Hill Companies, Inc. The categories of this data were several and required mapping to one of the four EIO LCA sectors of Table 2. For example, the McGraw-Hill categories "Offices and Bank Buildings" as well as "Hotels and Motels" were both included in EIO LCA sector 23022, "Commercial and Institutional Buildings." The entire map can be found in Appendix B of Bendewald and Olgyay (2011). Results are shown in Table 4.

Table 5 below shows the results of dividing the total carbon emitted by the total square feet of constructions starts for each EIO LCA Sector. While these coefficients are only accurate to one or two significant figures, they can be trusted since they are similar to coefficients produced by other studies, as discussed in Appendix C of Bendewald and Olgyay (2011) (Table 6).

Estimating emissions from building operation

During the operation of the building, the flow of carbon can move either into or out of the atmosphere. In order to determine the direction and magnitude of this net flow, the magnitude of each flow must be determined. Thus, the calculation of net emissions from building operation requires two steps.

The first step is to estimate the amount and type (electricity, natural gas, etc.) of energy the building will use. This can be done using average building energy use data (such as from the US Energy Information Administration's Commercial Building Energy Consumption Surveys) or a building energy simulation model (such as eQUEST). The building simulation model is always going to be more accurate than surveys since the model is specific to the building being designed. The uncertainty of the building model is highly dependent on the amount of time the modeler spends making the model accurate and even a good model's uncertainty can range as high as 20%.

Once an energy estimate is determined, it is straightforward to calculate the emissions of this mix of energy using emissions coefficients for each energy source. For each region in the US, the electricity coefficients in the method should come from the US Environmental Protection Agency's eGRID Subregion Emission Rates, Output Emission Rates, covering carbon dioxide, methane and nitrous oxide.[5] Other nations should have similar data sources. Emissions coefficients for electricity are more accurate than the eGRID data (or similar) if they take into account hourly variations in regional power sources (Mahone, Snuller, & William, 2009); for example, most electric utilities meet the base electric load with one technology (such as coal or hydroelectric power) and ramp up power generation to meet peak loads with different technologies (such as natural gas power). Since each technology has a different emissions rate, the emissions from using electricity from the grid can vary by the hour. Natural gas and other coefficients come from the US Energy Information Administration and, unlike electricity, are not dependent on time-of-use.[6] See the GHG Protocol for more details on how to translate energy consumption into carbon emissions.

The second step is to estimate the emissions offset through generating renewable energy on-site or purchasing off-site renewable energy and carbon offsets. The carbon intensity (kg CO_2e/kBtu) of on-site electricity should equal that of the purchased electricity. The carbon intensity of energy produced by a solar thermal system should equal that of whatever the auxiliary energy source is (in most cases, natural gas).

An optional third step is to calculate other operational emissions that were not included in the above steps, such as employee commuting.

$$O(t) = (E - EG)EI + (N - TG)NGI + (OF - TG)OFI + OR \quad (5)$$

Where

O = Carbon emissions from building operation (kg CO_2e)
E = Electricity used (kBtu)
EG = Electricity generated on-site (kBtu)
EI = Electricity carbon emissions intensity (kg CO_2e/kBtu)

Table 3
EIO LCA coefficients for new and renovation construction based on the US economy in 1997.

EIO LCA sector		Energy intensity (TJ/million USD)	Carbon intensity (t CO_2e/million USD)
23011	1-unit Residential	6.8	560
23012	Multifamily	7.9	640
23021	Manufacturing and industrial buildings	7.6	590
23022	Commercial and institutional buildings	7.7	600

Source: Carnegie Mellon University Green Design Institute. (2008) Economic Input-Output Life Cycle Assessment (EIO LCA), US 1997 Industry Benchmark model [Internet], Available from: <http://www.eiolca.net> Accessed 1 January, 2008.

Table 4
1997 characteristics of EIO LCA sectors in the US economy.

EIO LCA sector		Total industry output (million USD)	Area of construction starts (1000 ft^2)
23011	1-unit Residential	172,489	2,182,072
23012	Multifamily	26,234	403,362
23021	Manufacturing and industrial buildings	27,487	327,815
23022	Commercial and institutional buildings	190,818	958,231
Source:		Bureau of Economic Analysis, 1997 IO Item Output	McGraw-Hill Construction

[5] http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.
[6] http://www.eia.doe.gov/oiaf/1605/coefficients.html#tbl1.

Table 5
Energy and carbon intensity coefficients for building construction sectors.

EIO LCA sector		Energy intensity (kBtu/ft^2)	Carbon intensity (kg CO_2e/ft^2)
23011	1-unit Residential	510	45
23012	Multifamily	490	42
23021	Manufacturing and industrial buildings	610	49
23022	Commercial and institutional buildings	1500	120

N = Natural gas used (kBtu)
TG = Renewable thermal energy from on-site (kBtu)
NGI = Natural gas carbon emissions intensity (kg CO_2e/kBtu)
OF = Other fuel used (kBtu)
OFI = Other fuel carbon emissions intensity (kg CO_2e/kBtu)
OR = Other operational emissions (kg CO_2e)

Applying the method: Archbold biological station case study

Archbold Biological Station is an independent ecological research facility with a campus located inside a 5193-acre preserve of Florida scrub ecosystem. Sited in that campus, the Frances Archbold Hufty Learning Center is intended to support the research and educational programs of the Station. The ecologically sensitive location of the LLC and its educational intent drove the project team to pursue high goals including LEED Platinum and carbon neutrality. Carbon neutrality for the ABS project was based on native-site carbon storage.[7] This section will describe how the carbon neutrality assessment method was applied and how it informed design.

Establishing native- and design-site carbon storage

The 3.4-acre (1.4-ha) site of the Learning Center is on the northern edge of Archbold campus. Instead of using the more general carbon storage data from the IPCC, ABS provided carbon storage studies of the native-site ecosystem known as scrub oak. As shown in Fig. 6, the stored carbon in the vegetation ebbs and flows with each natural burn and produces a small amount of charcoal that eventually disintegrates (Alexis et al., 2007). Assuming that the natural burn cycle is about 17 years (Swain, 2008), the average carbon stored was 5.5 kg C/m^2 (1.9 kg CO_2/ft^2). This estimate does not include underground biomass or carbon in the soil. In the case of Florida scrub oak, the underground biomass accounts for more than 80% of the total (Swain, 2008). Therefore 5.5 kg C/m^2 is a major underestimate.

The team carefully considered how it could increase the amount of native vegetation for carbon sequestration as well as biodiversity and water control. As a result, over 50% of the site is to be returned to the native ecosystem. As shown in Fig. 7, the design-site carbon storage will be slightly more than half the native-site carbon storage after the vegetation is full grown. The 3.4-acre design site was modeled at 84,300 ft^2 scrub oak, 55,000 ft^2 nonporous surface, and 10,700 ft^2 building footprint.

Embodied carbon emissions

The embodied carbon emissions of the new construction of this facility were estimated using the factors in Table 5. The estimate is a national average and does not account for the efforts made by the ABS design team to reduce embodied carbon emissions, which included some materials reuse.

[7] The author Michael Bendewald provided carrying capacity analysis on the project.

Table 6
Embodied carbon emissions of the Learning Center.

National average carbon intensity (kg CO_2e/ft^2)	Building area (ft^2)	Total carbon emissions (metric tons CO_2e)
120	10,500	1300

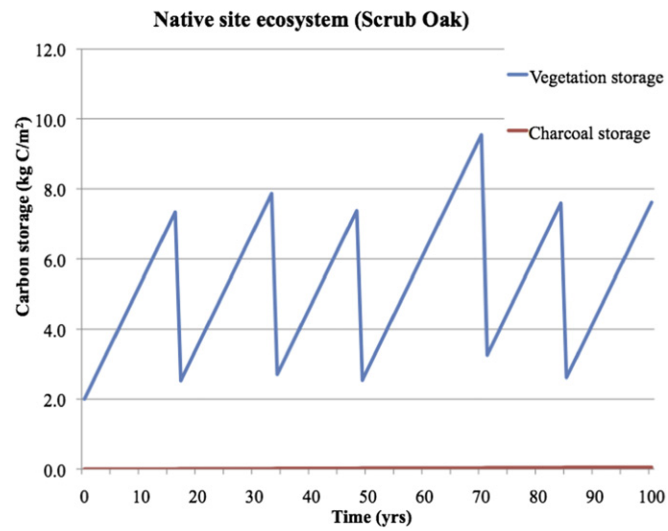

Fig. 6. Illustration of native-site carbon storage (productivity) with average 17-year burn cycle, including some variation, over the course of 100 years. The average carbon stored is 5.5 kg C/m^2 (1.9 kg CO_2/ft^2).

Operational carbon emissions

The operational carbon emissions were calculated using GHG Protocol standards. The electricity emissions coefficient is the US Environmental Protection Agency's eGRID emissions coefficient for the Florida region (FRCC), 0.60 kg CO_2e per kWh. The natural gas coefficient is from the Department of Energy's Energy Information Administration website, 0.053 kg CO_2e per kBtu. Extensive daylighting, lighting controls, and a variable-refrigerant-volume cooling system all contribute to the reduction

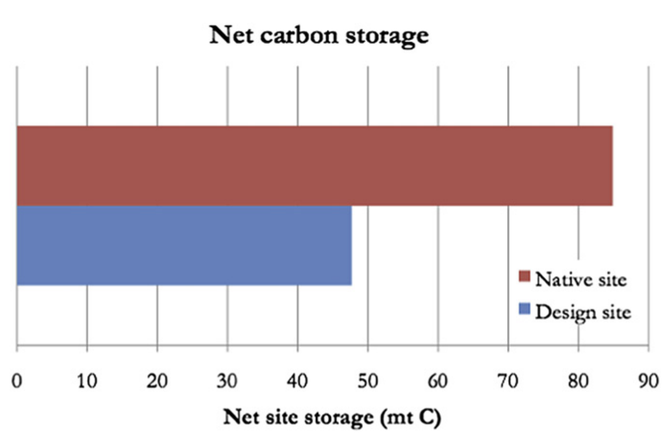

Fig. 7. Metric tons of carbon stored on the 3.4-acre (1.4 ha) site.

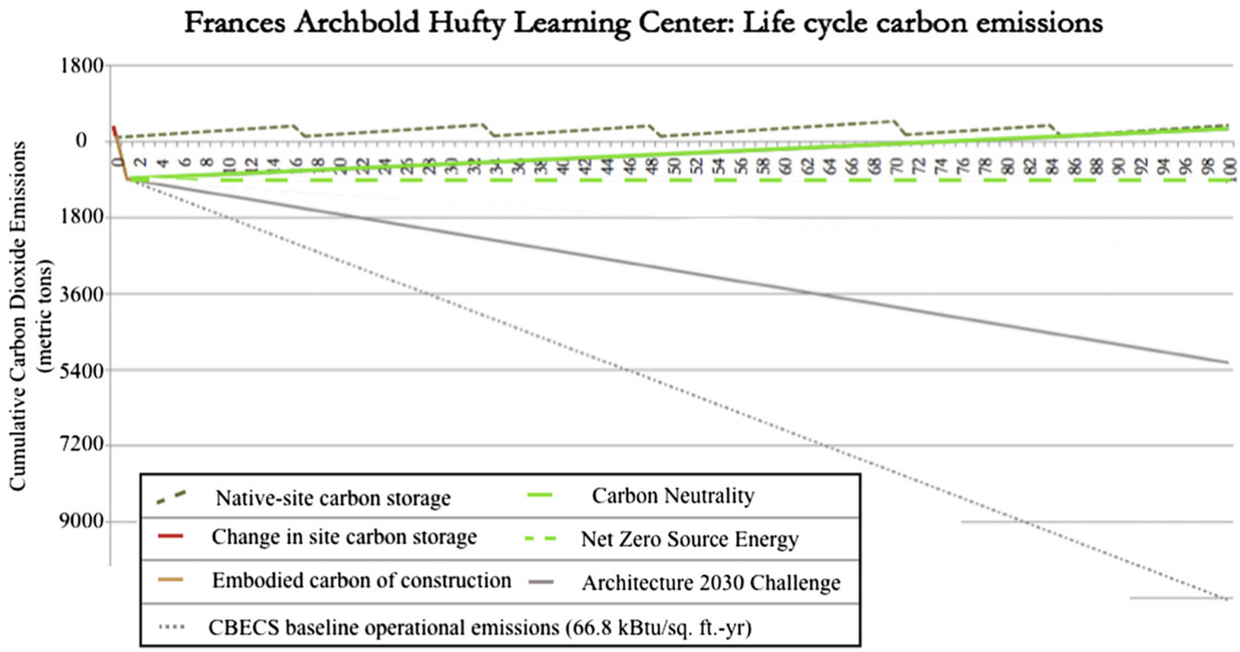

Fig. 8. Frances Archbold Hufty Learning Center life-cycle carbon emissions. The CBECS baseline was determined using the EPA's target Finder. The energy use intensity is a mix of 32% natural gas and 68% electricity. The Architecture 2030 challenge is a 60% savings of operational source energy from the CBECS baseline.

of operational carbon emissions, modeled to be around 40% (Ellis, 2010).[8]

Calculating carbon neutrality

The native-site carbon storage and sources of carbon emissions are all plotted over the anticipated lifetime of the building (100 years in this case) in Fig. 8. As noted above, the native-site carbon storage can be thought of as the carbon "in the bank." As the project design decisions are made, the trajectory of carbon emissions illuminates for designers the amount of incurred "carbon debt" (or carbon surplus) by the end of the building lifetime. It is important to note that neither embodied carbon of building retrofits nor other sources of operational emissions such as refrigerant leak and commuter transport are included in the Learning Center life-cycle carbon emissions estimate. It also does not account for future changes to the electricity emissions coefficient.

The design team and owner used this life-cycle carbon emissions perspective when evaluating design decisions. From the outset, as shown in Fig. 8, it was clear that achieving the Architecture 2030 Challenge would result in an unacceptable carbon debt (assuming no major future renovations that meet the Challenge). The project team used this framework to quantify how far the building will be from carbon neutrality by the end of building lifetime and after a certain number of years (such as up to the point of the first anticipated major renovation).

Discussion

At least three issues can be raised with this carbon model as a tool for assessing and influencing building design. First, the model does not quantify uncertainty and given the long time frames of analysis it seems important to do so. However, in order to address this issue we need to consider the ultimate purpose of the model, which is to provide a convincing argument for designers to radically reduce carbon emissions through design. After considering the uncertainty of the components as qualitatively and quantitatively noted above, the designer can ascertain that the building carbon emissions extend far beyond the carrying capacity of the site. Hence, no matter what the exact uncertainty is, the model urges designers to make design decisions to reduce emissions. That said, quantifying uncertainty should be a focus for future development as it may increase the cogency of the argument.

A second issue is regarding the degree at which the model actually informs design. It is clear that macro-level assessments of carbon emissions do little to inform design because they do not present options that would reduce carbon emissions. While this paper proposes macro-level data for both on-site vegetation and construction emissions, it is up to users as to what data they actually use. The only reason that more specific data was not presented was that it simply is not practical for users to obtain it. As more specific, micro-level data becomes accessible, users will be able to make low-carbon design decisions within the context of the carbon model. It is important to note that using this micro-level data in the context of the carbon model and the picture of carrying capacity that it provides is arguably much more sensible and helpful than using the data standalone. In that regard, the proposed carbon model represents a step toward creating a framework in which micro-level data would be most helpful to designers and, indeed, helps makes the case that such data would be useful to develop and make publicly accessible.

A third issue is that some designers may recognize that one way for the design to move closer to carrying capacity is to increase the size of the site, which may lead to urban sprawl. However, the designers should quickly realize that this strategy does not significantly help and it does not solve the fundamental problem that carbon emissions is very far beyond carrying capacity.

Conclusion

Building sustainability assessment is emerging as a major driver of the building design and renovation market. With this new market power comes questions about the ultimate purpose and effectiveness of the assessment methods. This paper has presented

[8] Baseline is ASHRAE Standard 90.1 2007.

a method—complimenting a broader sustainability assessment method—that equitably distributes carbon based on the native-site carbon storage and thereby provides an absolute assessment of sustainability with regard to carbon emissions. The method reveals the enormous amount of carbon that a typical building emits in relation to what would be sustainable to hopefully drive designers toward low-carbon design decisions. The approach gives rise to a new stewardship of carbon sequestration by biomass on a building site and shares its methodology with atmospheric science, helping designers relate their building projects to societal climate change goals.

The Archbold Biological Station project was presented to illustrate how the carbon neutrality calculations are made and how they can inform design decision-making. As shown in the case study, teams can use this methodology to target carbon neutrality, report life-cycle carbon emissions, estimate carbon debt and help assess building sustainability.

Acknowledgements

The authors would like to acknowledge Victor W. Olgyay, AIA, for his guidance and inspiration during the course of this research.

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