TOWARD FULLY FUNCTIONAL NET-ZERO-ENERGY BUILDINGS: An Engineering Perspective

By: Boggarm S. Setty, P.E., FASHRAE[1] and
James E. Woods, Ph.D., P.E., FASHRAE[2]
26 March 2014

Abstract

Throughout history, the tension between providing basic needs and conserving natural resources has resulted in challenges and opportunities to improve well-being and productivity. Policy, regulatory, and marketing efforts have recently focused on a concept that has become known as "net-zero energy buildings" (NZEB). From an engineering perspective, design and operations of these buildings must comply with the Laws of Thermodynamics, and should be based on calculations that are verifiable by measurement at the defined thermodynamic boundaries. In this article, current concepts of NZEB are analyzed; an operational definition of "Net-Zero Energy Commercial Buildings" (OZEB) is proposed; a design approach toward achieving site-specific OZEBs is presented; and examples of evidence-based results are reviewed and analyzed. Conclusions are: 1) the OZEB should reduce uncertainties of measured outcomes; 2) the stepwise engineering approach should "meet the needs and aspirations of the present without compromising the ability to meet those of the future"; 3) a dearth exists of evidence-based examples that demonstrate the effectiveness of NZEB and 4) increased accountability for design and operations of commercial buildings can result in significant reductions in depleteable energy resources while improving well-being and productivity; the challenge is to achieve this goal through engineering principles that minimize uncertainties and risks.

[1] President, Setty and Associates, Ltd., Fairfax VA, bsetty@setty.com.
[2] Indoor Environment Consultant, Charlottesville VA, jewoods3@aol.com.

Introduction

From the time fire was discovered and humans inhabited enclosed shelters, a need to burn natural resources was recognized for the basic requirements of survival: heating, cooking, lighting, and security. Soon after, the need to ventilate the enclosures for health and safety was discovered. Also from that time, it was realized that to meet these needs, depletion of natural resources would occur. Throughout history, the tension between providing basic needs and conserving natural resources has resulted in local, national, and international problems such as energy shortages, economic depressions, and wars. This tension also has resulted in opportunities to improve well-being and productivity through the discovery and applications of steam engines, electricity, and refrigeration in the 18th and 19th centuries; and the evolution of transportation, large buildings, urban centers, and information technologies in the 20th and 21st centuries. The purpose of this article is to provide guidance to those who are now attempting to balance this tension through the design and operations of buildings that "meet the needs and aspirations of the present without compromising the ability to meet those of the future" (1).

This article has three objectives: 1) to analyze the current concepts of "net-zero energy buildings" for consistency with the Laws of Thermodynamics and other engineering principles; 2) to describe a design approach toward achieving site-specific net-zero energy buildings (NEZB), which is consistent with the Laws of Thermodynamics and the constraints imposed by other high performance building attributes; and 3) to analyze examples of evidence-based results.

The focus of this article is on educational facilities and office buildings because these public facilities significantly impact the lives of many people in the developed world.

Concepts, Definitions, and Goals of Net-Zero Energy Buildings

Policy, regulatory, and marketing efforts have recently focused on a concept that has become known as "net-zero energy buildings." From an engineering perspective, design and operations of these buildings must comply with the First and Second Laws of Thermodynamics. Also, their designs should be based on calculated results that are verifiable by measurement at the defined thermodynamic boundaries.[3] In this section, five conceptual definitions of "*net-zero energy* buildings" (2), a composite definition of a "*zero-net-energy* commercial building" (3), and a modification of these definitions (4) are analyzed; from which an operational definition for engineering purposes is proposed.

[3] According to the First Law, the energy added or removed within the thermodynamic boundary of the building or property site (i.e., system) cannot be created or destroyed but can be changed from one form to another (e.g., heat and work are interconvertable). And according to the Second Law, a source of energy, which is external to the system boundary, must be irreversibly used to transfer heat to a higher temperature state of a process within the system (e.g., production of electricity for lighting, heating and cooling and other internal loads; refrigeration and HVAC systems to dissipate cooling and heating loads).

Background for Net-Zero Energy Buildings

After the energy shortages of the 1970s, a concerted effort was made to reduce the amount of energy needed in buildings to provide for occupant health, safety, and security and, concomitantly, to meet the functional, aesthetic, and economic needs of occupants, owners, and operators. Nearly 40 years ago, the first design standard in the United States for *site* and *source* energy conservation was published (5). During the same period, "building energy performance standards" (BEPS) were promulgated and a target energy utilization index[4] (i.e., EUI) of 55 kBtu/GSF (gross square footage of floor area) per year was recommended for *site* energy use in commercial buildings (6; 7).

Beginning in 1979 and continuing until 2003, the Energy Information Administration of the U.S. Department of Energy (EIA/DOE) published estimates of *site* energy consumed in commercial buildings from all fuels, and estimates of "primary" (i.e., *source*) and *site* energy consumed in the form of electricity.[5] These estimates were based on simulations and extrapolations from the Commercial Building Energy Consumption Surveys (CBECS) (8).[6] As shown in Fig. 1, these data reveal that, within the 95% confidence intervals, the mean annual *site* energy usage from the total of all major fuels (i.e., electricity, natural gas, fuel oil, and district heat) for all commercial buildings in the US during this period of time[7] was statistically flat at 92 kBtu/GSF and the subset of office buildings, which represents 17% of all commercial buildings in the U.S.,[8] was flat at 104 kBtu/GSF; values that have remained nearly double the BEPS target that was set in 1974-78 (9). A similar analysis of the CBECS data for this period reveals that the annual energy use was statistically flat at 79 kBtu/GSF for the subset of educational buildings, which comprises an additional 14% of all commercial buildings in the U.S.[9]

A likely cause of this "flatness" was first described by William S. Jevons in 1865 (i.e., the "Jevons Paradox") and reintroduced as the "Rebound Effect" by Harry D. Saunders in 1992 (10). Briefly stated: *As the efficiency of energy use increases, its use increases*. Although the validity of the Jevons Paradox or Rebound Effect is generally accepted, the magnitude of its impact has been debated for more than 10 years (i.e., negligible to more than 100% impact) (11). Common examples are 1) doubling the thermal resistance of glazing while doubling the area of glazing in the envelope; 2) doubling the volume of a household refrigerator at the same ampacity; 3) reducing the design lighting loads by 50%

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[4] The EUI is also known as the "Energy Utilization Intensity."

[5] See Tables C1, C3, C13, C1A, C3A, and C13A in the 2003 CBECS report (8).

[6] CBECS estimates have not been published since 2003. Data were obtained in 2012 and publication is scheduled to resume in 2014.

[7] The CBECS data estimated that the number of commercial buildings in the US increased from 3.1 million in 1979 to 4.8 million in 2003.

[8] As categorized by CBECS, office buildings include general office space, professional office space, administrative offices, and medical offices that do not include diagnostic equipment or services. Office buildings have the largest percentage of floor space (17%) of all categories of buildings in the CBECS database.

[9] As categorized by CBECS, educational buildings include those used for academic or technical classroom instructions such as elementary, middle or high school, and classroom buildings on college campuses.

but increasing the connected electrical loads by a similar amount; 4) doubling the energy efficiency ratios (i.e., EER) of chillers but also increasing the sizes, configurations, and cooling loads of commercial buildings.

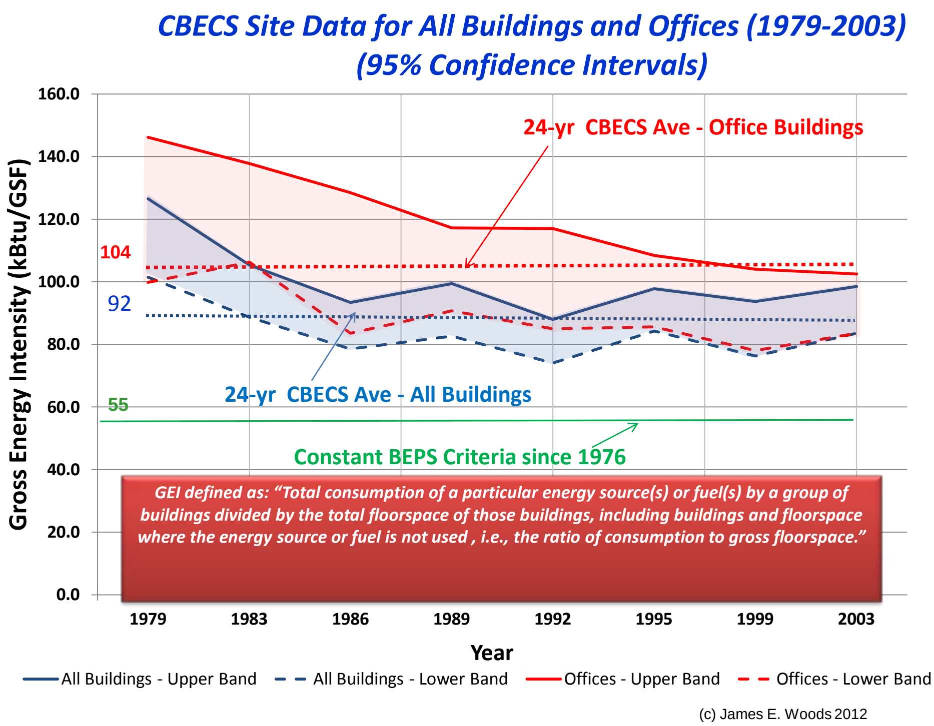

Figure 1. CBECS Energy Use Data - 1979 to 2003 (9)

During the last two decades, concepts, policies, and regulations regarding sustainable design, green buildings, and energy reduction programs have been introduced by the private and public sectors with the goal of further reducing building energy use and the depletion of natural resources without increasing owning and operating costs or compromising indoor and outdoor environmental quality. One of the latest of these concepts is the "zero energy building," which was introduced in 2005 by US DOE with the "*goal to create the technology and knowledge base for cost effective zero-energy commercial buildings (ZEBs) by 2025*" (2). This concept included a general definition with four variations. A composite definition was promulgated in EISA-2007 (3), which was derived from elements of the conceptual definitions. In 2008, ASHRAE adopted a modified version of the DOE's first variation (4). Since 2008, international researchers from 19 countries have been working on a joint research program, IEA Task 40/Annex 52: "Toward Net Energy Solar Buildings," which is sponsored by the International Energy Agency (12).

Conceptual Definitions

The general definition, which was proposed by Torcelinni et al (2), stated:

"A net zero-energy building (ZEB) *is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies*."

This definition implies two essential processes:

- Thermodynamically sound methods must be employed to reduce building loads, system capacities, operational inefficiencies, and resultant *building energy needs* to values that are substantially below the baseline of the current building stock (e.g., CBECS values).
- The resultant *building energy needs* must be provided from "renewable" (i.e., non-depleteable) resources.

The four variations were: 1) net-zero *site* energy; 2) net-zero *source* energy; 3) net-zero energy *costs*; and 4) net-zero energy *emissions*. Each of these variations is being reviewed by the IEA Task 40/Annex 52 for residential and commercial buildings (12). The following is a brief analysis of these variations for engineering design purposes:

1. Net Zero *Site* Energy**:** "*A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site*."
   - The thermodynamic boundary for this category can be explicitly defined either as the outer surfaces of the building enclosure or as the property site boundary.
   - For either boundary, the actual building energy use can be explicitly measured and verified as the sum of the contiguous meter readings of the energy resources crossing the boundary (i.e., defined by the location of the meter) for a year and converted to common *site* EUIs (e.g., MWh/GSM or KBtu/GSF).
   - The energy required to balance the "reduced energy needs" may be "generated on-site" (i.e., converted within the property site from renewable resources such as solar, wind, biofuels, hydropower),[10] or purchased off-site in the form of "Green Power" (e.g., electricity generated from renewable resources; biomass or biofuels for combustion on-site).
   - *Source* energy use, energy *costs*, and "green house gas" (GHG) *emissions* are not included in this definition.

[10] Note that for on-site generation, the thermodynamic boundary must be defined as the outer surfaces of the building enclosure so a balance with building energy use can be determined.

2. Net Zero *Source* Energy: "*A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source*."
    - Source energy generally refers to the "primary" energy resources that are converted off-site (i.e., outside the property boundary) to electricity, natural gas, fuel oil, district heating and cooling, biomass or biofuels, and delivered to the building or property site (5; 13).
    - The thermodynamic boundary for this category cannot be explicitly defined unless the specific locations of the primary energy conversion plants are known.
    - Currently, the building's *source* energy use can only be calculated; it cannot be explicitly measured and verified. Building *source* energy use is typically estimated from the on-site calculations or meter readings, multiplied by "appropriate" site-to-source conversion factors, and expressed in common *source* EUIs (e.g., MWh/GSM or KBtu/GSF) (14).[11] These calculations are likely to contain substantial uncertainties.
    - For this category, the *source* energy required to balance the "reduced energy needs" may be generated on-site or off-site from renewable resources such as solar, wind, biofuels, hydropower) for use in electrical and combustion processes on-site. However, for this balance to be evaluated, both the "reduced energy needs" and the available "renewable resources" must be expressed in terms of *source* energy.
    - Neither source energy *costs* nor GHG *emissions* are included in this definition.
3. Net Zero Energy *Costs*: "*In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year*."
    - The thermodynamic boundary for this category can be explicitly defined in the same manner as for Variation 1.
    - The annual cost of the actual building energy *demand and consumption* can be explicitly measured and verified as the annual sum of the contiguous billings from the meter readings for the depleteable and renewable resources crossing the defined boundary and converted to $/GSM (gross square meter) or $/GSF.
    - The annual billing of the renewable energy, which is to be metered and exported to the grid, must be negotiated with the utility companies. For this category, the exported renewable resources billed to the utility companies must balance the cost for the depleteable *and* renewable resources supplied to the site by the utility companies for the same period (e.g., annual).

[11] Source energy terms may also include such items as the energy used (and emissions generated) by employees commuting from their residences to their places of employment. This trade-off is an example of the Rebound Effect (11).

- The economic impacts of mixed energy *sources* and resultant GHG *emissions* may or may not be included in these calculations. Also, the first and operating costs (e.g., life-cycle costs) of the additional renewable energy systems are not typically included in this variation.

4. Net Zero Energy *Emissions*: **"***A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources*."

   - The thermodynamic boundaries for this category cannot be explicitly defined due to the same constraints as for Variation 2.
   - *Emissions* from on-site combustion processes can be measured and verified, but emissions from the combinations of fuel conversion plants and electrical generating plants that service the building from the grid, pipelines, or delivery trucks can only be estimated (13). Excluding the "imbedded energy" in products and materials within the building, annual *emissions* of GHG from the building can be estimated from the on-site energy use calculations or meter readings, by multiplying them with "appropriate" conversion factors, and by converting the results to common *emission* units (e.g., kg CO_2e/GSM or lb CO_2e/GSF) (14). These calculations are likely to contain substantial uncertainties.
   - "If an all-electric building obtains all its electricity from an off-site zero emissions source (such as hydro, nuclear, or large scale wind farms), it is already zero emissions and does not have to generate any on-site renewable energy to offset emissions. However, if the same building uses natural gas for heating, then it will need to generate and export enough emissions-free renewable energy to offset the emissions from the natural gas use. Purchasing emissions offsets from other sources would be considered an off-site zero emissions building" (2).
   - *This variation does not result in net-zero emissions*. Rather it allows a trade-off between the use of energy sources that produce GHGs and energy sources that do not. To actually result in net-zero emissions, the *source* energy required to balance the "reduced energy needs" must be generated on-site or off-site from renewable resources and processes that do not emit GHGs.

Composite Definition and Goals in EISA-2007

Definitions

EISA 2007 (3) mandates building energy reductions for federal agencies and provides initiatives to other public and private sectors for these reductions. Three synergistic definitions of particular engineering importance were promulgated in EISA-2007: 1) a "high performance building;" 2) life-cycle costing (LCC); and 3) a composite definition of a "zero-net-energy commercial building."

- Section 401(12) of EISA-2007 defines a <u>high-performance building</u> (HPB) as one that "*integrates and optimizes on a life cycle basis all major high performance attributes, including energy conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations*."[12]
- Section 401(16) defines <u>life-cycle costing</u> (LCC) as "*a technique of economic evaluation that (A) sums, over a given study period, the costs of initial investment (less resale value), replacements, operations (including energy use), and maintenance and repair of an investment decision; and (B) is expressed (i) in present value terms, in the case of a study period equivalent to the longest useful life of the building, determined by taking into consideration the typical life of such a building in the area in which the building is to be located; or (ii) in annual value terms, in the case of any other study period*."
- Section 401(22) defines a *<u>zero-net-energy commercial building</u> as a "commercial building that is designed, constructed, and operated to: (A) require a greatly reduced quantity of energy to operate; (B) meet the balance of energy needs from sources of energy that do not produce greenhouse gases; (C) therefore result in no net emissions of greenhouse gases; and (D) be economically viable."*

  This definition[13] is a composite of the four variations described above:

  - Part A is paraphrased from Torcelinni's "general definition." From an engineering perspective, the uncertainties in Part (A) include:
    - The term "greatly" is not quantitative or measurable, which leaves the energy reduction goal open to interpretation and potential risk to the designer of record.
    - The constraints imposed by the definition of an HPB (Section 401(12)) are not explicit in the requirement to reduce energy needs.[14] The absence of these constraints increases risk to occupants, owners and designers.

[12] Although not explicitly defined in this section, "health" is an implied attribute in several of the attributes including safety, security, accessibility, and environment. Also see the definition of "high-performance green building" in Section 401(13).

[13] Note that the EISA 2007 definition is for a "zero-net-energy commercial building" (ZNEB), rather than a "net-zero-energy building" (NZEB or ZEB) in Torcelinni's general definition.

[14] For example, the impacts of providing for elevated Levels of Protection on the building energy use can be significant (14).

- The "required" energy reduction is not stipulated to be in terms of *site* or *source* parameters and values.
  - ✓ Only if the energy reduction is evaluated at the site can the thermodynamic boundary of the system be explicitly defined (i.e., see analysis of Torcelinni's Variation 1).
  - ✓ However, to balance with off-site renewable energy sources, the "reduced energy needs" must be calculated in *source* energy terms, which results in substantial uncertainties (i.e., see analysis of Variation 2).

- Parts B and C eliminate any form of combustion processes.[15] From an engineering perspective, if the thermodynamic boundaries are not explicitly defined (i.e., Variation 1), results from design decisions regarding selections of systems, products, and materials to minimize energy use and GHG *emissions* will be highly uncertain.
- In Part D, the meaning of "economically viable" is vague. Neither Torcelinni's Variation 3 nor the definition of LCC in Section 401(16) is referenced in the EISA-2007 definition of ZNEB. However, the defined LCC provides an explicit method by which the design options may be evaluated for economic viability from an engineering perspective. Results from Variation 3 and LCC analysis will not be comparable. Moreover, the accuracy of the results in Part D will be significantly impacted by the uncertainties in Parts B and C.

Goals

Two sets of energy performance goals were established in EISA-2007:

1. For non-federal commercial buildings, Section 422 established *voluntary* "initiatives" to: "(A) reduce the quantity of energy consumed by commercial buildings located in the United States; and (B) achieve the development of zero-net-energy commercial buildings in the United States."

   Goals for the voluntary initiatives were not stipulated in Part (A) to be in terms of *site* or *source* energy parameters and values, but Part (B) requires compliance with all parts (i.e., A – D) in the definition of an ZNEB in 401(22); therefore the thermodynamic boundaries may be indeterminant and the estimated *source* energy balances are likely to have substantial uncertainties, which increases risks to the designers, owners, and operators. The goals were:

   - Any commercial building constructed after 2030 should function as a zero-net-energy commercial building.
   - By 2040, 50% of the commercial building stock should function as zero-net-energy commercial buildings.

[15] All combustion processes, including those that use biofuels or biomass, produce GHGs.

- By 2050, 100% of the commercial building stock should function as zero-net-energy commercial buildings.

No goals for other building performance attributes in Section 401(12) were established. Criteria for economic viability were not established (e.g., see Section 401(16)).

2. For new federal buildings and federal buildings undergoing major renovations, Section 433 mandated that buildings be designed to:
   - Reduce the “fossil fuel-generated energy consumption of the buildings” by 65% in 2015, 80% in 2020, 90% in 2025, and 100% in 2030 *when compared to the 2003 CBECS data for a similar building* (See Fig. 1).[16] These reductions were not stipulated to be in terms of *site* or *source* energy terms; therefore the thermodynamic boundaries may be indeterminant and results may contain substantial uncertainties.
   - Comply with “sustainable design principles” for the siting, design, and construction of such buildings.[17] According to the 2010 edition of the U.S. GSA P100 (15), which responded to EISA-2007, the essential principles of sustainable design and development were defined but no quantitative or measureable criteria were provided in terms of the HPB attributes identified in Section 401(12):
     - optimize site potential;
     - minimize nonrenewable energy consumption;
     - protect and conserve water;
     - use environmentally preferable products and materials;
     - enhance indoor environmental quality; and
     - optimize operations and maintenance practices.
   - Compliance with the definition of a “zero-net-energy commercial building” was not mandated for federal buildings:
     - Reductions in energy needs were not stipulated to be in terms of *site* or *source* parameters and values; however the CBECS data are only in terms of *site* energy.
     - Use of renewable energy resources to meet the balance of the reduced energy needs to control for the attributes identified in Section 201(12) was not required or restricted to those that do not produce GHGs.
     - Measures of economic viability, such as that defined in Section 401(16), were not stipulated.

[16] The CBECS energy use data in Tables C3 and C3A are in terms of *site* energy.
[17] The “sustainable design principles” were not defined in EISA 2007 (3).

ASHRAE's Modified Definition

Because of the complications involved in making the computations in all but the first variation of the Torcelinni definitions (i.e., net-zero *site* energy), ASHRAE adopted a modified version of this definition in 2008 for its 2020 Vision (4). This definition, which is nearly identical to Torcelinni's Variation 1, was endorsed in an agreement of understanding between ASHRAE, the American Institute of Architects (AIA), the U.S. Green Building Council (USGBC), and the Illuminating Engineering Society of North America (IESNA):

"A NZEB is a building that produces as much energy as it uses when measured at the site."

In its 2020 Vision, ASHRAE recognized three limitations to this definition:

- "The concept of NZEBs includes only the energy flows of the building, not the overall sustainability of the building."
- "The quality of the indoor environment must not be sacrificed in the pursuit of NZEBs."
- "While new buildings are the focus of ASHRAE's NZEB vision, existing buildings must be addressed as NZEB strategies are implemented."

Analysis

From an engineering perspective, all of these definitions have significant deficiencies:

- Although thermodynamic boundaries can be explicitly defined to calculate and measure rates of *site* energy use and corresponding green house gas (GHG) emissions from combustion processes located within the building enclosure or property site, the thermodynamic boundaries for *source* energy use or GHG emissions cannot be reliably determined unless the specific locations of the primary energy conversion plants are known.
- *Source* energy use rates are typically extrapolated from *site* energy values by applying "appropriate" site-to-source conversion factors. These extrapolations are likely to have significant uncertainties.
- If GHG emissions are to be eliminated, neither on-site nor off-site combustion processes can be used.
- Constraints, which must be imposed for compliance with the attributes that are required in the definition of a "high performance building" (3), are not explicit in the requirement to reduce energy use in any of the definitions. The absence of these constraints increases risks to occupants, owners and designers.
- Methods for calculating first, operating, and maintenance costs (e.g., life-cycle costs) are not prescribed or referenced in any of the definitions.

Operational Definition for Net-Zero Energy Office Buildings

As revealed in the previous analysis, the probability of accurately achieving compliance with these definitions is low. Therefore, an operational definition (OZEB) is introduced with which engineering principles can be applied toward cost-effectively achieving the goals of net-zero energy commercial buildings.

This operational definition is predicated on three principles: 1) the primary purpose of a building is to provide for the health, safety, and security of occupants while meeting its functional needs (e.g., enhanced learning, improved productively) (16); 2) according to the Laws of Thermodynamics, energy balances must occur across defined boundaries; and 3) use of physical and economical resources should be managed to “meet the needs and aspirations of the present without compromising the ability to meet those of the future” (1; 11):

> Operationally, a *‘‘net-zero energy commercial building’’ is a facility that is designed, constructed, and operated to simultaneously provide for the needs of the occupants, and for the functional and economic needs of the facility, through the balance between measurably effective energy needs and use of renewable resources within the defined thermodynamic boundaries.*

Compliance with this operational definition is expected to be achieved through five objectives:

1. Define attributes[18] and measureable criteria for building performance as a coherent set of parameters and values that “meets the needs and aspirations of the present without compromising the ability to meet those of the future” (1).
2. Provide for the health, safety, security, and performance of occupants by measurably effective control of the four primary indoor environmental exposures (i.e., lighting, thermal, acoustic, and air quality) (16).
3. *Reduce energy waste and consumption* at the building or property boundary by cost-effectively reducing external and internal loads of the building, and by selecting systems with the capacities and controllability to match the full and part loads imposed on the building.

> *Note that the reduction of site energy waste is not limited, but reduction of energy use is constrained by: a) the occupant exposure requirements; b) the functional and aesthetical needs of the owners and operators; and c) the economic (e.g., LCC) criteria.*

[18] See EISA-2007 definitions 401(12) and 401(16).

4. Offset the reduced energy *needs* with cost-effective renewable resources that do not emit GHGs (i.e., all combustion systems, on-site or off-site, generate GHGs).
5. Approach long-term net-zero energy management with reliable and cost effective information technology and control strategies (e.g., Building Automation Systems) that are compatible with the level of knowledge and skills of the operators.

An Engineering Approach to Fully Functional NZEB

To achieve the five objectives in the operational definition, a systemic design approach is needed. Such an approach is shown in Figure 2[19] in which Steps 2 – 7 are iterated: first, to design and evaluate a postulated baseline building and its systems for compliance with the set of performance objectives defined in Step 1; and second, to design and evaluate optional solutions that could offset the reduced energy needs and waste (i.e., including GHGs) from the baseline design.

Step 1: Define Performance Objectives

To increase design options and accountability, measurable parameters and explicit values for the set of attributes[20] should be identified, prioritized, and specified for the attributes that pertain to the project (17; 14; 18).

These performance criteria, which should be assimilated in an Owners Program Requirements manual (OPR) (14); should be established before preliminary design of the baseline system commences: and should not be changed during design, construction, or operations of the baseline or optional designs without concurrence of owners, designers, and operators.

[19] This flowchart is based on procedures described by GSA and NIBS (18; 14).

[20] Implicit values of parameters, such as "lighting power densities" (21; 19) and "ventilation rates" (29), limit flexibility in meeting the human response needs, reducing energy requirements, and improving cost-effective designs. Examples of quantitatively explicit values are: luminous criteria (e.g., luminance, contrast and glare); thermal criteria (e.g., dry-bulb, mean-radiant, and dew-point temperatures; air movement and turbulence intensity); air quality criteria (e.g., concentrations of particulates, gases, and vapors); acoustic criteria (e.g., Noise Criteria, Room Criteria, Reverberation Time).

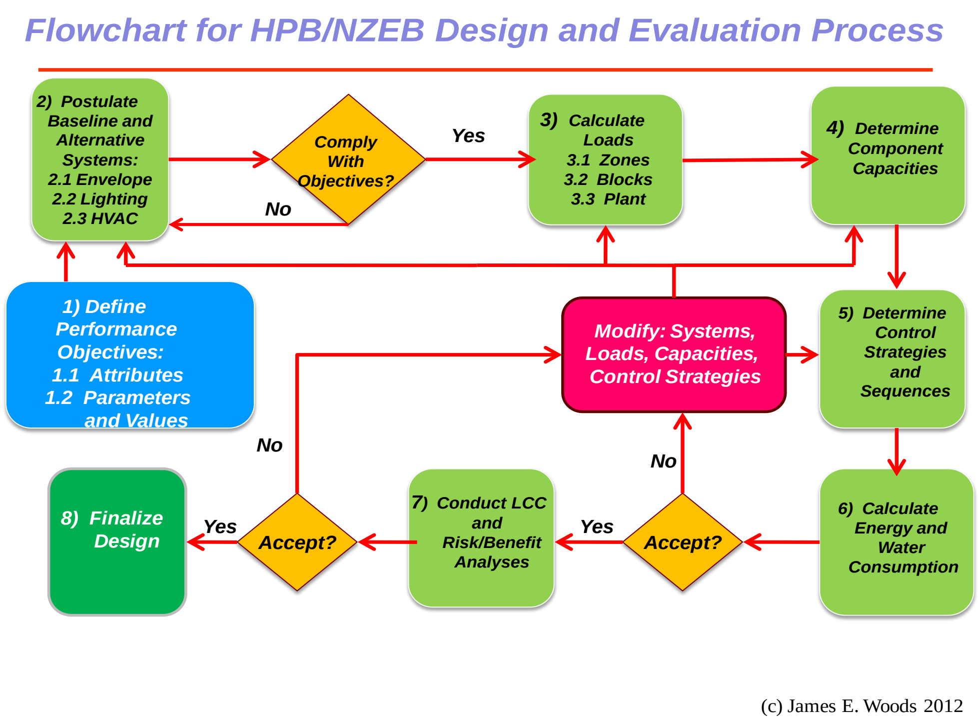

Figure 2. Flowchart for Approach to Net-Zero Energy Commercial Buildings.

Step 2: Postulate Baseline and Optional Systems

Based on the criteria derived from the OPR and relevant codes and standards (i.e., Step 1), the preliminary design of the building and its systems should be postulated and evaluated:

- For a specific site and defined functions, the orientation, shape, and size of the building should be *optimized* for performance (i.e., energy use is only one of the parameters to be considered: occupant and community responses, safety and security, maintainability, productivity, and aesthetics are others).
- As shown in Fig. 3, the characteristics of the building as a system should be determined with regard to the residual risks that are likely to be incurred at the specific location, including operations during normal conditions, and operations in preparation for, during, and recovery from extraordinary conditions (i.e., resilience) (16; 17).

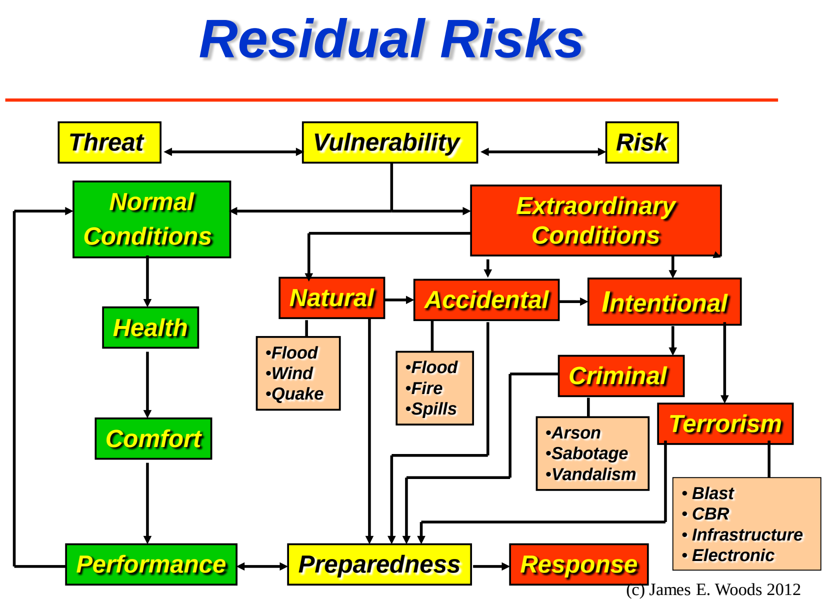

Figure 3. Residual Risks for buildings operating during normal and extraordinary conditions (16).

- Candidate MEP (i.e., mechanical, electrical, plumbing) systems should then be postulated. As shown in Fig. 4, these systems may be categorized as three subsystems that have different impacts on loads (e.g., thermal, lighting, air quality, and acoustic loads), component selections, energy conversion pathways, and controllability:

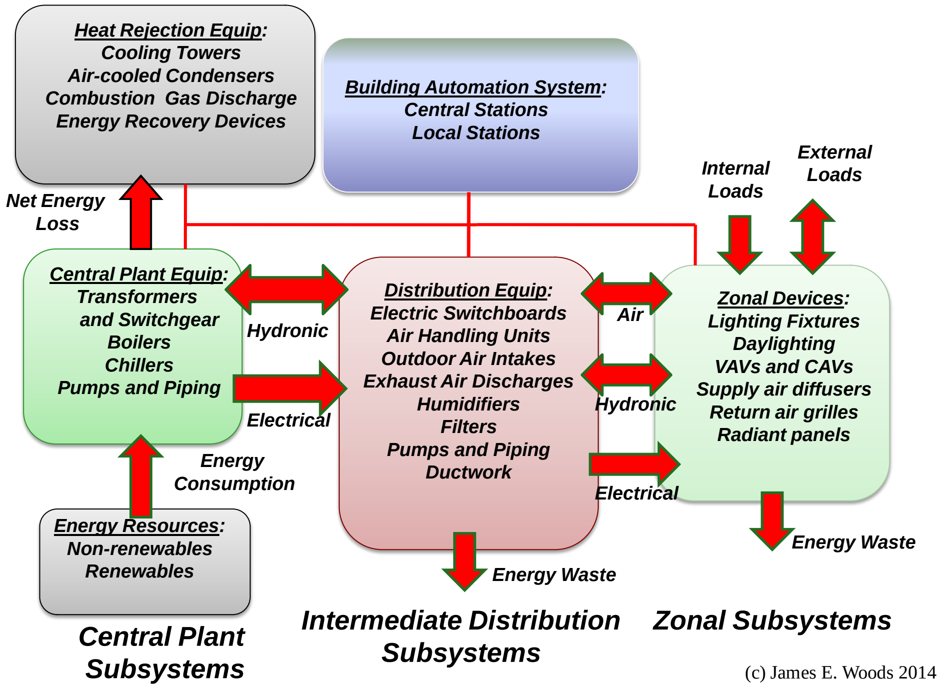

Figure 4. Building system components, loads, and energy conversion pathways for high performance (e.g., net-zero energy) commercial buildings.

- Lighting and power systems should be postulated for:
  - Interactive effectiveness of daylighting and electric lighting components on occupant exposures in the perimeter and interiors zones;
  - Conversion and distribution effectiveness of electrical power in the central, intermediate and zonal subsystems, including transformers, switchgear, and emergency and standby systems, and branch distribution circuits.
- Plumbing systems should be postulated for:
  - Storage and distribution effectiveness for hot and cold water supply to central, intermediate, and zonal subsystems;
  - Effectiveness of sanitary waste and discharge from all three subsystems;
  - Effectiveness of storm water collection, reuse, and discharge in the intermediate and central subsystems.
- HVAC systems should be postulated for:
  - Effectiveness of hydronic and forced air heating and cooling (i.e., radiant and convective heat transfer) on occupant exposures within spaces and zones;

  - Effectiveness of hydronic and forced air distribution (ducting and piping) to and from spaces and zones;
  - Ventilation effectiveness by dilution and filtration through air handling units (e.g., Dedicated Outside Air Ventilation Systems - DOAVS, filter efficiencies, air exchange rates, pressurization control) on occupant exposures within spaces and zones;
  - Size and location effectiveness of air handling units (DOAVS, VAV[21], heat pumps, hydronic zoning systems, supply and exhaust air fans, pumps, and motors) to provide tempered, noise attenuated, and cleaned air for control of occupant exposures within spaces and zones;
  - Size and location effectiveness of central plant equipment (boilers, combustion gas discharges, chillers, cooling towers and air cooled condensers, ground-source-heat-pumps, heat recovery devices, pumps and piping) to provide thermally controlled water to and from distributed AHU and hydronically zoned systems.
- Building Automation Systems should be postulated based on the availability and the training of personnel who are to operate and maintain the systems, including:
  - Sensing, monitoring and control effectiveness of indoor exposure conditions and alarms;
  - Monitoring and interface effectiveness with fire, life-safety, and security systems;
  - Monitoring and control effectiveness for energy use and operational costs at zonal, intermediate, central, and whole building thermodynamic boundaries;
  - Monitoring and control effectiveness on renewable energy production and delivery to the building boundary and to the grid.

Step 2A: Evaluation of Postulated Design Compliance

If the design concept complies with the evaluation criteria in Step 1, proceed to Step 3; else modify the postulated systems and repeat Step 2.

Step 3: Calculate Peak, Block, and Plant Loads (thermal, lighting, acoustic, air quality)

After compliance with Step 2A, the thermal, lighting, acoustic, and air quality loads associated with the postulated systems should be determined. These loads are generally characterized as “external loads,” which are imposed by forces outside of the thermodynamic boundary of the building, and “internal loads,” which are imposed by people and processes within the thermodynamic boundary (see Fig. 4). The accuracy of these load calculations will significantly influence the selection of the system capacities, controllability, and building energy use, and ultimately, the likelihood of success in achieving a net-zero energy building (14).

[21] Variable Air Volume terminal units.

Types of Loads

As shown in Figs. 3 and 4, external and internal loads are imposed on building subsystems during "*normal conditions*," which will occur during more than 90 – 95% of the lifetime of the building, and during "*extraordinary conditions*," which occur much less frequently but with stronger forcing functions (14).

- Normal loads.
  - *External loads* on a building should be calculated as a function of variations due to the season, time of day, local weather, community activities, and air and noise pollution conditions. The forces that influence normal loads on the building enclosure include:
    - Outdoor and indoor dry-bulb and dew-point temperatures, wind, rain and snow, solar and daylight, external contaminant or pollutant emissions, and external noise generation; and
    - The physical characteristics of the envelope including structural and thermal mass, sizes and locations of fenestrations, types of thermal and acoustic insulation, air leakage rates, and chemical outgassing characteristics (14; 19).

    These forces and characteristics may act on the building enclosure, independently or interactively, to cause dynamic changes in the external loads.
  - *Internal loads* in a building should be calculated as a function of the occupancy density, activities within the facility (e.g., lighting, air quality, acoustics and thermal needs for educational and office functions), and location within the building (i.e., perimeter and interior zones). In perimeter zones, stronger interactions and more variations will occur between the external and internal loads than in the interior zones.
- Extraordinary loads. The additional external and internal loads should be calculated based on the residual risks imposed by the expected frequencies and magnitudes of occurrence of natural, accidental, or intentional forces as shown in Fig. 3 (17; 14):
  - Sources of external loads to the building boundary include floods, fires, quakes, blasts, and CBR (i.e., chemical, biological, radiological) emissions or releases.
  - Sources of internal loads within the building boundary also include floods, fires, spills, blast and CBR emissions or releases. Loads from these sources may be intensified or isolated within a zonal subsystem, or may be distributed through the other subsystems as shown in Fig. 4.

Magnitude of Loads

Before the capacities and control strategies of the MEP equipment can be selected to meet the objectives defined in Step 1, the magnitude, diversity, and variability of the normal and extraordinary loads must be calculated. To more accurately determine system capacities and controllability, these loads are typically considered as "peak," "block," "plant," and "part" loads.

- Peak loads. Normal and extraordinary loads in individual spaces or zones (i.e., zonal subsystems in Fig. 4) have direct impact on the health, safety and security of occupants and the performance of functional activities. *Therefore, rapid and effective responses are required to the "peak" loads imposed on these spaces*.
  - Perimeter spaces or zones are likely to have higher magnitudes of peak loads than interior spaces or zones during both normal and extraordinary conditions, unless special care is taken to reduce the effects of the envelope (e.g., thermal and acoustic insulation, fenestration and shading treatments, air tightness) (17; 14).[22]
  - The magnitudes of the peak loads are typically used as the basis for selecting the capacities of the controlled (i.e., terminal) devices (e.g., supply air diffusers, VAV units, fan-coil units, radiant ceilings or floors) that will be used to dissipate the loads from these individual spaces or zones.
- Block and plant loads. The peak loads from sets of individual spaces or zones will be transferred to intermediate distribution subsystems where the loads will be dissipated by heat exchangers, noise attenuators, air cleaning devices, and air exchangers (Fig. 4). These sets of loads are known as "block loads." Likewise, all of the block loads will be transferred to the central plant subsystem where they will be dissipated by the primary heat transfer equipment (e.g., boilers, chillers) (Fig. 4). These loads are known as "plant loads."
  - Because all of the individual peak loads and block loads will not occur simultaneously, the loads in the intermediate zones and central plant are typically less than the sums of the peak and block loads, respectively. The block and plant loads are calculated by applying *diversity factors*, which are usually determined by engineering judgment.
  - When block and plant loads are calculated by software programs, "default" values for the diversity factors may be applied that are counter-productive to an engineering approach toward fully functional NZEBs.
- Part loads. Peak loads are likely to occur less than 10% of the annual operational hours of a commercial (e.g., office or educational) facility. Therefore, for substantial periods of normal operations, the peak, block and plant loads will be less than those used to select the capacities of the subsystems. These reduced loads are typically known as "part loads."
  - In individual spaces or zones, part loads will vary from the peaks to some minimum values depending on scheduled and unscheduled changes to both the envelope and internal loads.
  - Corresponding changes, including diversities, will also occur to the block and central plant loads.

[22] The means and methods of reducing these loads can be synergistic. For example, increasing air tightness of the envelope can also result in reduced thermal, air quality and acoustic loads.

- Thus, part load calculations are needed to:
  - *Establish control strategies that minimize energy* *waste*,
  - *D*esign the control and building automation system; and
  - *S*pecify the performance characteristics of the controllers and controlled devices (e.g., valves, dampers, motors) to accommodate changes and rates of change in normal and extraordinary loads.

Step 4: Determine System Capacities for Peak, Block and Plant Loads

After completion of Step 3, the capacities and locations of the MEP equipment, which were postulated in Step 2, should be selected to match the calculated peak, block and plant loads, and their rates of change, for normal and extraordinary conditions. If the capacities are selected to meet only the magnitude of the peak loads or their rates of change, oversizing is likely, which can result in excess energy use and waste.

Step 5: Determine Control Strategies and Sequences of Operations

After completion of Step 4, the control strategies and sequence of operations of the building automation system should be designed to achieve the objectives in Steps 1 and 2 for normal and extraordinary conditions:

- A primary control objective should be to provide the same quality of control during all part-load conditions as the capacities can provide during the "full load" (i.e., peak, block, and plant load) conditions.
- The sensors, controllers, and controlled devices should be selected to be sufficiently responsive to the rates of change of the loads so that the objectives in Step 1 are maintained during normal conditions and during preparation and recovery periods (i.e., resiliency) for extraordinary conditions (14).
- For an engineering approach toward a fully functional NZEB, another primary control objective should be to manage the balances of peak, block and plant loads to minimize the waste, power, and energy to maintain the objectives in Step 1 during normal and extraordinary conditions.
- To achieve these control objectives, the design should accommodate long-term net-zero energy management through reliable and cost effective information technology and control strategies (e.g., Building Automation Systems) that are compatible with the level of knowledge and skills of the operators.

Step 6: Calculate the Expected Energy Use

After completion of Step 5, an estimate of the resultant on-site energy needs should be prepared, using a calibrated simulation program that is computer-based and developed for energy analyses in buildings.[23]

- The simulation should include:
  - 8,760 contiguous hours of operation including loads, operational schedules, and control strategies for normal conditions; and for preparation times, test periods of emergency operations, and recovery periods for extraordinary conditions.
  - Actual parameters and values defined in Steps 1 - 5; not values based on defaults assigned by the simulation program.
  - *All* energy-consuming components, assemblies, and subsystems (i.e., fixed or moveable) within the thermodynamic boundary of the building or property.[24]
- Results should include:
  - Calculated needs in terms of *site* energy, MWh or kBtu, and normalized as EUI (MWh/GSM or kBtu/GSF) for the whole building and for each fuel type available on site, including electrical.
  - A statement of the expected errors or uncertainties in the *site* energy analysis.
  - A means to meter or measure, and validate the *site* energy consumption after occupancy, at the same thermodynamic boundaries that were used for the simulations.
- Results may also include:
  - Calculated needs in terms of *source* energy for each fuel type and for the whole building (MWh, kBtu, and EUI), based on the calculated *site* energy values, and the conversion factors stated in the OPR (Step 1).
  - Calculated annual *emissions* of GHG for the whole building and for each type of fuel to be used in the facility, based on *site* energy consumption calculations, and the conversion factors stated in the OPR.
  - A statement of the expected errors or uncertainties in the *source* energy and GHG *emission* analyses.

[23] See GSA P100-2010 (18), Section 5.4 and Appendix A-6 for additional guidance.

[24] It should be noted that some reports of expected energy needs have only included "regulated" loads such as lighting and building enclosures, but not "unregulated" loads such as fixed equipment loads (e.g., computers, electrical processing appliances). These results typically under-estimate actual needs.

Step 6A: Evaluation of Energy Need Compliance

If the energy calculations for the postulated system comply with the objectives in Step 1, proceed to Step 7; else modify the postulated systems, loads, capacities, or controls by repeating Steps 5, 4, 3, or 2, as needed; then repeat Step 6.

Step 7: Calculate the Expected Costs

After compliance with Step 6A is achieved, estimates of first-costs, operational costs, or life-cycle costs should be calculated, using a method specified in Step 1 such as Torcelinni's Variation 3; EISA-2007, Paragraph 401(16); or other recognized methods (14; 17; 18).

Step 7A: Evaluation of Cost Compliance

If the cost calculations comply with the objectives in Step 1, proceed to Step 7B; else modify the postulated systems, loads, capacities, or controls by repeating Steps 5, 4, 3, or 2, as needed; then repeat Steps 6 and 7.

Step 7B: Optional Systems for Net-Zero Energy Performance

If renewable energy subsystems are to be considered in approaching net-zero energy for the building, proceed to iterations of Steps 2 – 7; else, finalize the design (Step 8).

- In Step 2, renewable energy subsystems to offset the energy needs estimated in Step 6 may be selected from those that: 1) either do or do not result in the production of GHGs; and 2) can be provided on-site, off-site, or both.
    - On-site options have thermodynamic boundaries defined by the building enclosure. These options do not depend on an electrical grid and can provide independent power for the building. However, the sizes, capacities, and storage provisions of the optional renewable energy subsystems in the central plant (see Fig. 4) may be larger than off-site options needed to offset the estimated baseline annual energy needs (2).
        - For options that are "off the grid," emergency electrical and thermal power for extraordinary conditions (see Fig. 3) may have to be produced by on-site generators, which use fossil or biofuels that produce GHGs, especially for those buildings that are at elevated Levels of Protection (14).
        - On-site options that do not produce GHGs may be limited to:
            - ✓ Photovoltaic or solar-thermal arrays placed on the building enclosure or elsewhere on the site to generate electrical power, or to heat air or water for distribution within the building.
            - ✓ Wind turbines placed on the building enclosure or elsewhere on the site to generate electrical power for distribution within the building.
    - Off-site options may not have well-defined thermodynamic boundaries. These options:

- Generally depend on an electrical grid, which may or may not distribute power exclusively from renewable resources that do not produce GHGs.
- Do not provide independent power for the building, but do allow excess electrical power that has been generated on-site to be distributed to the grid.

Off-site options that do not produce GHGs include "Green Electrical Grids" that exclusively distribute power generated by non-combustion processes such as hydro-power, wind farms, solar farms, and geothermal power.

- Emergency and standby power for extraordinary conditions (see Fig. 3) may be produced by on-site or off-site generators supplied by renewable energy sources (e.g., bio-fuels) that produce GHGs (14).

- In Step 3, the peak, block, plant, and part loads should be re-evaluated with regard to effects that might be caused by the locations and sizes of the on-site renewable energy subsystems (e.g., roof-top placement of PV or solar-thermal arrays).
- In Step 4, the capacities of the renewable energy subsystems should be selected with regard to the percentage of peak, block, plant and part loads that can be cost-effectively offset, with and without the production of GHGs. Resiliency and redundancy of the optional equipment capacities must be considered, especially for those facilities that require higher Levels of Protection (14).
- In Step 5, the control strategies and sequences of operations should be re-designed to manage the balance of peak, block and plant loads to minimize the waste, power and energy used by the baseline and renewable energy resources to maintain the objectives in Step 1 during normal conditions; and to effectively switch to various sources of power in preparation for and recovery from extraordinary conditions.
- In Step 6, an estimate of the resultant *on-site net-energy* balances should be determined, using a calibrated simulation program, which is computer-based and developed for energy analysis in buildings.
  - In addition to the items described for the baseline analysis, the simulation should include:
    - Calibrated or validated modules for simulation of the optional renewable energy components, assemblies and subsystems.
    - Actual parameters and values redefined in Steps 1 – 5, including those for the optional renewable energy subsystems; not values based on defaults assigned by the simulation program.
    - *All* renewable energy-producing components, assemblies, and subsystems (i.e., fixed or moveable) within the thermodynamic boundary of the building or property.
  - Results should include:

- Calculated annual *renewable energy production* in terms of *site* energy, MWh or kBtu, and normalized as EUI (MWh/GSM or kBtu/GSF) for each fuel type available on site, including electrical, and for the whole building.
- Calculated *percentages of annual energy needs* in terms of *site* energy expected to be provided by the renewable resources for replacement of each depleteable energy source and for the whole building (i.e., energy balances).
- A statement of the expected errors or uncertainties in the *site energy balances.*
- A means to meter or measure, and validate the *site energy balances* after occupancy, at the same thermodynamic boundaries that were used for the simulations.

o Results may also include:

- Calculated *annual renewable energy production* in terms of *source* energy for each fuel type (MWh or kBtu) and for the whole building (MWh, kBtu, and EUI), based on the calculated *site* energy values, and the conversion factors stated in the OPR (Step 1).
- Calculated *percentages of annual energy needs* in terms of *source* energy expected to be provided by the renewable resources for replacement of each depleteable energy source and for the whole building (i.e., energy balances).
- Calculated annual *net emissions* of GHG for each type of fuel consumed, based on *site* energy consumption calculations, and the conversion factors stated in the OPR.
- A statement of the expected errors or uncertainties in the *source* energy and GHG emission balances.

- In Step 7, estimates of first-costs, operational costs, or life-cycle costs should be *recalculated*, using the same method as for the baseline analysis.
  - o If the results are acceptable and comply with the objectives in Step 1, proceed to Step 8; else modify the postulated systems, loads, capacities, or controls by repeating Steps 5, 4, 3, or 2, as needed; then repeat Steps 6 and 7.

Examples and Analysis of Performance Outcomes

Although the concepts of NZEB have been promulgated for nearly a decade, measured performance data are scarce. For this analysis, examples from two functional categories of "commercial buildings" (i.e., educational facilities and office buildings) were selected as they represent nearly one third of the commercial building stock in the US, and affect the well-being and productivity of a large population in public facilities. Based on available information in the literature, examples of baseline data, from which site-specific values of reduced energy needs in an NZEB design might be compared, are shown in Table 1 from simulations and from verified field data; in Table 2, targets from simulations are summarized for achieving fully functional NZEB; and in Table 3, performance data from a sample of occupied facilities, which reportedly have approached or exceeded NZEB, are summarized and analyzed.

Baseline Data

Table 1 summarizes reported values of *site* EUIs from three sets of simulation data and two sets of measured data.

- The first set is from the 2003 CBECS report that extrapolates values from a sample of 0.01% of the population of commercial buildings (8; 9). For office buildings and educational facilities in the US:
  - The sizes of both types of buildings ranged from approximately 1,000 to over 500,000 GSF. Both the median and mean sizes for educational facilities were larger than for office buildings.
  - The average GEIs for offices and educational facilities were reported as 93 and 83 kBtu/GSF, respectively. Within the 95 % confidence intervals (CI), the difference in these GEIs is not statistically significant.
  - The thermodynamic boundaries for these "sites" are indeterminant, as the GEIs are for groups of buildings, which only provide a "pooled value" as a statistical reference with which the EUI of a specific building can be compared.
  - Compliance with the attributes that define a "high performance building" (3) has not been addressed in the reported GEIs. The absence of these this information increases risks to occupants, owners and designers who may use the GEIs as baselines.

Table 1. Baseline Energy Use for Educational Facilities and Office Buildings

Source of Data	Reference	Building Size (kGSF)	Site EUI (kBtu/GSF)	GHG emissions (lbs CO_2e/GSF)	Comments
CBECS (2003)	(8)	Office: Mean = 14.8 Median = 4.0 Educational: Mean = 25.6 Median = 7.0 Range for Office and Educational: 1 - >500	Office: Mean = 93 95% CI = 83-103 Educational: Mean = 83 95% CI = 69-97		o Site EUI is reported as Gross Energy Intensity (GEI) o See CBECS Tables A1 and C3A. o Estimates of Source GEIs, or GHG emissions, were not reported. o The impacts of other attributes were not reported.
ASHRAE 90.1-2004 (Office)	(14)	<20 - >100	46 – 70	9 – 25	o Site EUIs based on computer

Source of Data	Reference	Building Size (kGSF)	Site EUI (kBtu/GSF)	GHG emissions (lbs CO_2e/GSF)	Comments
ASHRAE 90.1-2010 (Office)			31 – 43	6 – 15	simulations. o Source EUIs were not reported. o GHG emissions estimated by NIBS (14). o Ranges account for climatic locations.
Five "Non-federal" Office Buildings	(9)	53 – 189	41 – 79		o Initial occupancy: 2003-2005. o Occupant response, exposure data, and system performance data were obtained. o Buildings were at various Levels of Protection. o EUIs verified in 2009.
Four US Courthouses		246 – 492	54 – 82		• Initial occupancy: 2003-2007. • Buildings were at elevated Levels of Protection. • Occupant response, exposure data, and system performance data were obtained. • EUIs verified in 2009.

- The second and third sets are based on simulations of two modeled office buildings (one at 5,000 GSF and one at 53,000 GSF) that were evaluated for several climatic zones (14). Results indicate that:
  - Only those attributes that directly impacted energy use, such as thermal and lighting characteristics, were addressed in these models. The Level of Protection was constrained to baseline (i.e., no elevated Levels of Protection). The lack of constraints on the attributes increases risks to occupants, owners and designers who may use these EUIs as baselines.
  - The thermodynamic boundaries for these simulations were defined as the building enclosures.

- EUIs that complied with ASHRAE Standard 90.1-2004 were 25 – 50% below the 2003 CBECS average and approached the 1974 BEPS target of 55 kBtu/GSF (see Fig. 1).
- EUIs that complied with ASHRAE Standard 90.1-2010 were 23 – 45% below the 90.1-2004 values, 54 – 67% below the 2003 CBECS average; and lower than the BEPS target.
- GHG emissions were calculated from the *site* EUI estimates, the mix of fuel types in the modeled systems, and standardized conversion factors recommended by the US EPA (14). Results indicate that compliance with ASHRAE Standard 90.1-2010 could reduce the emissions by 33 – 40% compared with the 90.1-2004 compliance.

- The fourth and fifth sets are from occupied office buildings in which parameters and values for human response, system performance, and energy use were measured, validated, and analyzed (9). Results indicated that:
  - Construction or renovation was completed between 2003 and 2007.
  - The thermodynamic boundaries were defined as the building enclosures.
  - All five of the non-federal office buildings and three of the four US Courthouses had LEED™ ratings of Gold or Platinum.
  - All four of the US Courthouses were designed for elevated Levels of Protection.
  - The occupancy densities were low, ranging from 400 to 1782 GSF/person during the periods of measurement.[25]
  - EUIs for non-federal buildings were similar to the values from the models that were simulated for compliance with ASHRAE 90.1-2004, but higher than for 90.1-2010 values. EUIs for US Courthouses were 4 – 32% higher than for non-federal buildings.
  - GHG emissions were not calculated for any of these nine office buildings.
  - The measure of "overall acceptability" by occupants within the facilities ranged from 56 – 91% for the US Courthouses and from 61 – 83% for the non-federal buildings.[26]
    - The importance of this finding is that reducing energy usage may be counter-productive, if care is not taken in also achieving acceptability of the other performance attributes.
    - To address this issue, the term "Acceptability Index Value" (AIV) was introduced as a "gateway." If the AIV is achieved, other similar "figures of merit," such as for occupant performance or productivity, can be subsequently evaluated (9).

      As shown in Fig.5, the AIV is the ratio of the EUI to the Acceptability Percentage. AIVs above the thresholds (e.g., 55,000 Btu/GSF divided by 80% = 687) are an indication that

[25] The occupancy densities for occupied spaces in office buildings are typically designed for a range of 20 – 200 GSF/person (29).
[26] The goal for overall acceptability is 80% in most voluntary consensus standards.

further effort is needed to improve the system performance. Note that only one of the seven cases shown in Fig. 5 had overall and specific AIVs below the thresholds.

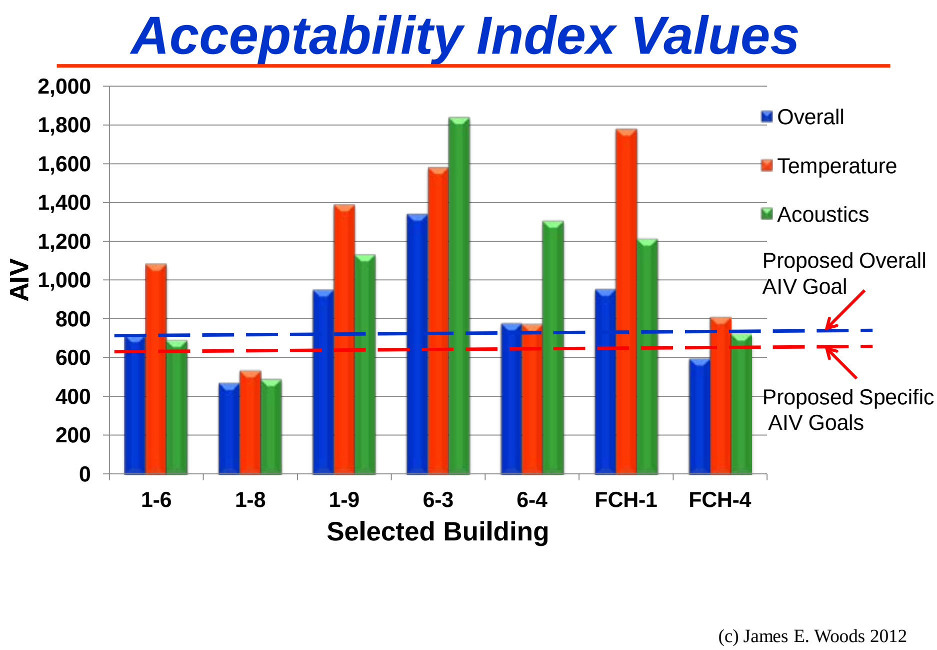

Figure 5. The Acceptability Index Value is the ratio of EUI to occupant acceptability. The goal is to achieve AIVs below the thresholds. (9).

Targets for Reduced Energy Needs:

Table 2 summarizes three sets of targets and timelines for reductions in energy needs and the corresponding consumption rates of depleteable energy resources.

Table 2. Targets for site EUIs (kBtu/GSF) and GHG emissions (lb CO_2e/GSF) from fossil fuels.

Source of Data		Date of Intended Compliance for site-EUI (kBtu/GSF)					
		2015	2020	2025	2030	2040	2050
(3)	Federal Buildings	32.5	18.6	9.3	Zero		
	Non-Federal Buildings (including educational facilities)				Zero for all new construction	Zero for 50% of all building stock	Zero for 100% of all building stock
(15)	All building owned or leased by GSA	31 – 47, depending on climatic zone, or					

		ASHRAE 90.1-2010 if lower						
High Performance Office Buildings (14)	Date of Intended Compliance not specified							
Measure	Site annual EUI (kBtu/GSF) and percentages from renewables at base Level of Protection				Site annual GHG emissions (lb CO_2e/GSF) and percentages from renewables at base Level of Protection			
Performance Classification	Base	Improved (P+)	Enhanced (P++)	HPB (ZEB)	Base	Improved (P+)	Enhanced (P++)	HPB (ZEB)
Values without solar assist	46 – 70	31 - 43	22 - 31	20 - 29	9 – 25	6 – 15	4 – 11	3 – 10
Percents of EUIs to be produced by solar assisted processes that do not produce GHGs (%)	43 – 65%	46 – 65%	48 – 68%	100%	43 – 65%	46 – 65%	48 – 68%	100%

- The first set of values is for compliance with EISA-2007. The values of site-EUIs are shown in terms of annual consumption rates of depleteable energy resources.
    - The values shown for federal buildings represent the results of the required reductions as compared to the average EUI for office buildings in the 2003 CBECS database (see Table 1).
    - The difference between the values shown and the EUI needed for the federal or non-federal building to fully perform (i.e., design intent) is expected to be provided by renewable resources.
    - No goals for other building performance attributes in Section 401(12) of EISA 2007 were established. Criteria for economic viability were not established (i.e., see Section 401(16)).
    - Federal buildings are not required to comply with the definition of ZNEB (i.e., see Section 401(22).
    - Incentives and grants to comply with the energy reduction goals are provided for non-federal buildings such as Healthy High Performance Schools (Subtitle E) and Institutional Facilities (Subtitle F) of EISA-2007.
- The second set of values is for compliance with P100-2010, which pertains to "commercial buildings" owned or leased by the Federal Government.
    - P100-2010 also requires compliance with the specific criteria for the other performance attributes in Section 401(12) of EISA 2007.
    - The only target provided was for 2015; these EUI values are similar to those shown in Table 1 for compliance with ASHRAE Standard 90.1-2010, and can be from depleteable resources.

- The third set of values proposes target values for EUIs, corresponding GHG emission rates, and percentages of EUIs that might be cost-effectively provided by solar assisted processes that do not produce GHGs for four levels of energy performance in office buildings, if constrained to the base Level of Protection (14).[27] This set does not propose target dates for compliance.
  - The four levels of energy performance and values for EUIs without solar assist were defined as:
    - Base = ASHRAE 90.1-2004
    - P+ = 30% below 90.1-2004
    - P++ 50% below 90.1-2004
    - High (ZEB) 60% below 90.1-2004.
  - The percentages for solar assist were assumed to provide:
    - Electrical capacity for external and internal lighting, and fixed and plug loads for Base, P+, and P++ performance.
    - All of the energy capacity for High (ZEB) performance.
- AIV thresholds, shown in Fig. 5, would have to be decreased to achieve the EUIs in Table 2 and the Acceptability criteria for NZEB (e.g., new threshold = 20,000/80 = 250).

Expected Energy Balances within Buildings

The amount of energy used within a building is primarily determined by two factors: 1) the types and magnitudes of external and internal loads (see Step 3); and 2) the quality of the system capacities and control strategies (see Steps 4 and 5). As an example, Fig. 6 demonstrates how energy resources, which are provided at the building's thermodynamic boundary (i.e., *site* EUI), are likely to be disseminated to end-uses and balanced within office buildings of 5,000 – 50,000 GSF that do not require elevated Levels of Protection or special treatments for control of other attributes. These values have been derived from the simulations for the *base* and three *benchmark* targets shown in Table 2 (14). The ranges of these values reflect the impact of the six climate zones that were modeled for each target.

[27] As the Levels of Protection increase, the EUIs are also likely to increase. No other performance attributes were constrained in the report (14).

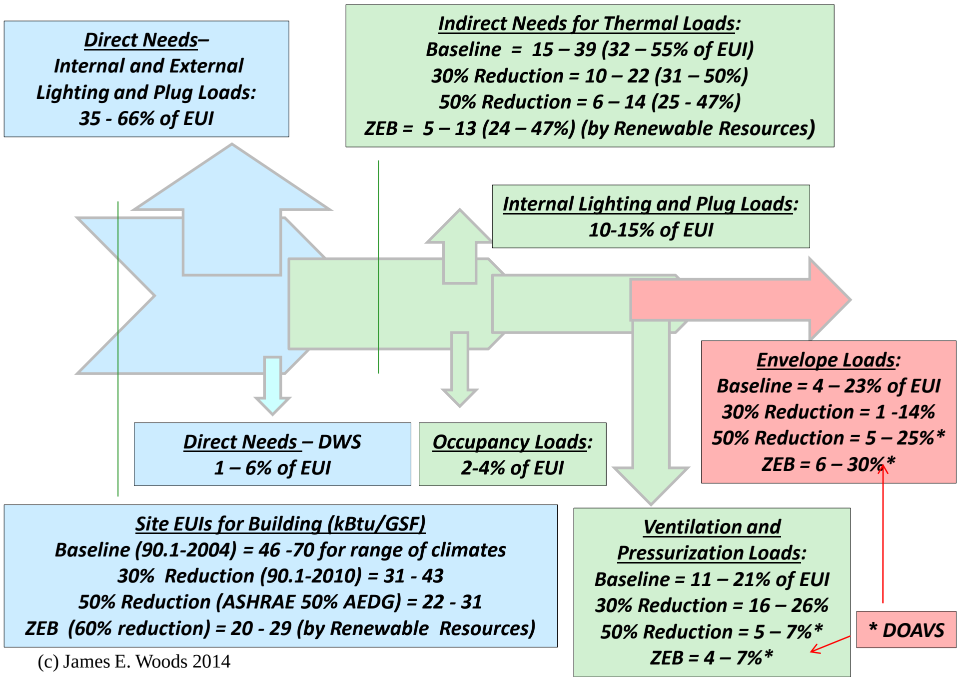

Figure 6. Expected Energy Balances for Various Types and Magnitudes of Loads within Office Buildings at base Level of Protection (14).

Site EUIs at Building Boundary

The ranges of site EUIs are for the targets in Table 2 without solar assist, except for the HPB (ZEB) case where the EUIs are to be provided from renewable resources that may or may not produce GHGs. The site EUIs bifurcate within the building into *direct needs,* and *indirect needs* .

Direct Needs

Electrical power is used directly for external and internal lighting and for all fixed and plug loads. Fuels are also used directly for processes such as domestic hot water, and emergency and standby electrical generators:

- Direct electrical needs are expected to require 35 – 66% of the site EUI, depending on the climate zones and the selected target EUI:
  - At the base target: 43 – 65%;
  - At P+: 47 – 66%;
  - At P++ and HP (ZEB): 35 – 50%.
- Direct fuel needs are expected to require 1 – 6% of the site EUI.

Indirect Needs

The indirect energy needs, shown in Fig. 6, are for dissipation of thermal loads, including those from the lighting, other electrical loads, and processes. The indirect energy needs are expected to require 24 – 55% of the site EUI, depending on the climate zones and the selected target EUI:

- Dissipation of internal loads:
  - Lighting and other electrical loads: 10 – 15% of the EUI;
  - Occupancy loads from employees and visitors: 2 – 4%.
- Dissipation of external loads:
  - Ventilation and pressurization loads: 4 – 26% of the EUI;
  - Envelope load, including opaque and fenestration areas: 1 – 30%.

Achieving Balance toward NZEB

As shown in Fig. 6, the energy needs within the building are expected to bifurcate into two approximately equal components: direct needs and indirect needs. Therefore, an important design objective in achieving balance while reducing the EUI is to reduce the direct component without compromising the performance of the building to cost-effectively provide for the health, safety, security, functionality and other attributes (see Steps 1 and 2 in Fig. 2, and Fig. 5). As revealed in Fig.6, substantial constraints must be applied to the potential reductions in the direct component to provide for the health, safety, and security of the occupants, especially for a NZEB design.

Further reductions in the EUI must therefore come from reductions and balances in the thermal loads and energy waste (see Steps 3 – 5 in Fig. 2, and Fig. 4). As shown in Fig. 6, dissipation of internal loads typically accounts for less of the EUI percentage than does dissipation of external loads. The two main components of the external load are: 1) the heat transmission through the opaque and fenestration areas of the enclosure; and 2) the thermal loads imposed by the ventilation rates needed for air quality and pressurization control. By using DOAVS with heat recovery, it is feasible to safely reduce the thermal load for ventilation while relaxing the thermal load through the enclosure, thus achieving balance between these components while reducing the EUI.

Reducing energy waste is the third objective in reducing the EUI while meeting the criteria established in Step 1. Waste and inefficiencies in HVAC systems have been estimated to account for approximately 30% of the energy use in office buildings (20). This waste is primarily in inefficiencies in motors, fans, duct losses, and control strategies. Reduction in this waste component can be achieved through design, but also through operations and maintenance.

Examples of Measured Energy Performance Data reported to Approach or Exceed NZEB

Within the last decade, few cases of NZEB educational facilities and offices with measured performance data have been reported. Table 3 summarizes measured data, which have been published on 17 examples of occupied facilities that approached the expected energy performance of NZEBs.

- The sizes of the selected examples ranged from 13 – 251 kGSF for the five educational facilities, and from 3.6 – 222 kGSF for office buildings. These ranges compare to mean sizes of 25.6 kGSF for educational facilities, and 14.8 kGSF for offices (see Table 1).
- Eleven of the 17 buildings were occupied after the DOE definitions of NZEB were published in 2005 (2); nine after the EISA-2007 definition of ZNEB was promulgated (3); and four after ASHRAE 90.1-2010 was promulgated (21).
- Five educational facilities and seven office buildings reportedly received LEED™ Certifications; and one educational facility and four office buildings received certifications as Zero Energy Buildings.
- The site EUIs ranged from 10 – 35 kBtu/GSF for educational facilities, and from 15 – 40 kBtu/GSF for office buildings. Six of these buildings complied with the P100-2010 target and the NIBS P+ target without solar assist (see Table 2); three complied with P++; and eight complied with the HPB (ZEB) target.
- All of the buildings had solar assist (i.e., PV) systems. Thirteen produced more than 30% of the whole building EUIs. Of these, nine reportedly produced more than 100% of the energy needs, which surpassed the NIBS HPB/NZEB target (see Table 2).
- The first costs for the new office buildings ranged from $89/GSF – $944/GSF, and for renovations from $95/GSF - $322/GSF; first costs for new educational facilities ranged from $196/GSF - $389/GSF (no renovation projects were found in the review). The cost effectiveness of these systems (e.g., Life-Cycle-Costs) was not reported.

Table 3. Example Cases of Net-Zero Energy Office Buildings, with actual data, from US DOE Building Database (22).

Case	Occupancy Date	Size (kGSF)	Rating	Site EUI (kBtu/GSF)	% EUI from on-site solar assist (PV) - without GHG emissions	First Cost ($/GSF)	Comments
Department of Environmental Protection, New, Office, Cambria, PA	2000	36	LEED Gold	40.1	4	89	Ref (22)
Lewis Center (higher education) Oberlin College, OH	2000	13.6	Green Building Challenge in 2000, (ZEB)*	32	112	357*	Ref (23) *Ref (22)
Woods Hole Research Center, 62% Renovated and 38% New, Falmouth MA	2003	19.2	Not Rated	16	34	322	Ref (22)
Alberici Corp., Office Corporate, Renovation, Overland KS	2004	109	LEED Platinum, 4 Green Globes	34	9.3	184	Ref (22)
Hawaii Gateway Energy Center, New, Office, Kailua-Kona, HI	2005	3.6	LEED Platinum, (ZEB)	27.7	112	944	Ref (22)
Whitman-Hanson School (K-12 –Whitman MA)	2005	251	CHPS – 35 pts	35.4*	2.4**	196***	Ref: (22) *Annual energy used (34.2)+0.841 = 35.4 kBtu/GSF **Reported PV production = 0.841 kBtu/GSF ***Derived from data on

Case	Occupancy Date	Size (kGSF)	Rating	Site EUI (kBtu/GSF)	% EUI from on-site solar assist (PV) - without GHG emissions	First Cost ($/GSF)	Comments
							the website
Sidwell Friends Middle School – Washington DC	2006	72	LEED® Platinum	20.0*	2.9**	389***	Ref: (22) *Annual energy used (19.4)+0.582 = 19.98 kBtu/GSF **Reported PV production = 0.582 kBtu/GSF ***Derived from data on the website
Aldo Leopold Legacy Center, Corp Office, New, Baraboo, WI	2007	11.9	LEED Platinum, (ZEB)	15.6	110	331	Ref (22) Energy data may have been simulated.
ONRL Office Building 3156, Renovated, Oak Ridge, TN	2009	6.9		32	104	95	Ref (22) Project was designed and constructed with in-house personnel.
DPR Construction (office - retrofit) San Diego CA	2010	24	LEED Platinum ILFI NZEB	15	113	Not Reported	Ref (23)
NREL Research Support Facility (office) Golden CO	2010	222	LEED Platinum*	33	100	259*	Ref (23) Ref (24)
Richardsville Elementary, Warren County KY	2010*	72	LEED® Platinum	17.3	94**	206	Ref: (25) *Claimed as first NZEB school in US. **Derived from data on the website

Case	Occupancy Date	Size (kGSF)	Rating	Site EUI (kBtu/GSF)	% EUI from on-site solar assist (PV) - without GHG emissions	First Cost ($/GSF)	Comments
Turkey Foot Middle School (Kenton County KY)	2010	133	LEED® Silver	12.9*	111**	200	Ref: (26) *Interpreted as "energy need" from website: "Operating at 12.9 kBtu per square foot with solar." **Derived from data on the website assuming 12.9 is valid "energy need."
Locust Trace Agri-Science High School (Lexington , KY)	2011	70	LEED® Gold*	10	110	235**	Ref: (23) * Ref: (27) ** Ref: (26)
David and Lucile Packard Foundation (office) Los Altos CA	2012	49	LEED Platinum	24	114	790*	Ref (23) *Ref (28)
DPR Construction Phoenix Regional (office retrofit), Phoenix, AZ	2012	16	ZNE certified by the International Living Future Institute	27	111	Not reported	Ref (23)
*Leon County Cooperative Extension (*office retrofit), Tallahassee, FL	2012	13		19	100	Not reported	Ref (23)

Analysis of Published NZEB Data

The data in Table 3 were derived from two prime sources (22; 23), and supplemented with various websites pertaining to the specific projects. These references focused primarily on promoting the advantages of NZEB and did not provide in-depth evaluations of the overall performance of the buildings. Thus, the validity of the quantitative data, and claims underlying the reported certifications should be considered. Neither the DOE Database (22) nor the NBI report (23) indicated that the data had been obtained through a protocol, such as a Post-Occupancy Evaluation (POE) procedure. As a result, Table 3 provides only an energy use perspective of the NZEB performance. From an engineering perspective, more system performance and occupant response data are needed in accordance with the OZEB definition.

- Definitions of NZEB or ZNEB were not provided for the examples. Therefore, various interpretations of compliance are likely.
    - The examples selected in Table 3 all consist of PV solar assist but the thermodynamic boundaries of the projects were not reported.
    - Compared to the definition of OZEB, these examples do not address performance attributes other than function (educational facility or office building). From an engineering perspective, the specific needs of the facility must be provided before loads, system capacities and controllability, energy needs, and first and owning and operating costs can be evaluated.
- References for these examples did not provide performance data on reliability, redundancy, or maintainability of the NZEBs; only energy use and first costs, consisting of design and construction, including the PV arrays, were provided.
    - The complexities of NZEB systems are likely to be greater than for conventional systems. No information was provided on the skill level required to operate and maintain these system, or on the accountability of those responsible for the operations of these systems during normal and extraordinary conditions.
    - Owning and operating costs of the NZEBs were not provided in the references for these examples.

Conclusions

The purpose of this article was to provide guidance to those who are now attempting to balance the tension between providing for the functional needs of the occupants and owners, and conserving natural resources through the location, siting, design and operations of buildings. Three issues were analyzed from an engineering perspective: 1) the concepts and objectives of "net-zero energy buildings" (NZEB) with an emphasis on commercial buildings and special focus on educational facilities and office buildings; 2) engineering means and methods to achieve these conceptual objectives; and 3) examples of evidence-based results in achieving "net-zero energy" educational facilities and office buildings. Conclusions from this analysis are:

1. Operational definitions of NZEB must comply with the First and Second Laws of Thermodynamics. Also, designs that incorporate these definitions should be based on calculations from parameters and values that are verifiable by measurement at the defined thermodynamic boundaries. The definition of "Zero-Net-Energy Commercial Buildings," expressed in EISA-2007, is not consistent with either of these engineering principles. Moreover, the conceptual definitions and variations proposed by Torcelinni et al in 2005, and the consensus definition proposed by ASHRAE in 2008 neglect the impact that health, safety, security and economic attributes have on the performance of a building, whether or not served by renewable resources.

   To adjust for these inconsistencies, an operational definition of "Net-Zero Energy Commercial Buildings" (OZEB) has been introduced, with the intent of reducing uncertainties of the performance outcomes.

2. A stepwise approach has been described that complies with the operational definition with the intent to "meet the needs and aspirations of the present without compromising the ability to meet those of the future" (1). To capitalize on the Rebound Effect (11), this stepwise approach has two stages:

   a. Reduce, by measurable means and methods, the use of depleteable energy sources for normal conditions and in preparation for the occurrence of extraordinary conditions through: i) reductions in peak, block and plant loads and system capacities and ii) enhancement of control strategies to provide the same values of the defined attributes during part and full load conditions.

   b. Consider design options that can further reduce the use of depleteable energy resources, measurably and cost effectively, through supplemental systems that utilize non-depleteable energy resources to meet all or part of the energy needs throughout the lifetime of the building, preferably without producing greenhouse gases.

3. Comparisons of available data from operational buildings to baselines and targets reveal significant challenges in measurably reducing the use of depleteable resources in commercial buildings, such as educational facilities and office buildings, through means and methods that are thermodynamically achievable and cost-effective.

a. Physical limits exist in reductions of energy needs (e.g., *site* EUIs) for buildings to provide for the health, safety, and security of the occupants while also meeting the functional, aesthetic, and economic needs of occupants, owners, and operators.

b. Larger commercial buildings may be more suitable for *off-site* renewable energy technologies than for *on-site* alternatives, especially when elevated Levels of Protection are required.

c. Reductions in *source* energy depletion or GHG emission rates cannot be measured, because the thermodynamic boundaries are indeterminant. Values for these terms can only be calculated and may result in significant uncertainties.

d. From a life-cycle perspective, and to minimize risk, a decision to approach but not reach 100% NZEB may be a reasonable alternative.

e. This analysis indicates that accountability for designs and operations of commercial office buildings can result in significant reductions in depleteable energy resources, and that NZEB is technically feasible. The challenge is to achieve this goal through engineering principles that minimize uncertainties and risks.

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