1 Introduction

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1.1 Evolution to net-zero energy buildings

Buildings have evolved over time from largely passive systems into structures with increasingly high levels of environmental control, partly through the addition of man-made insulation materials, such as fiberglass and polystyrene. The adoption of electric lighting in early twentieth century buildings, contributed to a reduction in window areas and reliance on artificial lighting, particularly in the period from 1950 to 1970. But in the 1980s, the development and acceptance of sealed double-glazed windows with an insulating airspace, or insulating windows with special coatings to reduce heat transfer and optimize transmission of solar radiation (Athienitis and Santamouris, 2002), led to the adoption of larger fenestration areas (up to 60% of the façade area) in both the residential and commercial buildings. These large fenestration areas – as much as 90% of the façade area – lead to high heating and cooling energy consumption. Thus, fenestration and daylighting significantly influence the design of commercial buildings. The drivers of the design of residential buildings are shifting from space conditioning to appliances, lighting, and integrated energy systems, as building envelopes and HVAC become more efficient and passive techniques are employed.

Since the early 1990s the potential of solar radiation incident on building surfaces to satisfy all their energy needs has contributed to the idea of net-zero energy buildings gaining widespread acceptance as a technically feasible long-term goal (for most regions). *A net-zero energy building (Net ZEB) is normally defined as one that, in an average year, produces as much energy (electrical plus thermal) from renewable energy sources as it consumes*. When the energy production is on-site the Net ZEB definition is most strict.

The visible part of the solar spectrum (nearly half of total solar radiation) is useful as daylight. Almost all of solar radiation can be converted to useful heat for space heating, as well as other useful purposes, such as heating water and drying clothes, or even solar cooling using passive and active solar systems (International Solar Energy Society (ISES), 2001). Another solar technology – photovoltaic (PV) – that converts solar radiation to electricity has recently experienced significant advances and dramatic reductions in cost (almost 90% cost reduction per watt of generating capacity in the last 10 years). Both technologies can be integrated and optimized for combined heat and power generation to advance buildings toward net-zero energy consumption.

Most inhabited areas receive significant amounts of sunshine that enable the design of technically feasible Net ZEBs with current solar and energy efficiency technologies. For example, in Canada between latitudes 40–53 °N where most of Canada's population lives, a suitably oriented façade or roof on a typical building receives up to ~6 kWh/m^2 per day, and the incident solar energy often exceeds total building energy consumption. Photovoltaic panels integrated on the roof and façade can typically convert 6–20% of the sun's energy into electricity, and 50–70% of the remainder can be extracted as heat from the PV panels, while 10 to 30% can be utilized for daylighting in semitransparent systems. Combined solar energy utilization efficiencies on the order of 80% can be

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Table 1.1 Challenges for smart Net ZEBs

Building systems, design and operation	Current buildings	Smart Net ZEBs
Building fabric/ envelope	Passive, not designed as an energy system	Optimized for passive design and integration of active solar systems
Heating, ventilation and air conditioning (HVAC)	Large oversized systems	Small HVAC systems optimally controlled; integrated with solar systems, combined heat and power; communities: seasonal storage and district energy
Solar systems/ renewables, generation	No systematic integration – an afterthought	Fully integrated: daylighting, solar thermal, photovoltaics, hybrid solar, geothermal systems, biofuels, linked with smart microgrids
Building automation systems	Building automation systems not used effectively	Predictive building control to optimize comfort and energy performance; online demand prediction/peak demand reduction
Design and operation	The design and operation of buildings are typically not considered together	Design and operation of buildings fully integrated and optimized together subject to satisfying comfort; integrated design of the above four building subsystems

achieved if proper integration strategies are implemented and nearly the full spectrum of solar radiation can be utilized as daylight, useful heat, or electricity.

The energy generation function in Net ZEBs using solar energy – as *daylight*, *useful heat, and electricity* – requires a transformation of the way buildings are designed and operated so as to be cost effective and affordable. The key challenges for smart Net ZEBs to overcome are summarized in Table 1.1 for each of the four major building subsystems where the current situation is contrasted with the expected characteristics of Net ZEBs. In addition, the integration of design with operation is considered.

1.1.1 Net ZEB concepts

The convergence of the need for innovation and the requirement for drastic reductions in energy use and greenhouse gas (GHG) emissions in the building sector provides a unique opportunity to transform the way buildings and their energy systems are conceived. Demand abatement through passive design, energy efficiency, and conservation measures needs to be simultaneously considered with integration of solar systems and on-site generation of useful heat and electricity using a whole building approach.

Building energy design is currently undergoing a period of major changes driven largely by three key factors and related technological developments:

1. The adoption in many developed countries, and by influential professional societies, such as ASHRAE, of net-zero energy [3] as a long-term goal for new buildings;
2. The need to reduce the peak electricity demand from buildings through optimal operation, thus reducing the need to build new central power plants that often use fossil fuels; and,
3. The decreasing cost of energy-generating technologies, such as photovoltaics, which enables building-integrated energy systems to be more affordable and competitive. This is coupled with increasing costs of energy from traditional energy sources (e.g., fossil fuels).

A key requirement of high performance building design is *the need for rigorous design and operation of a building as an integrated energy system that must have a good indoor environment suited to its functions.* In addition to the extensive array of HVAC, lighting, and automation technologies developed over the last 100 years, many new building envelope technologies have been established, such as vacuum insulation panels and advanced fenestration systems (e.g., electrochromic coatings for so-called smart windows), as well as solar thermal technologies for heating and cooling, and solar electric or hybrid systems and combined heat and power (CHP) technologies. A high-performance building may be designed with optimal combinations of traditional and advanced technologies depending on its function and on climate.

Solar gain and daylight control through smart window systems, in which the transmission of solar radiation can be actively controlled, remain a challenge in building design and operation because of the simultaneous effects on instantaneous and delayed heating/cooling loads, and on thermal and visual comfort. Solar gains may be controlled through a combination of passive and active measures – with the passive measures employed during design and active measures, such as positioning of motorized venetian blinds during operation. Since solar gains have delayed effects because of building thermal mass, there is significant benefit in predictive control and optimal operation of passive and active storage that utilizes real-time weather prediction (Athienitis, Stylianou, and Shou, 1990).

New building technologies, such as phase change materials (PCM), active façades with advanced daylighting devices, and building-integrated solar systems, open up new challenges and possibilities to improve comfort and reduce energy use and peak loads, and they need to be taken into account in developing optimal control strategies. The energy requirements and control needs of commercial and residential buildings are usually quite different. For example, in commercial buildings, cooling and lighting play major roles, while in houses, especially in cold climate regions, space heating and domestic hot water heating dominate energy consumption.

Plug loads (e.g., due to appliances and office equipment) represent a large portion of building energy consumption and their share is increasing, as HVAC and lighting systems become more energy efficient. Demand response strategies, such as scheduling of appliances, are becoming more popular as a way to significantly reduce the impact of plug loads on peak electric demand.

1.1.2 Design of smart Net ZEBs and modeling issues

The design of smart net-zero energy buildings requires the following three key approaches:

1. An integrated approach to energy efficiency and passive design;
2. An integrated approach to building design and operation. Optimized net-zero energy buildings need to be designed based on anticipated operation so as to have a largely predictable and manageable impact on the grid. Smart buildings optimally linked with smart grids will enable a reduction in the need to build new power plants; and,
3. The concept of solar optimization requires optimal design of building form and orientation so as to provide the maximum capture of solar energy from near-equatorial facing façades and roofs for conversion to solar electricity, useful heat, and daylight.

To design a Net ZEB efficiently in an optimal manner, a rigorous quantitative approach is required in all stages of design starting from the conceptual phase. One of the unique challenges is how to handle the interaction and integration between the energy generating systems (such as building-integrated photovoltaic/thermal systems), the heating, cooling, and ventilating systems, and the building envelope in the different design stages. Model resolution and complexity is a key issue addressed in this book (Chapter 2) and gaps in simulation are also discussed, particularly in relation to four in-depth case studies (Chapter 7).

1.2 Scope of this book

Chapter 2 discusses fundamental concepts, such as building thermal dynamics and different modeling approaches, design strategies (passive solar and energy efficiency measures), and technologies (renewable energy systems, heating and cooling technologies, and thermal storage) required to achieve net-zero energy in buildings. Because net-zero energy is an ambitious goal, the combination of systems and their integration is fundamentally important from the start of the design process to detailed design and building operation. This chapter discusses not only the individual technologies, but also effective integration strategies. It provides links to the application case studies that further exemplify the modeling techniques and technologies presented in the chapter.

Chapter 3 focuses on comfort considerations and models for different climates. Thermal comfort models are discussed, together with visual and acoustic comfort, as well as indoor air quality. Because of the highly efficient building envelopes in Net ZEBs, greater reliance on passive approaches, and a general trend toward higher glazing areas, comfort is particularly important for Net ZEBs. For example, in Net ZEBs with hybrid/natural ventilation systems there is a strong link between visual, thermal, and acoustic comfort.

Chapter 4 discusses different design processes and tools to support the design of Net ZEBs. Unlike other types of high-performance buildings, the net-zero energy target necessarily requires a high degree of accuracy in performance predictions, an integrated design process, and a combination of energy efficiency measures and renewable energy technologies. This chapter demonstrates the value of building performance simulation in design from conception to detailed design by providing accurate predictions for energy performance.

Chapter 5 presents different approaches, techniques, and considerations for Net ZEB optimization, including cost minimization and comfort. Examples from different countries, such as Finland and Italy, are presented.

Chapter 6 introduces matching of load with generation, grid interaction, and advanced control issues for Net ZEBs. Since the load profile of such buildings often peaks at different times from the generation peak, it is important to study this mismatch and how it can be addressed in order to optimize the interaction with electricity grids by shifting and reducing peak demand.

Chapter 7 provides detailed information about four diverse Net ZEBs (Figure 1.1), which are summarized in Table 1.2. These high-quality case studies were selected because they have at least one year of high-resolution measured data and the authors were intimately involved in all of them from conception to operation. The aim of this chapter is to draw lessons from the case studies, the design and simulation tools used and

Fig. 1.1 The four Net ZEB case studies. Clockwise from top left: ÉcoTerra (Image courtesy of Agnieszka Koziol), Leaf House (Image courtesy of Loccioni Group), ENERPOS (Image courtesy of Jérôme Balleydier), and NREL RSF (Image courtesy of Dennis Schroeder, NREL)

Table 1.2 Summary of four in-depth case studies presented in Chapter 7

Case Study	Description	Location and Climate
ÉcoTerra House *Detailed monitored data available – partly designed by some of the authors; related scientific publications also by authors (Athienitis, O'Brien, Chen)*	Canada's first near net-zero energy demonstration house. Completed in 2007, commissioned for 2 years, now occupied with feedback from occupants; 200 m^2 rural detached house with building-integrated thermal/photovoltaic roof, ventilated concrete slab, passive solar optimized, and a ground source heat pump	Eastman, Quebec, Canada Cold, relatively sunny climate
Leaf House *Detailed monitored data available – engineers who participated in design provided input; related scientific publications also by authors (Cellura, Guarino, Cesarini)*	6-unit low-rise multiunit residential building with passive solar features, both solar thermal and photovoltaic collectors, and a heat pump	Ancona, Italy Mediterranean climate – hot summers, mild-cold winters
National Renewable Energy Laboratory – Research Support Facility (RSF) *Detailed monitored data available – task participants work in the building; task meeting was held in the building; related scientific publications also by authors (Chen, Yip, Athienitis)*	A large institutional building consisting of offices, laboratories, and a large server room. Energy features include good natural ventilation and advanced daylighting design using fixed louvers and high, reflective ceilings; radiant cooling, a large photovoltaic array; and a transpired solar collector to preheat fresh air	Golden, Colorado, USA Cold sunny – mountain climate
ENERPOS *Detailed monitored data available – task participants work in the building; related scientific publications also by authors (Lenoir, Kapsis, Garde)*	A medium-sized energy-positive academic building with natural ventilation, daylighting, solar shading, and a large photovoltaic array	St-Pierre, Reunion Island, France Tropical climate

their gaps, and finally the technologies used and their integration. The last section of each of the case studies examines the redesign of archetype buildings based on additional information, new technologies, and lower material and component costs since they were built.

Chapter 8 concludes with a discussion on challenges and future directions in the design of Net ZEBs.

This book was written primarily by Subtask B of the International Energy Agency Solar Heating and Cooling Program Task 40/Energy in Buildings and Communities Annex 52. Subtask B, titled *Net ZEB Design Processes and Tools*, was focused on studying modeling methodologies and design processes for the state-of-the-art Net ZEBs. Subtask B participants used carefully selected high-quality Net ZEB case studies to form a greater understanding of practical and technical challenges, including modeling considerations. Members of Subtask B were a diverse group of researchers and designers. Readers are encouraged to explore the products of five years of in-depth studies by the 50 IEA Task/Annex researchers world-wide on the Web site task40.iea-shc.org.

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