Chapter

Net-Zero Energy Buildings: Principles and Applications

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Abstract

Global warming and climate change are rising issues during the last couple of decades. With residential and commercial buildings being the largest energy consumers, sources are being depleted at a much faster pace in the recent decades. Recent statistics shows that 14% of humans are active participant to protect the environment with an additional 48% sympathetic but not active. In this chapter, net-zero energy buildings design tools and applications are presented that can help designers in the commercial and residential sectors design their buildings to be net-zero energy buildings. Case studies with benefits and challenges will be presented to illustrate the different designs to achieve a net-zero energy building (NZEB).

Keywords: energy consumption, energy conservation, net-zero energy, building performance, sustainable development, sustainable energy sources

1. Introduction

Global warming and climate change are rising issues during the last couple of decades. Buildings including commercial and residential ones are major contributors to energy consumption [1]. Energy consumption in buildings significantly increases on a yearly basis due to the increased human comfort needs and services [2]. Multiple factors affect the energy consumption used for cooling buildings such as wall structure, window to wall ratio, and building orientation in addition to weather conditions [3]. Energy consumed by buildings was reported to compose a relatively large proportion of the global energy consumption [4]. The building construction and the way it is operated and maintained have a significant impact on the total energy and water usage of the world resources [5].

Buildings are the primary energy consumers contributing to more than 40% of the US energy usage [6]. According to the US Department of Energy (DoE), the heating, ventilation, and air-conditioning (HVAC) systems consume approximately 17–20% of the total energy bill of any facility or building [7]. The world equipment demand for HVAC systems has increased worldwide from approximately 50 billion US dollars in 2004 to more than 90 billion US dollars in 2014 and for the United States from almost 11 billion to 19 billion US dollars over the same period [8].

Thermal characteristics of building envelopes have become of rising significance for designers and owners due to its relation to energy consumption reduction. Improper thermal insulations in buildings can lead to higher chances of surface condensation when air has relative humidity higher than 80% and when the convective and radiative heat transfer coefficients of the exterior walls are small [9].

The purpose of this chapter is to discuss benefits and design guidelines for zero energy buildings. NZEBs have tremendous potential to transform the way buildings use energy. In response to regulatory mandates, federal government agencies and many other state and local governments are beginning to move toward targets for NZEBs.

Many states in the United States are mandating many rules and regulations to reduce the buildings' energy consumption. For example, New York and California, which house more than 20% of the United States' population, produce less than 10% of its carbon emissions [10]. These two states are leading the way in decreasing energy use through the proliferation of net-zero energy building in addition to other strategies.

2. Building performance metrics

According to the US Department of Energy (DoE), a zero-energy building was defined as the building that produces enough renewable energy to meet its own annual energy consumption requirements [11]. According to the European Union Article 2, a nearly zero-energy building is a building that has a very high energy performance where low energy is required by the building which should be covered to a very significant extent from renewable sources including sources produced on-site or nearby [12].

There are several metrics that define the performance of buildings such as the net-zero site energy building, net-zero source energy buildings, net-zero energy cost building, and net-zero energy emission building.

The net-zero site energy building is defined as the building that produces as much energy as it consumes when measured at the site. The net-zero source energy building is the building that produces as much energy on an annual basis as it uses as compared to the energy content at the source. On the other hand, the net-zero energy cost building is the building that uses energy efficiency and renewable

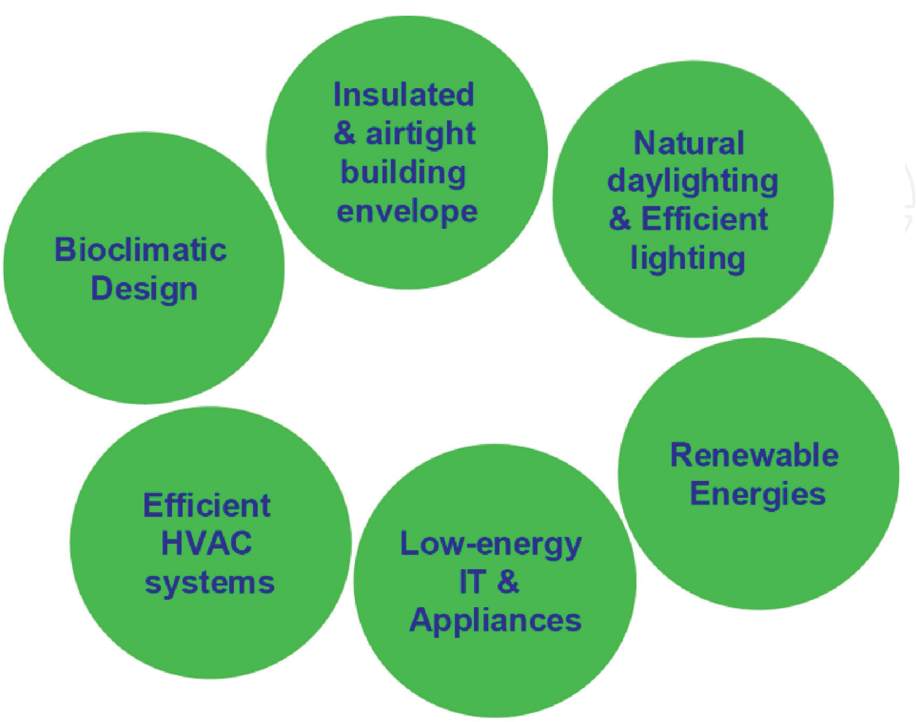

Figure 1.
Various energy efficiency measures.

energy strategies as part of the business model. Lastly, the net-zero energy emission buildings is the building design that looks at the emissions that were produced by the energy needs of the building. **Figure 1** shows various energy efficiency measures.

3. Why net-zero energy buildings?

In the last decade, energy costs have been rising, fuels are running out, and there have been global warming issues. For example, the United Kingdom has only 2 years of gas reserve, which has been put on hold of usage, and is currently buying from other countries such as Qatar and the United States. In addition to that, there have been many other issues such as health, well-being, and pollution which could be reduced if emissions are reduced as a result of better energy consumption plan.

Power stations convert only 30–35% of the input energy into electricity. The rest is rejected as waste heat. The United Kingdom alone wastes £20 billion each year by heat rejection from power plants which if used appropriately could heat Britain.

Earth's source of fossil fuel is vanishing at a much rapid pace during the last 200 years causing high damage rates to climate change. New reserves of fossil fuels are becoming harder to find. Those that are discovered are significantly smaller than the ones that have been found in the past. Oil reserve is expected to vanish between 2050 and 2060 and so does that for gas. Coal will last longer and is expected to last till 2100 [13].

Other aspects of increased emissions and increased rate of energy consumption are global warming and significant increase rate of ice melting and glaciers. A prominent red flag out of these aspects is that nine of the ten warmest years since 1880 have been in the last decade [14]. For global warming concern, Miami has seen a temperature rise of 3°C.

A building that is designed to be more sustainable has the potential to reduce the human impact on the environment. This effect is shown in **Figure 2**.

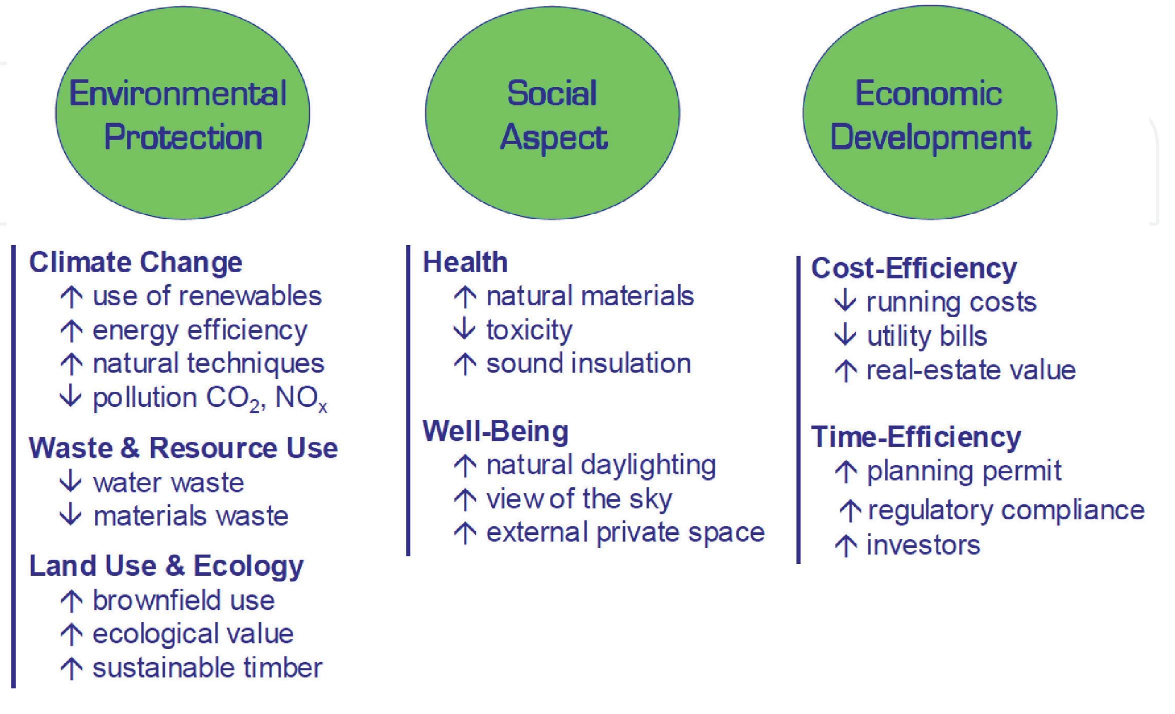

Figure 2.
Effect of sustainable buildings on the environment, social life, and economic development.

4. Sustainable development

Sustainable development is the development that meets the present needs without compromising the ability of future generations to meet their own needs [15].

There are three pillars for sustainable development:

i. Environmental protection

ii. Social concerns

iii. Economic development

The environmental protection aspect deals with climate change issues, resource depletion, land use and ecology, and waste concerns and impact of cities. The human social concerns and issues deal with justice, intragenerational equity, intergenerational equity, and health and well-being issues. On the other hand, the economic development deals with developed and developing counties, employment, modernization, and technological changes.

To solve current issues toward sustainable designs, designers should meet most of the items listed under each of the three pillars. These could be visualized as the intersection common areas shown in **Figure 3**.

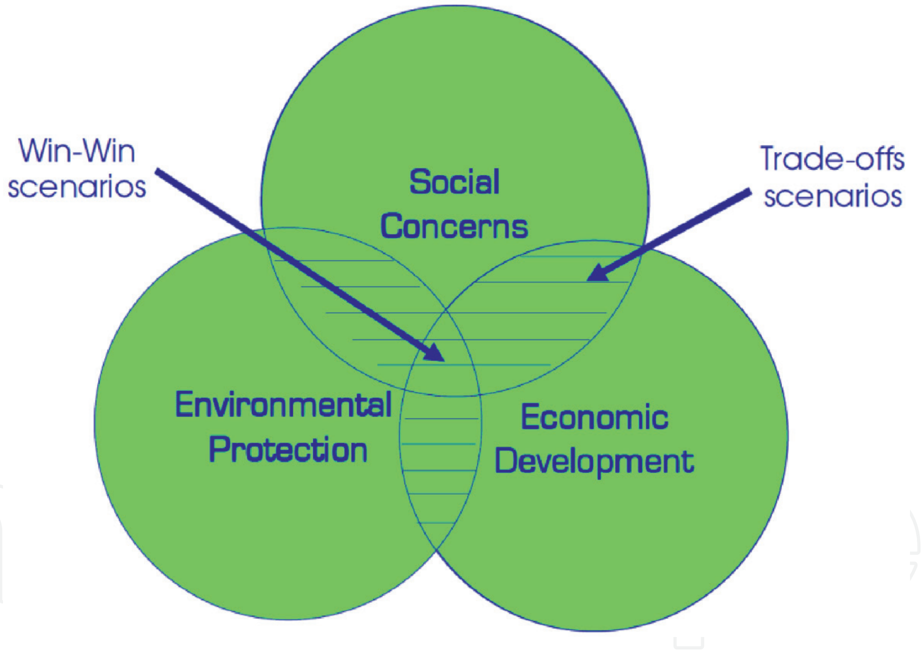

Figure 3.
Designers' choice to achieve the best results that meet sustainable designs.

5. Moving toward sustainable development and net-zero building designs: what it takes?

Spreading knowledge and engagement are ultimately the top most factors to help in reducing energy consumption, pollution and emission, and other issues such as global warming. The process starts with engagement and knowledge spreading, but it should be a closed cycle and thus needs feedback on performance. There has to be supplies that provide low and zero carbon energy and, lastly, investment. With no commitment from big industrial countries, no progress would be achieved.

There are many organizations who started net-zero marketing and application such as environmental organizations, research centers, universities and schools, and some engineering solutions which aimed to save costs and energy. In the United States, California and New York are leading the way to net-zero designs. Although they occupy more than 20% of the total population in the United States, they contribute to less than 10% of the total pollution emissions.

Following design standards is the first step in the design to achieve a net-zero energy building as it is important to define the sources and inputs that would be necessary to quantify the outputs and check what it needs to balance the net-energy consumed. The next step is to simulate the energy consumption using various energy modeling techniques and tools to optimize the following:

- Building orientation
- Glazing area, exposure, and shading
- Heat island reduction
- Lighting systems and capacities
- Temperatures, humidity, and relative humidity levels
- Landscaping
- Natural resources
- The overall system efficiency

All factors should be considered together by employing passive heating or cooling strategies, such as solar chimney and direct heat gain through south-facing glazing and/or isolated gain or sunspace, considering all possible exterior wall construction that avoids thermal bridging and increasing the R-value in all roof construction, using efficient lighting system, utilizing daylighting sensors and occupancy sensors, and lastly using energy-efficient office equipment for commercial buildings and energy-efficient utilities for residential houses and buildings.

The designer should then implement life cycle analysis, net-zero water system, and net-zero energy and optimize the design as per occupancy levels.

There are three principles to achieve a good net-zero energy building design:

A. Building envelope measures

Not only the building should be oriented to minimize HVAC loads, but shades and overhangs should be used to reduce the direct sunrays. Multiple options are available such as roof overhangs, shades and awning, and vegetation. To reduce the heat gain through windows, the designer should avoid glazing on the east/west façade. Other measures to reduce heat gains are to increase insulation on opaque surfaces, use glazing with low solar heat gain coefficient values, use double-skin façade, and refine the building envelope to suit location conditions.

B. Energy efficiency measures

The first utmost factor is selecting the right-size systems for the building. This can be achieved by following ASHRAE Standard 90.1 safety factors in the design, applying factors to reasonable baseline cases, and using simulation to model the design and predict the optimized requirements. In the simulation, part load performance should be considered which would come useful when using variable volume systems, variable speed drives, variable capacity boilers, variable capacity chiller systems, and variable capacity pumping systems as well. In addition to this, the designer should consider using high-efficiency lighting and control systems such as LED lights, high-performance ballasts, dual circuited task lighting, occupancy sensors, and daylighting dimming sensors.

The designer should shift electric loads during peak demand which would optimize the energy consumption. Some recommendations for optimizing the HVAC loads are (1) using heat recovery chillers, (2) using underfloor air distribution systems, (3) using high-efficiency chillers, (4) using passive cooling, (5) applying thermal storage using phase-change materials (PCMs), (6) using combined heating and power (CHP), and (7) using natural ventilation.

At the end of the construction phase, commissioning is a crucial step to ensure the building is performing as the intended design and is meeting its objectives. Commissioning phase verifies that the building's energy-related systems are installed and calibrated and perform according to the owner's project requirements, basis of design, and construction documents. The commissioning phase should cover at least the HVAC systems and controls, lighting and daylighting controls, domestic hot water system and any renewable system such as wind and solar. Building commissioning can reduce energy use, lower operating costs, reduce contractor callbacks, and improve occupant productivity. Successful implementation of the commissioning process can yield 5–10% improvements in the energy efficiency.

C. Renewable energy measures

Go green! Maximizing the energy sources are done through the first two measures, the building envelope which promotes using less energy and the efficient utilities and equipment measures. The renewable energy measures are more expensive than these two measures, and for that designers should start with the first two measures and optimize their design which would reduce the energy requirement needed in this step.

There are various renewable energy resources, such as solar which can be used for generating electricity, storing energy, and heating water, wind, biomass systems, and other sources.

Solar water heating systems include roof-mounted solar collectors that heat a fluid which would be used to heat water stored in a cylinder. Two collector types are usually used: the flat plate and the evacuated tube type. Flat plate collectors are usually cheaper. The solar water collectors heat the water that would be stored in a cylinder directly or indirectly by heating another fluid that would heat the water. Photovoltaic systems can be used to store energy and help in shifting the peak load.

Wind systems provide energy a very effective cost if the wind is continuous and steady and its speed above 10 mph (4.47 m/s), but it is recommended to be above 25 mph (11.2 m/s).

DOI: http://dx.doi.org/10.5772/intechopen.92285

Biomass systems could provide heat by burning the biomass material. Some examples include forests, urban tree pruning, farmed wastes, wood chips, or pellets. However, the burners usually require more frequent cleaning than oil and gas boilers.

Geothermal systems provide good source for both cooling and heating by running the refrigerant pipes under the ground that usually provide nearly constant temperatures. These systems do not produce emissions. Such systems can provide coefficient of performance of 3 or even higher.

6. Applications with benefits and challenges

In this section, different case studies will be presented that implemented sustainable development and net-zero energy principles. The cases were selected based on their impact as reduced energy consumption and optimized sustainable resources used for energy and water.

6.1 The Bullitt Center

The Bullitt Center in Seattle was opened on Earth Day on April 22, 2013. The building is shown in **Figures 4** and **5** and is rated as the greenest commercial

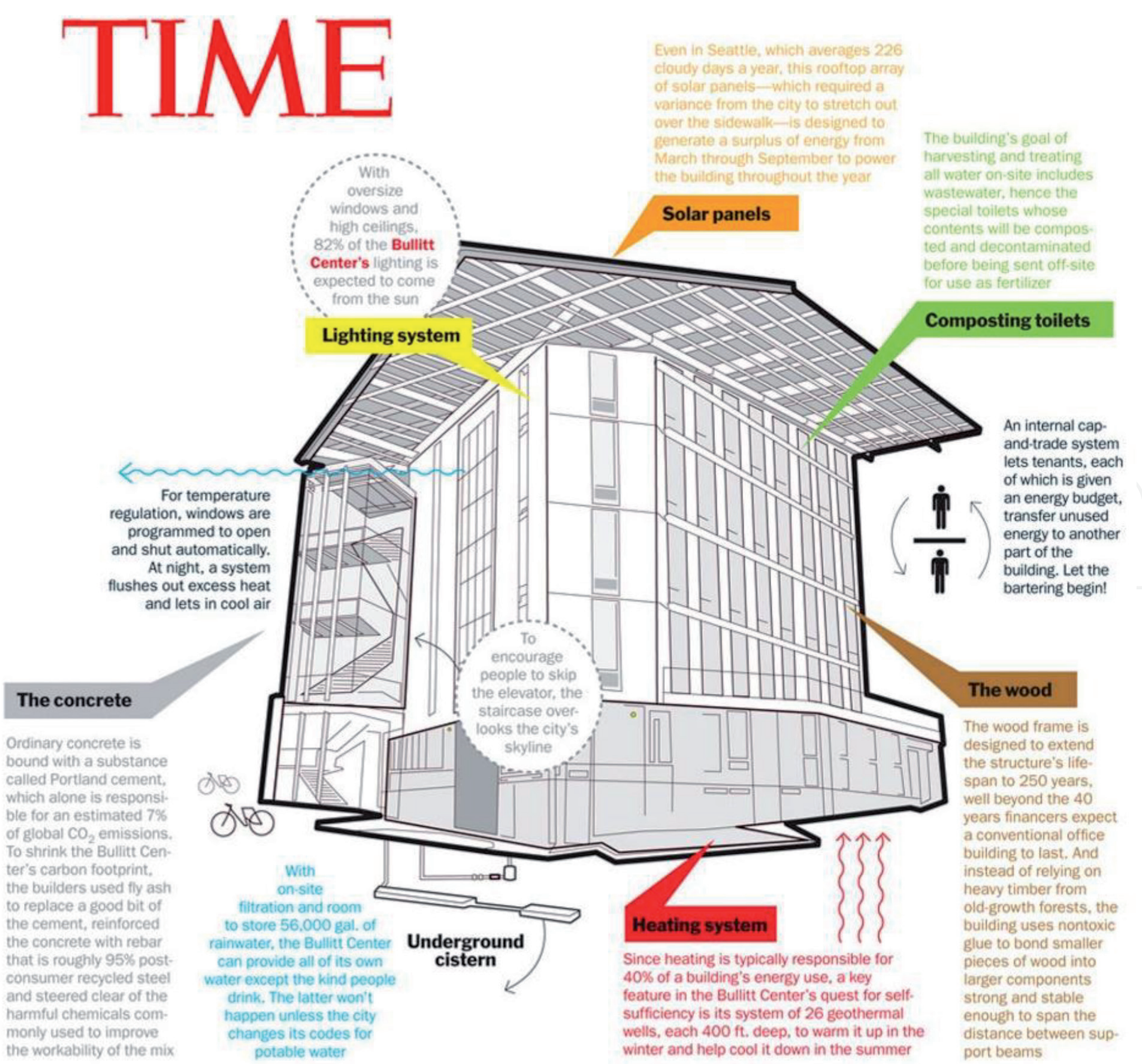

Figure 4.
Seattle's net-zero energy building (Bullitt Center) [17].

Figure 5.
Seattle's net-zero energy building (Bullitt Center).

building in the world. It is a six-story building and has a total area of 52,000 ft^2 (4800 m^2). The building is energy and carbon neutral, but its cost reaches as high as $18.5 million which yields $355 per square foot (per 0.09 m^2). The center's energy efficiency is 83% better than a typical office in Seattle with many efficient and sustainable energy sources including a 242 kW photovoltaic array, ground source geothermal heat exchange system, radiant floor heating and cooling, and retractable external blinds that block heat from warming the building. For water usage aspect, the center is 80% more efficient than a typical office in Seattle with live rainwater-to-portable water system that can collect up to 56,000 gallons (211,948 L) of rainwater [16]. The building also uses gray water reclamation using compositing foam flush toilets that save up to 96% of water as compared to traditional flush toilets. The building has also green roof and wetlands.

6.2 La Jolla Commons

La Jolla Commons II is a 13-story office at the University Town Center which is considered to be one of the largest NZEB in the United States. The building has a total area of 415,000 ft^2 (38,555 m^2) and was completed in April 2014 in San Diego, California. The completed building is shown in **Figure 6**. The building is rated as pre-certified silver as per US Green Building Council and a potential building for LEED platinum. The building has slab on-grade foundation. Other sustainability features include low-emissive coatings that reflect invisible long-wave infrared (IR) heat, reduce heat gain or loss in the building, and provide greater light transmissions. The walls were all glass as shown in **Figure 6** [18]. The air was supplied through underfloor air distribution (UFAD) system at 68 F (20°C). The cooling loads were 15 tons per floor and were supplied through two 560 tons cooling towers that served chillers located in the basement of the building. To achieve the net-zero energy efficiency, the building reduced the consumption through efficient designs and sustainable practices in addition to on-site generation. Fuel cells were generated at a rate of 5.4 megawatt-hour, whereas the historical expected consumption was approximately 4.5 megawatt-hour. The fuel cell technical data are shown in **Table 1**. The fuel cells are shown in **Figures 7** and **8**. The building is fed by biogas which would reduce energy costs. The cost per square footage was higher but it came with more benefits.

Figure 6.
La Jolla Commons [18].

Inputs	
Fuels	**Natural gas, directed biogas**
Input fuel pressure	15 psi, gage (6.89 kPa, gage)
Fuel required at the rated power	1.32 MMBtu/h of natural gas
Outputs	
Base load output (net AC)	200 kW
Electrical efficiency (LHV net AC)	>50%
Electrical connection	480 V at 60 Hz, three- or four-wire three-phase
Physical	
Weight	19.4 tons
Size	26' 5" × 8' 7" × 6' 9" (8 m × 2.6 m × 2 m)

Table 1.
Technical highlights for the La Jolla Commons fuel cells.

6.3 Aldo Leopold Legacy Center

It is classified as one of the greenest buildings on the planet as depicted by the US Green Building Council Prez [19]. The project consists of three one-story buildings. The project is located in Baraboo, WI, with cold and humid air conditions, with over 11,900 ft^2 area (1105 m^2). It has a platinum rating from the USGBC LEED-NC with net-zero energy rating. The first features of this project were the reduction in water consumption which reached up to 65% through the usage of waterless urinals, dual-flush toilets, and efficient faucets. The other features were the efficient irrigation features implemented using crushed gravels instead

Figure 7.
Fuel cells used at the La Jolla Commons building.

Figure 8.
Fuel cells used at the La Jolla Commons building.

of blacktop or concrete paving which increased the rainwater infiltration and helped in blending the developed areas with the surrounding landscape which eliminated the need for irrigation. The utmost feature for this project was the significant reduction in energy usage which reached to 70% less than a comparable conventional building by using 39.6 kW rooftop photovoltaic arrays that produces more than 110% of the project's annual electricity needs. A sketch for the design is shown in **Figure 9**, and a picture showing the installed cells on the roof is shown in **Figures 10** and **11**.

The buildings were oriented properly to have the maximum solar radiation source. Not only ground heat pumps were used as sources for heating and cooling, but Earth tubes were used to preheat and precool ventilation air, as well. Windows were utilized and properly oriented toward the south to get the maximum daylight that can reduce heat needs and lighting. The window area was maximized to optimize these two factors as shown in **Figure 12**.

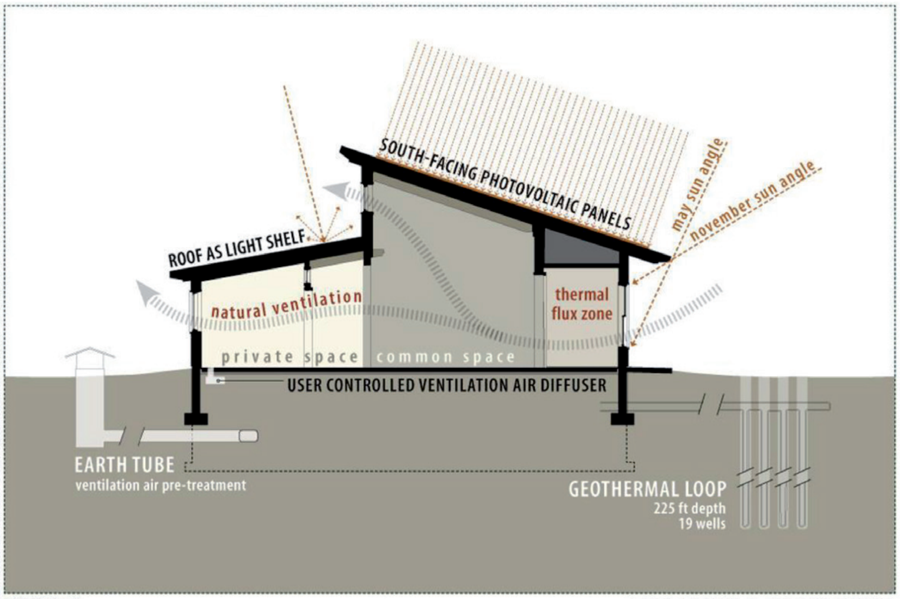

Figure 9.
Aldo Leopold Legacy Center in Wisconsin [20].

Figure 10.
Photovoltaic cells used for the Aldo Leopold Legacy Center project [20].

For additional heat, EPA-approved wood stove or fireplace was used. The final couple features were the usage of displacement ventilation and demand-controlled ventilation through the usage of variable frequency drives for fans that would control the amount of cooling or heating supplied to the spaces based on actual load and not the maximum designed.

The payback period for this project is expected to be around 14 years [20].

6.4 Hawaii Gateway Energy Center

The center is located on the island of Hawaii and is used by the Natural Energy Laboratory of Hawaii. The center is used for energy and technology research and development. The center is shown in **Figure 13**.

Figure 11.
Photovoltaic cells used for the Aldo Leopold Legacy Center project [21].

Figure 12.
Window orientation used to aid heating and lighting in the Aldo Leopold Legacy Center [21].

Figure 13.
Hawaii Gateway Energy Center [20].

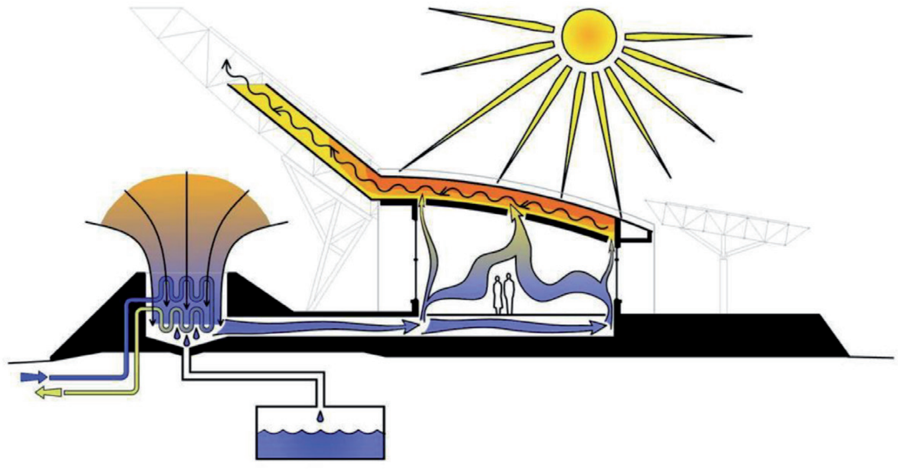

Figure 14.
Hawaii Gateway Center radiant roof system.

Natural ventilation is used through copper roof that radiates heat from the sun into a ceiling plenum as shown in **Figure 14**. Fresh outdoor air is pulled through the natural ventilation process into the occupied space from a vented underfloor plenum. Seawater at around 45 F (7.2°C) is used to cool the air to 72 F (22.2°C) as shown in **Figure 14**. As with the Leopold Legacy Center, the building is properly oriented to benefit from daylighting that aids lighting and reduces the energy needed to light the interior of the building. In summer, to prevent the negative affect of solar heat gain, shades are used on all windows. The center uses photoelectric daylight sensors to control the lights in addition to occupancy sensors. This prompted lights to be off 100% during daylight hours.

The building has 20-kW photovoltaic array which produces approximately 25,000 kW-hr due to high insolation in the area. Part of this power is used to power the pumps that draw seawater to cool the air and power the lights and other auxiliary electrical equipment. The building itself consumes 20% of the energy that comparable buildings use. In 2006, adjustments were made to the pumping systems which resulted in excess energy from the photoelectric system.

7. Conclusions

This chapter reviewed various techniques and designs that help achieve a net-zero energy building. The most important techniques are optimizing HVAC designs to reduce energy consumptions and usage of renewable sources. Some of the techniques include geothermal heat pumps, underfloor air distribution, radiant floor heating and cooling, retractable external blind on windows, and proper orientation of the building which would maximize heat gains in cold weather and minimize it in summer using trackable blinds, photoelectric daylight sensor, and occupancy sensor. Renewable sources include fuel and biomass cells, biogas, photovoltaic cells, and EPA wood stove for heating. Water usage as well could be optimized by using gray water reclamation and by using rainwater-to-potable live water systems.

Net-zero energy building design starts with ethical clients and demonstrators. Designers and users need to be lean in their designs to reduce the energy consumption, be clean by using energy-efficient utilities and systems, and be green by using renewable energy sources such as biomass, wind, solar, geothermal heat sink, and rivers. Canals could be a good source for heat pumps in cold weather regions [22].

Future buildings will focus more on renewable and sustainable energy resources by implementing an efficient building envelope and utilizing energy-efficient and high-performing utilities promoting reduced energy consumption levels. Future design will benefit from various potential energy resources including solar, wind, tidal, biomass, and other resources. Future system design and selection will need to simulate the various cases, variables, and scenarios to decide on optimized building design such as exposure, orientation, window to wall ratio, shading, building envelope, etc. In addition to that, artificial intelligence (AI) will play a major role in the operation and maintenance of such buildings including smart meters, smart display boards that recommend actions to tenants to reduce energy consumption, lighting control versus shading, and air-conditioning operation. Governments, local states, and cities have to commit to get this into track. They should facilitate sources access and should force using the guidelines and codes.

Nomenclature

NZEB	net-zero energy buildings
HVAC	heating, ventilation, and air-conditioning
DOE	Department of Energy
USGBC	US Green Building Council
LEED	Leadership in Energy and Environmental Design
LEED-NC	LEED-New Construction
EPA	Environmental Protection Agency
HEPA	high-efficiency particulate air
CFM	cubic feet per minute

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