Chapter

Definition and Design of Zero Energy Buildings

Yuehong Lu, Xiao-Ping Zhang, Zhijia Huang, Jinli Lu and Changlong Wang

Abstract

The wide application of renewable energy system (RES) in buildings combined with numerous financial incentives on RES paves the way for future zero energy buildings (ZEB). Although the definition of ZEB still lacks a national building code and international standards, the number of ZEB projects is still increasing worldwide which seems to be the pioneer ZEB buildings. However, due to the intermittency of the renewable resources, various uncertain parameters, and dynamic electricity price from the grid, how to select the renewable energy system for buildings is one of the challenges and therefore becomes an extensive concern for both researchers and designers. In addition, questions like how to achieve the target of zero energy for different types of buildings, should the building be designed as an independent ZEB or a group of buildings to be a ZEB cluster, and how to make building owners actively involved in installing enough RES for the building are still on the air. This chapter will present a comprehensive view on several key issues related with ZEB, that is, definition, evaluation criteria, design method, and uncertainty analysis, and the penalty cost scheme is also proposed for consideration as one policy to assist the promotion of ZEB.

Keywords: renewable energy, optimal design, zero energy building, robust method, feed-in tariff, penalty cost

1. Introduction

Building energy consumption is generally recognized as one of the main sectors contributing to the whole primary energy consumption and greenhouse gas emissions in the world, which greatly raise public awareness on building energy conservation in recent years. Green building (GB), low-energy building (LEB), and nearly/net-zero energy building (ZEB/nZEB/NZEB) are widely developed for the advantages of low-energy demand in the building, efficient energy system operation, and integration of renewable energy system [1–5]. In addition, numerous incentive policies, such as investment subsidies, feed-in tariff, net-metering schemes, etc., have been applied to promote the application of renewable energy sources [6–16], thus paving the way for future zero target for buildings.

The concept of ZEB/nZEB is extended from autonomous buildings that are targeted to operate off-grid by installing enough solar PV and/or wind turbine for the generation of all the energy the building required to include grid-connected ZEB that is aimed to balance annual energy exchange with the grid. The off-grid ZEB has also been named “autonomous” or “stand-alone” building as shown in

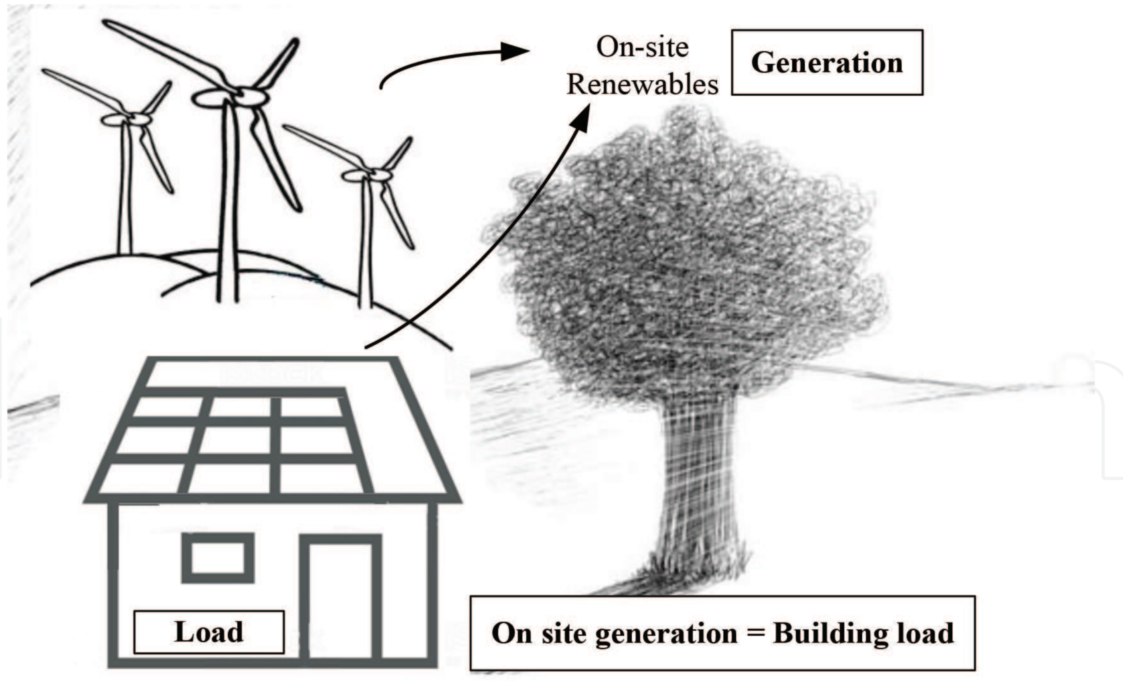

Figure 1.
Basic elements in the definition of off-grid zero energy building.

Figure 1, which can be defined as "Zero Stand Alone Buildings are buildings that do not require connection to the grid or only as a backup. Stand-alone buildings can autonomously supply themselves with energy, as they have the capacity to store energy for night-time or wintertime use" [17].

The on-grid ZEB is a "grid-connected" or "grid-integrated" net-zero energy building that is connected to one or more energy infrastructure as shown in **Figure 2**; it can be defined as "Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid" [17].

However, no national ZEB codes and international standards have been developed since numerous proposed approaches spotlight different aspects of ZEB. The metric applied for the "zero" balance is a vital issue since it affects how renewable energy system will be selected to achieve this goal. Torcellini et al. [18] introduced four different nZEB definitions, including site nZEB, source nZEB, emissions nZEB, and cost nZEB, as defined below:

- Site nZEB: A site nZEB produces at least as much energy as it uses in a year when accounted for at the site.

- Source nZEB: A source nZEB produces at least as much energy as it uses in a year when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site.

- Emission nZEB: A net-zero emission building produces at least as much emission-free renewable energy as it uses from emission-producing energy sources.

- Cost nZEB: In a cost nZEB, 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.

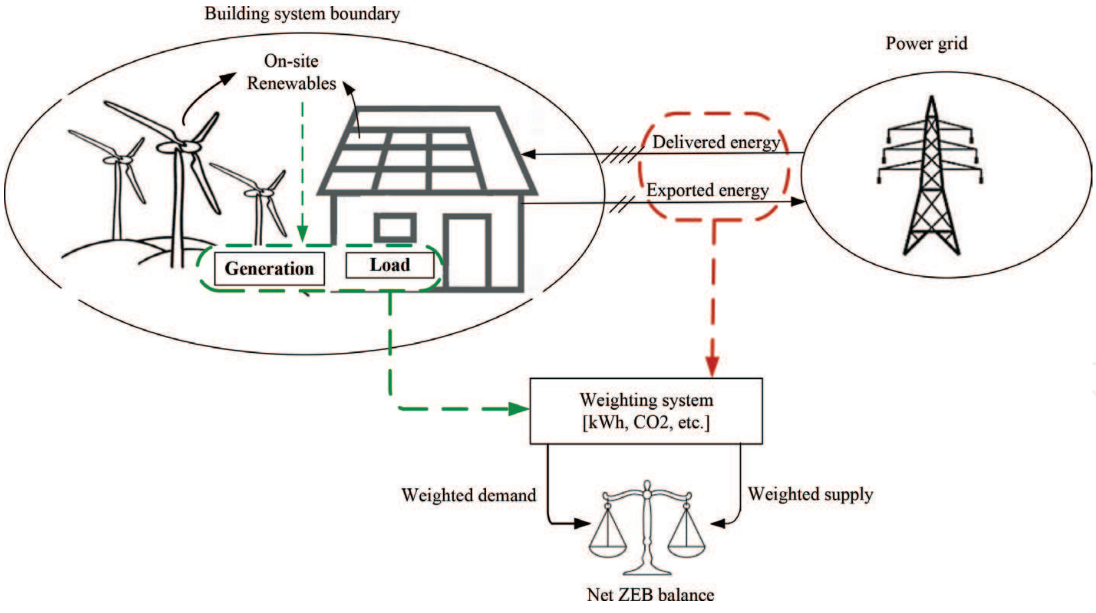

Figure 2.
Basic elements in the definition of on-grid net-zero energy building.

The concept of balance can be defined in the following mathematical equations, the balance between export and import energies (Eq. (1)) or the balance between load and generation (Eq. (2)) [19]. The balance between load and generation is generally used as a basic requirement during the design phase of ZEB. By contrast, the balance between export and import energies is particularly useful for evaluating its matchability between load and generation and the interaction between building and grid. In the previous study, most studies defined "net" as the building energy consumption and RES generation to be equal:

$$\text{Net energy} = /\text{Export}/-/\text{Import}/ \geq 0 \tag{1}$$

$$\text{i.e.} \sum_i \text{Exported\_energy}(i) \times \text{weight}(i) - \sum_i \text{Imported\_energy}(i) \times \text{weight}(i) \geq 0$$

$$\text{Net energy} = /\text{Generation}/-/\text{Load}/ \geq 0 \tag{2}$$

$$\text{i.e.} \sum_i \text{Generation\_energy}(i) \times \text{weight}(i) - \sum_i \text{Load\_energy}(i) \times \text{weight}(i) \geq 0$$

2. Incentive policies

Substantial policies and regulations have been provided to support the installation of RES power plants and thus simulate the widespread of ZEB applications. Under the support of these policies, an increasing number of ZEB case studies have been conducted, and there are over 360 ZEB projects which had been identified in different countries till 2013, as shown in **Figure 3**.

The continued growth in ZEB projects is mainly driven by the progressive financial incentives on renewable energy promotion, which is summarized for several countries from different parts of the world, as shown in **Table 1**. The main support policies on RES in different countries are described as follows [6]:

- Investment subsidies: Based on a percentage of the renewable energy output or the specific investment upfront cost.

Figure 3.
World map of more than 360 internationally known net-zero energy buildings [20].

Incentive policies	Australia	Belgium	China	France	Germany	Italy	Japan	Spain	The United Kingdom	The United States
Renewable energy targets	O	O	R	R	O	O	R	O	O	R*
Feed-in tariff/ premium payment	•		R	R	R	R	R		O	R*
Electric utility quota obligation/ RPS	O	•	O				O		O	R*
Net metering		•				O	O	O		R*
Tradable REC	O	O		O		O	O	O	O	•
Capital subsidy, grant, or rebate	O	•	O	O	O	O	O	O	O	O
Reductions in sales, energy, CO_2, VAT, or other taxes		O	O	O	O	O			O	O
Public investment, loans, or grants	O		O	O	O	O	O		O	O

*O, existing national (may also include state/provincial); •, existing subregional (e.g., state/provincial); R, revised (*indicates state/provincial).*

Table 1.
Promotion policies of renewable energy in several countries [21].

- Feed-in tariff: The producer receives total payments per kWh of generated electricity at a fixed price. It is guaranteed by the government.

- Net-metering schemes: Net-metering (NM) and self-consumption (SC) schemes. Billing agreement between utilities and their customers to feed electricity the producer does not use back into the grid.

- Tradable Green Certificates: Certificates that can be sold in the market, allowing RES generators to obtain revenue, in addition to the earnings from the sale of electricity fed into the grid.

3. Design methodologies

3.1 Design step

Although no exact approach has been developed for the target of zero balance during the design phase of ZEB, there are still some consensus and several common design elements for designing ZEB. A thorough design approach was proposed which involves 12 steps containing four foundational procedures, that is, applied metrics (e.g., primary energy, the cost), passive design (e.g., building envelope, orientation), active design (e.g., HVAC, lighting), and renewable energy system design (e.g., photovoltaic panel, wind turbine) for the design of ZEB [22, 23], as shown in **Figure 4**. Theoretically, design optimization of ZEB should be conducted considering the three vital design steps, that is, steps 7, 8, and 9, simultaneously to obtain a comprehensive combined design option for ZEB. Therefore, design optimization for ZEB is usually solved by integration of two or more software.

Passive design is an important procedure to reduce the building energy demand as much as possible. Then, high-efficiency active energy systems such as heating, cooling, and ventilation systems and lighting systems should be applied and improved together with high-performance control strategies; these could further reduce operational energy consumption in the building. Lastly, the feasibility of renewable energy technology should be assessed and selected as an on-site power supply system which works together with the power grid to reach the target of zero energy demand.

Various software tools have been developed to facilitate the selection of passive design, active design, and RES for buildings; several popular software are listed and compared in **Tables 2** and **3**. In ZEB design, the building energy demand can be firstly evaluated by using building energy simulation software such as EnergyPlus or TRNSYS. The selection of suitable renewable energy system for the building can then be conducted in software such as HOMER and TRNSYS. The design optimization software, HOMER, is developed by the US National Renewable Energy Laboratory (NREL) to assist in design optimization of hybrid energy systems for both grid-connected and autonomous building based on net present cost [24–27]. However, HOMER can only address a single-objective function for minimizing the net present cost, and it cannot solve multi-objective problems [28].

3.2 Performance evaluation criteria

It is important to determine the evaluation criteria at the design stage. Various criteria have been proposed from a different perspective of users, which can be classified into four aspects covering technical and environmental issues, economic factors, and the interaction between building and grid, as shown in **Figure 5**.

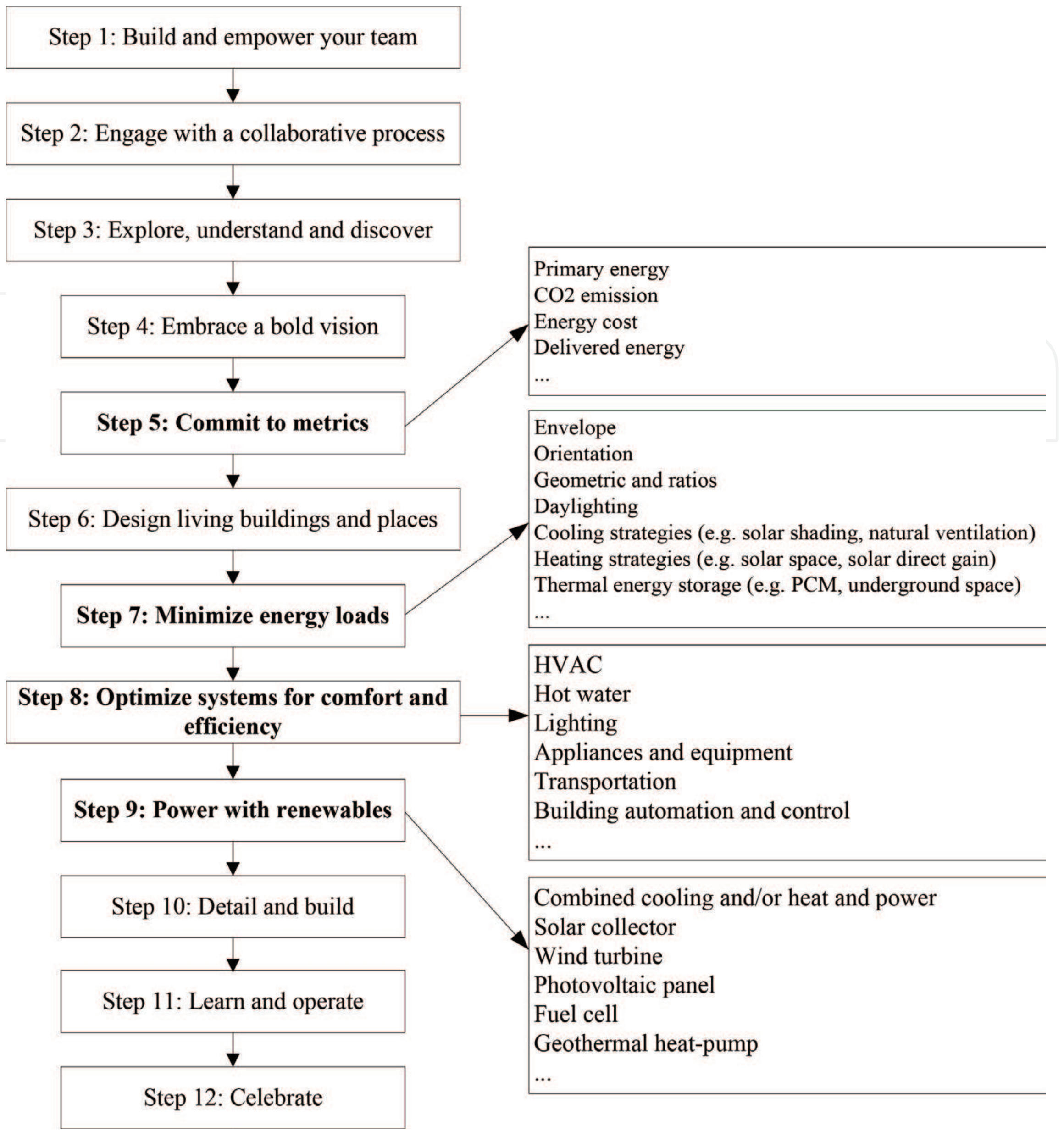

Figure 4.
The main steps to designing nZEB.

	DOE-2	eQUEST	EnergyPlus	ESP-r	DeST	TRNSYS
Room heat balance calculation		√	√	√	√	√
Humidity calculation		√	√	√	√	√
Heat comfort calculation			√	√	√	√
Nature ventilation calculation		√	√	√	√	√
Sunlight analysis	√	√	√	√	√	√
Greenhouse gas	√	√	√	√	√	√
Connection with other software			√	√	√	√

Table 2.
Comparison of building energy consumption software [29].

	HOMER	HYBRID2	iHOGA	RETScreen
Economical analysis	√	√	√	√
Technical analysis	√	√	√	√
PV system	√	√	√	√
WT system	√	√	√	√
Generator set	√	√	√	
Storage device	√	√	√	√
Bioenergy	√			
Hydro energy	√		√	
Thermal system		√		
Advantage	User-friendly, easy to understand, efficient graphical representation of results, hourly data-handling capacity	User-friendly, multiple electrical load options, detailed dispatching option	multi- or mono-objective optimization, sensitivity analysis, low computational time, net balance	User-friendly, strong product database, financial analysis

Table 3.
Comparison of renewable energy simulation software [30].

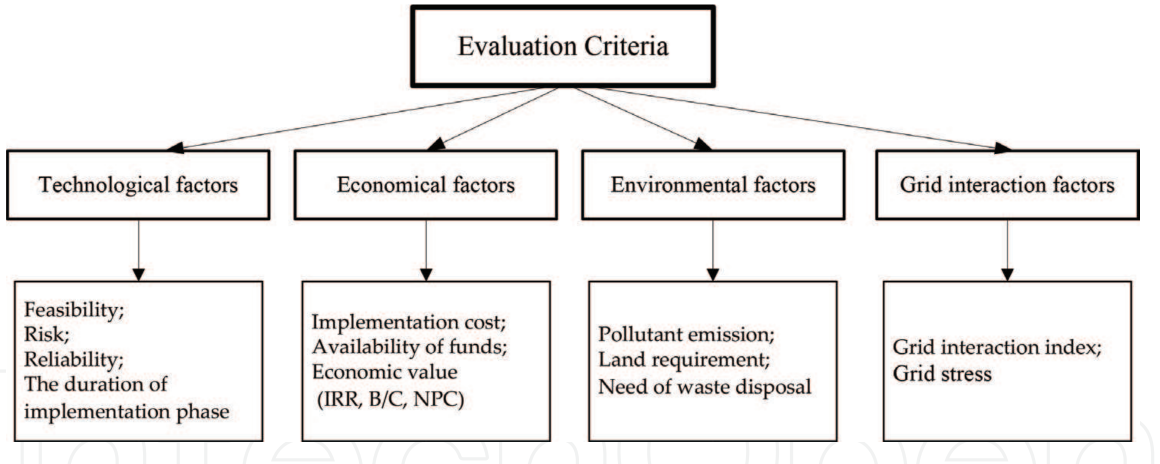

Figure 5.
The main four factors for evaluating ZEB performance.

In terms of technological factors, recent researches have been focused on feasibility and/or reliability study of different technologies (passive design, active design, RES) for ZEB.

- Feasibility: Available technologies should be assessed to identify the possibility for the building to achieve zero energy building for a particular region.

- Reliability: The criterion estimates the ability of the selected combined technologies for the building to perform its required function for a specified time.

In terms of economic factors, ZEB users are more concerned about the economic value, especially the cost and its payback period of installing on-site RES.

- Economic value [life cycle analysis (LCA), net present cost (NPC)]: The proposed renewable energy alternative will be assessed using one of the engineering economic techniques which are net present cost (NPC), life cycle analysis (LCA), benefit/cost analysis, and payback period.

In terms of environmental factors, the reduction of building load will definitely reduce the energy required from the grid and on-site RES size, which can be measured as pollutant emission.

- Pollutant emission: The criterion measures the equivalent emission of CO_2, air emissions which are the results of applying different technologies in ZEB for a particular period.

In terms of grid interaction factors, the two-way electricity flow between building and grid poses more than technological challenges; those ZEB homeowners may make heavier use of the grid than the conventional building under one-way power flow. Grid interaction index is one of the indicators used to assess the grid stress caused by ZEB.

- Grid interaction index (GII): The criterion is defined as the standard deviation of the building-grid interaction over the specified time (e.g., 1 year). It is used to estimate the average stress of building on the grid, and a low standard deviation is preferred [28].

3.3 Optimization method

3.3.1 Single-objective design optimization

It is reported that there are more than 50% of design optimization problems that are addressed as single-objective optimization problems, and they are usually focused on the most important criteria such as economic cost or environmental issues. For designing ZEB, the optimization may be conducted by focusing on the only one aspect of ZEB performance, e.g., NPC and CO_2 emissions. Besides, since multi-objective design optimization problems can also be transformed into single-objective optimization problems by using weighting factor, it is reasonable to convert all of the concerned ZEB performance indices into one combined function, as shown in (Eq. (3)). Where X represents a vector of design variables at the design stage, f_{ave} and f_i ($i = 1, 2 \ldots n$) are the combined objective and the normalized sub-objectives, respectively; w_i is the corresponding weighting factor for each sub-objective:

$$\text{Min} f_{ave} = w_1 \times f_1(X) + w_2 \times f_2(X) + \ldots + w_n \times f_n(X) \tag{3}$$

$$\text{s.t.} AX \le a \tag{4}$$

$$g_1(X) \ge 0 \tag{5}$$

$$g_2(X) = 0 \tag{6}$$

3.3.2 Multi-objective design optimization

The design and operation of ZEB are actually integrated with building owners, environment, energy source, and smart grid; it is, therefore, a multi-objective design optimization problem with even contradicting objectives. In general, genetic algorithm (GA) is the most popular optimization approach for single-objective and multi-objective optimizations of energy systems in numerous studies [31, 32]. Besides, particle swarm optimization (PSO) is another favored method for optimal design of energy systems in recent papers [33, 34]. A typical optimization process is shown in **Figure 6**.

3.4 Penalty cost for ZEB

Although the progressive incentive policies have been recognized to widely encourage the installation of renewable energy system for buildings, the financial support scheme is forecasted to be downtrend and RES cost to be high, which are a barrier for promoting future buildings to be zero energy buildings. Therefore, a penalty cost scheme may be a good solution to build up the public's confidence and encourage them to be actively involved in ZEB application.

A comparison of the building cost under different mismatch ratios is shown in **Figure 7**. It is found that the minimum total cost is supposed to be located in O1 under mismatch ratio less than 0, possibly between −1.0 and 0.0, indicating that the selection of design option under mismatch ratio of 1.0 is not cost-effective. However, the introduction of penalty cost can move the minimum cost from O1 to O2, or the higher mismatch ratio the less cost, depending on the type of penalty cost designed by designers.

The total cost (TC) of the building basically consists of the initial cost (IC) of RES (e.g., PV, WT) and the operation cost (OC) during the building usage stage due to the electricity consumption from grid and oil consumption (Eq. (4)). The penalty cost can be expressed as a mathematic expression, which is assumed to follow a segmented function, as shown in Eq. (5). It should be noted that the cost results may be greatly different according to the designed penalty cost:

$$TC_P = IC + OC + PC \tag{7}$$

$$PC = \begin{cases} TC_{1.0} \times (a - \alpha \times SF), SF < p_1 \\ TC_{1.0} \times (b - \beta \times SF), p_1 \leq SF < p_2 \\ TC_{1.0} \times (c - \delta \times SF), SF \geq p_2 \end{cases}. \tag{8}$$

3.5 Individual ZEB or ZEB cluster

In recent years, wide ranges of researches are available on the topic of RES design/control for an off-grid building or a village in a remote area [25–27].

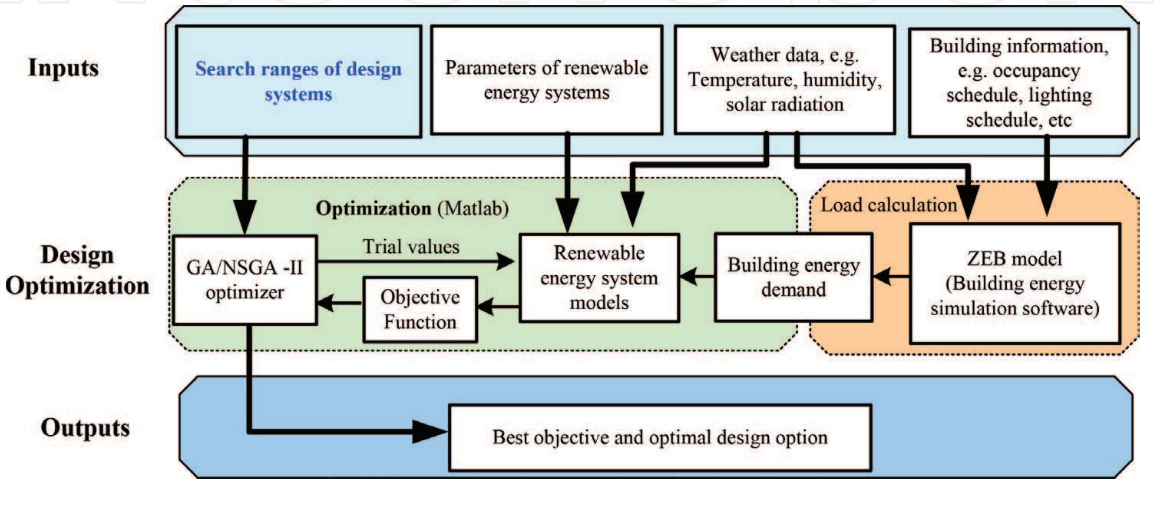

Figure 6.
Single-/multi-objective design optimization using GA/NSGA-II.

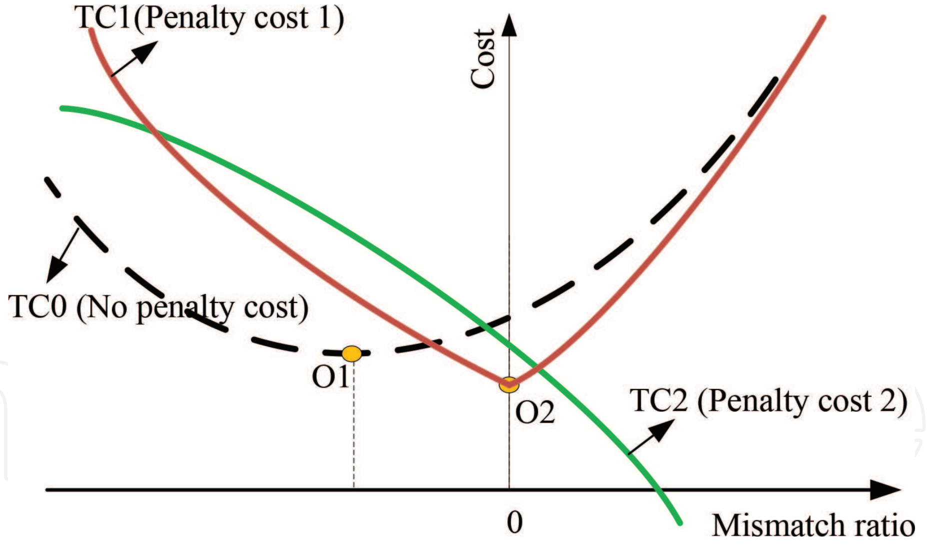

Figure 7.
The cost of building under different mismatch ratios.

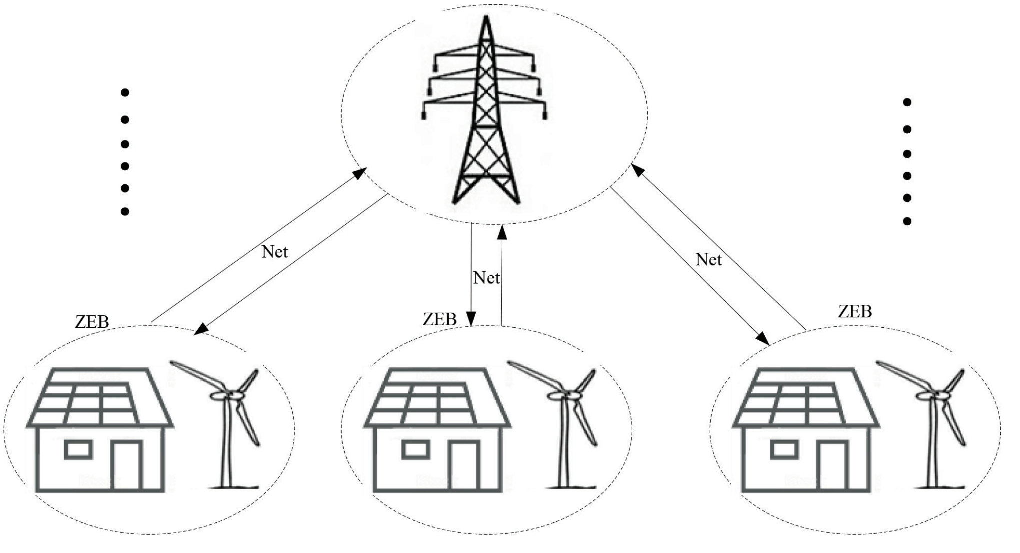

Figure 8.
A typical diagram of individual on-grid ZEB.

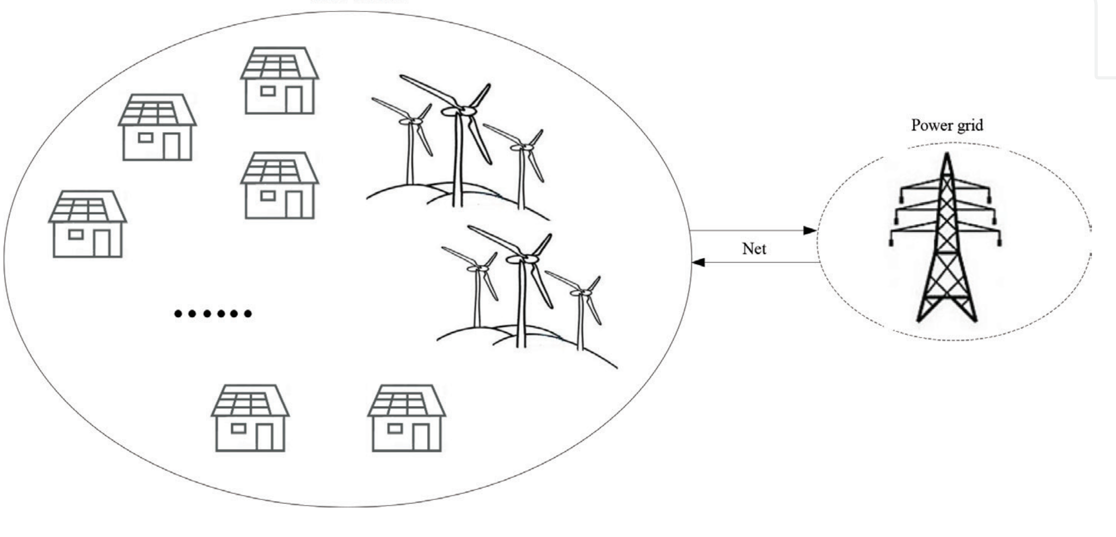

Figure 9.
A typical diagram of on-grid ZEB cluster.

However, the question is, are the buildings better to be designed as individual ZEB separately (**Figure 8**) or a ZEB cluster (**Figure 9**) when the grid power is available? By considering the dynamic electricity price from the power grid and dynamic financial incentives of sell back price from RES, the investment of RES is supposed to be different, while electricity exchange between the building and the grid is also supposed to be greatly different since the building in ZEB cluster can share on-site generation among these grouped buildings. In the study of Sun et al. [35], performance potentials are investigated by comparing single-building level using non-collaborative controls and building-group level using collaborative controls. However, a systematic and comprehensive comparison of the differences between design/control strategies for individual on-grid ZEB and on-grid ZEB cluster should be further explored and formed for ZEB development.

4. Uncertainty analyses

4.1 Uncertain parameters

ZEB is generalized as a type of sensitive building since its target is affected not only by the variation of building energy load but also by the fluctuation of local renewable energy resources. In general, a comprehensive sensitivity analysis is required to be conducted by considering both on-site generation and building energy load, as shown in **Figure 10**.

In terms of on-site RES generation, the availability of renewable resources (e.g., solar radiation and/or wind speed) and RES parameters (e.g., PV/WT efficiency and life time) can directly affect on-site energy generation for building electricity supply and thus greatly affect RES selection as well as the corresponding building performance.

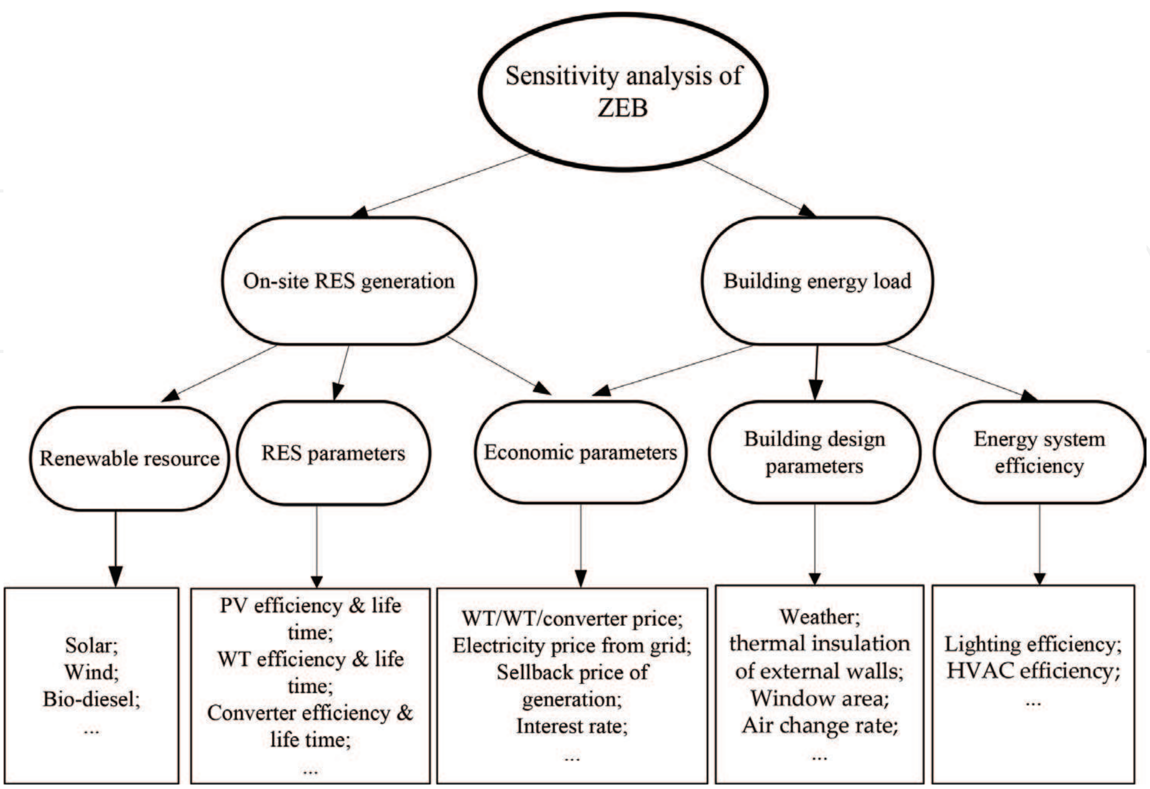

Figure 10.
Four aspects in terms of sensitivity analysis for ZEB.

In terms of building energy load, building design parameters (e.g., indoor set temperature and humidity, thermal insulation of external walls, window area, etc.), operational parameters (e.g., outdoor temperature and humidity, solar radiation, etc.), and energy system efficiency (e.g., lighting efficiency, HVAC efficiency, etc.) are the main parameters affecting building load.

Economic parameters including the price of RES, feed-in tariff, and electricity price from/to the grid are also key parameters affecting RES selection and ZEB performance. In addition, many researches have found that both the building energy load and the local renewable resources are different even for the same building located in different climate zones, which indicate that different key design parameters may exist for different climate zones and should be further identified.

4.2 Robust design

Therefore, there are many uncertain parameters which may cause great performance discrepancy between the design stage and operation stage of ZEB. The impact of uncertain parameters on system selection can be illustrated in **Figure 11**. In convention building, since it has no constraint on the mismatch between building energy consumption and on-site generation, the optimal design option O is usually selected within all the design options (Area of A), which is located below the net-zero balance line with 100% confidence level. When designing ZEB using deterministic approach, the constraint of annual energy balance is achieved for the design year, and thus the optimal design option O′ is usually selected within a few design options (Area of B), which is located on the net-zero balance line with approximately 50% confidence level. When uncertain parameters are concerned for a robust ZEB design, a narrowed area of C is identified as the selected option is required to satisfy many years of operation. Therefore, the optimal design option O″ is selected on/above the net-zero balance line with 100% confidence level. In the study of Lu [36], the RES size should be selected with a mismatch ratio of about 30% to ensure a probability of 100% of being ZEB in different years.

4.3 Impact of key parameters on ZEB performance

As mentioned in **Figure 12**, various parameters can affect ZEB system selection and performance. Six key parameters are selected here and grouped in pairs according to their specifications, i.e., PV price (ranges between 1200 and 2000 $/kW) and

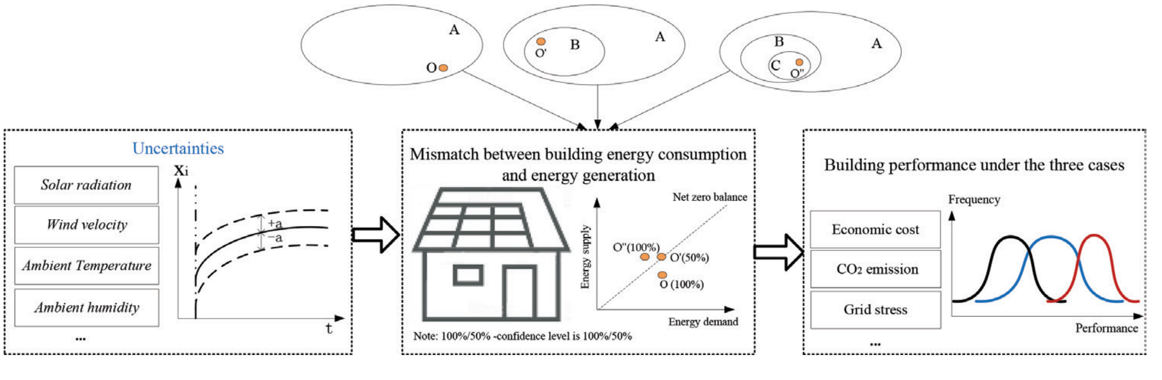

Figure 11.
Impact of uncertain parameters on ZEB performance. Note: A, all design options; B, design options for nZEB based on deterministic condition; C, design options for nZEB under uncertainties; O/O′/O″, optimal design option.

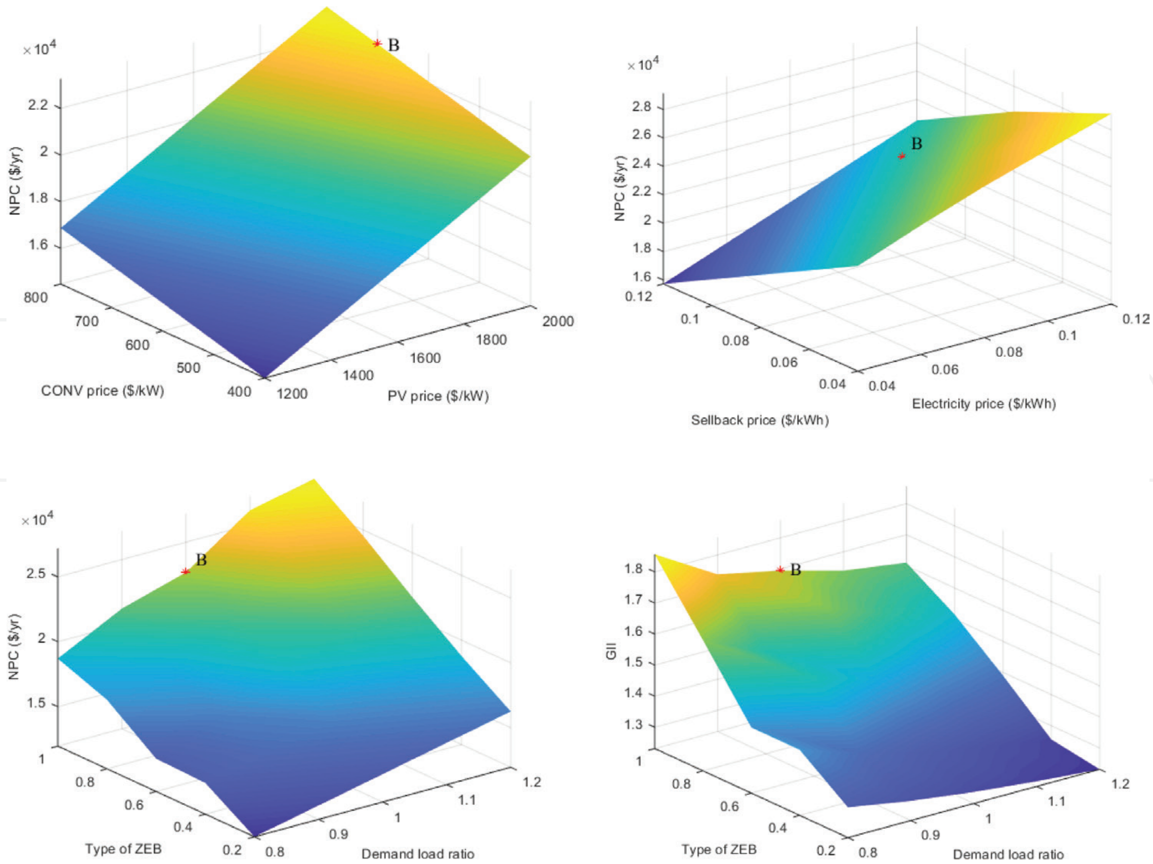

Figure 12.
Variations of NPC and GII under the effect of two factors (Note: The point B is the value under basic case.).

converter price (ranges between 400 and 800 $/kW), electricity price (EP) (ranges between 0.04 and 0.12 $/kWh) and sellback price (SP) (ranges between 0.04 and 0.12 $/kWh), and demand load ratio (ranges between 0.8 and 1.2) and the type of ZEB (ranges between 0.2 and 1.0), respectively. The impact of the group in pairs on NPC and GII is compared based on a hypothetical residential house (an area of 120 m^2) that is located in Shanghai, China. Under the selected ranges of parameters, electricity price, sellback price, demand load ratio and the type of ZEB are identified to be more important on NPC than PV and CONV price. It should be noted that the results may be different when applied for different parameter variation ranges.

5. Conclusion

This chapter aims to present a comprehensive view of the key issues related to the development of zero energy building including the definition, supporting incentives, evaluation criteria, design methodologies, and uncertainty analysis. Although a wide range of researches can be found to investigate one aspect of the ZEB study, there are still a lot of challenges faced to be solved in the future:

1. A consensus definition and interpretation of national/regional ZEB should be further declared; then, the design/control strategies with the corresponding performance of ZEB can be investigated and compared under the same standard.

2. Since a lot of factors/parameters can cause the discrepancies between predicted and realized target and ZEB performance, it should be noted that even the same factors may have a different effect on ZEB design for a specified

region considering the applied energy systems and its financial support. So, it is necessary to identify and classify the key factors affecting ZEB performance for different conditions.

3. The future grid-connected ZEB seems to definitely pose a great challenge for smart grid considering the new complex energy usage as well as on-site RES generation features of ZEB. The stress caused by ZEB on the grid is different from conventional buildings, which should be further identified and taken into consideration on ZEB design.

4. ZEB is generally catering for an individual building, while the investigation of zero energy building cluster, zero energy community, and zero energy high-rise building is still required and thus forms some standards for the design/control strategies in each type of ZEB application.

5. The existing financial incentives are mostly proposed to promote the wide-spread application of RES, while a systematic financial scheme should be developed to further assist and stimulate ZEB development in a standard and rapid way.

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