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Review

Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings

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HIGHLIGHTS

- Key design issues (climate effects, methods and uncertainties) are summarized.
- The control methods of energy generation/storage systems are summarized.
- The applications of MPC methods and smart control technologies are reviewed.
- An outline of the progress of nZEBs worldwide is presented.

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ABSTRACT

Nearly/net zero energy buildings (nZEBs) have attracted increasing attention particularly when high and complex performance is required in terms of energy-saving, indoor thermal comfort, environmental friendliness and grid-friendliness. However, there is no exact approach at present for the design and control of buildings to achieve the nearly/net zero energy target. This is mainly due to the complex interplay of energy production/consumption/storage systems as well as the automatically and manually controlled systems/elements in the highly integrated buildings. This paper therefore presents a comprehensive review on the issues related to the design and control of these buildings, i.e. the effects of climate/site on design, design optimization methods, uncertainty and sensitivity analysis for robust design and system reliability, efficient and optimal control of high efficient generation systems and energy storage systems for alleviating/shifting the peak load, model predictive control for fast responses to smart grid, and adoption of advanced smart technologies. An outline of the progress of nZEBs is presented by summarizing the internationally known nZEBs identified including 30 case studies on the design strategies applied and the actual building performance. This review could also support the future development of methods that address the design and control of buildings with a holistic view.

Contents

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1. Introduction

Energy consumption of buildings accounts for 40% of the primary energy in USA and Europe, nearly 30% in China and even up to 80% in Hong Kong [1–3]. Buildings are also one of most significant contributors of greenhouse gases. Nearly/net zero energy buildings (nZEBs), an innovative concept for sustainable buildings, has attracted increasing attentions, which is regarded as a mean to energy-saving and carbon emission reduction. By applying energy sufficiency measures and the integration of renewable energy systems in buildings, it is possible to achieve the target of nearly/net zero energy balance and maintain a sustainable, healthy and grid-friendly building [4–6].

Plenty of efforts have been made on establishing regulations and quite a few regulations on nZEBs have been proposed and promoted at the international level, such as:

- Under the umbrella of international energy agency (IEA) solar heating and cooling program (SHC), researchers and experts from Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Korea, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, United Kingdom and USA have been working together on the task 40 "Towards net zero energy solar buildings". The aim of the task is to study nearly/net zero energy buildings and to develop a common understanding and a harmonized international definition framework as well as tools, innovative solutions and industry guidelines [7].
- In Europe, the Directive on Energy Performance of Buildings establishes the goal of 'nearly net zero energy buildings' for all the new buildings from 2020 [8].
- ZEBRA 2020 (Nearly zero energy building strategy 2020) covering 17 countries, was launched in 2014 aiming at creating an observatory for nZEBs based on market studies and various data tools and therefore generates data and evidences for optimization and policy evaluation [9].
- In United Kingdom, the ambition is to have zero carbon homes by 2016.
- In France, all new buildings should comply with energy positive by 2020.
- The California Public Utilities Commission of the USA has set a net zero energy target for all new residential buildings by 2020 and for all new commercial buildings by 2030 [1].
- Similar promotion proposals and developments can be also observed in Japan, China and Australia [10–12].

More than 360 internationally known net zero energy buildings are listed and edited in a world map [13]. A net zero energy building database also provides some demonstration projects containing realistic experiences of design, operation and test [14].

There are a few review papers in the literature addressed different aspects related to sustainable building design and optimization. Regarding the design of buildings, Sadineni et al. [15] reviewed the building envelop components. Shameri [16] reviewed the double skin facade systems in buildings. Pacheco [17] reviewed the energy efficient design of buildings. Regarding energy production systems, Chauhan [18] and Bajpai et al. [19] reviewed integrated renewable energy systems and the hybrid renewable energy systems respectively for stand-alone applications. Regarding the optimization methods, Baos et al. [20] reviewed the optimization of sustainable renewable energy. Pezzini et al. [21] reviewed the optimization techniques applied to power systems. Sinha et al. [15] reviewed the software tools for hybrid renewable energy systems. Banos et al. [22] reviewed optimization methods applied to renewable and sustainable energy. Fadaee [23] reviewed multi-objective optimization of a stand-alone hybrid renewable energy system using an evolutionary algorithm. Shaikh et al. [24] reviewed the intelligent control strategies and optimized control systems for the comfort management of buildings.

Regarding the progress of nZEBs, Marszal et al. [25] presented a review on the definitions and calculation methodologies of zero energy buildings (ZEBs). Deng et al. [26] summarized the widely-used research methods, tools and performance evaluation indicators for ZEBs. Li et al. [27] presented a review on zero energy buildings and sustainable development implications. Kolokotsa et al. [28] reviewed the technological developments in various aspects for buildings toward intelligent net zero/positive buildings.

However, the design and control strategies of nearly/net zero energy buildings (nZEB) are not straight-forward since the buildings may involve complex integration of different energy systems, such as renewable energy generations, energy appliances, energy storages and may also interact with the smart grid. Previous literature also did not present a comprehensive review on the effects of climate/site on design, design optimization, the uncertainties/sensitivities for robust design and control techniques for nZEB. Discussion of these underlying issues is very important for developing methods that can address the design and control of buildings with a holistic view, ensuring that the aim of nZEB is achieved with a high-level performance.

This paper therefore presents a review on the design and control issues of nZEB, particularly the effects of climate and site, design optimization methods, uncertainties/sensitivities analysis for robust design and system reliability as well as the control and scheduling issues related to building demand response, model predictive control methods and the use of advanced smart technologies.

2. Design optimization of nearly/net zero energy buildings

2.1. nZEB definitions

Consistent nZEB definitions are definitely needed for the design, operation, and performance evaluation of nZEBs since the way to define a nZEB affects significantly the way to design the building in order to achieve the target. In the existing literature, the definition/framework of nZEB is still ambiguous and lacking of common and consistent concept at the international level [25]. The definition involves different elements, such as: boundary, weight, metrics and criteria. Based on individual considerations on local