Sustainable Cities and Society 32 (2017) 130–141

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Quantitative analysis on a zero energy building performance from energy trilemma perspective

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ARTICLE INFO

Keywords:
zero energy building
performance index
energy security
cost
CO_2 emissions

ABSTRACT

Zero energy buildings (ZEBs) have been conceptualized as a major solution to adopt an efficient energy management and saving scheme in the building sector. Given that the sustainability of the ZEB relies heavily on both the on-site renewable sources and battery, their capacities had to be carefully selected to ensure that the ZEB meets the intended performance goal. As such, indicators that are related to energy trilemma for the evaluation of ZEB performance is first identified. Subsequently, a new ZEB performance framework is developed based on the set of five chosen indicators. Finally, ZEB performance index is derived and analyzed using the developed framework to select the appropriate capacity combination both the on-site renewable sources and battery. Through the analysis, it has been discovered that energy loss from energy conversion into and out of the battery can be considered as a less impact factor for ZEB performance taking into account the correlation of five indicators. The quantitative analysis of ZEB performance based on this developed framework from energy trilemma perspective would be hopefully of use to policymakers in designing a well-grounded and sustainable energy policy in the long run.

1. Introduction

In the last several decades, the increasing energy demand and heavy reliance on fossil fuels to ensure energy security had raised alarming global warming issues. As such, balancing the trade-offs between the three major energy goals: energy security, environmental issues and economic aspect (World Energy Council (WEC), 2012), which is also known as the energy trilemma, is of paramount importance. Given that the building sector consumes 40% of the primary energy use and contributes to 24% of the greenhouse gas emissions worldwide (International Energy Agency (IEA), 2011), the adoption of an efficient energy management and saving scheme in the building sector (Clift, 2007) has huge potential to address the global energy trilemma. Consequently, zero energy buildings (ZEBs) were conceptualized as a major solution among the various energy saving options (Deng, Wang, & Dai, 2014; Voss, Musall, & Lichtmeß, 2011), which had also been considered in many countries for their future building energy target.

In general, ZEB can be categorized into on-grid ZEB and off-grid ZEB. The on-grid ZEB is connected to energy infrastructure such as electricity grid. On the other hand, the off-grid ZEB is not connected to any external infrastructure. As such, electricity has to be generated on-site to meet the local demand and the energy storage system is of significant importance to avoid electricity supply disruption in an off-grid ZEB (Kramer, Krothapalli, & Greska, 2007; Laustsen, 2008; Voss et al., 1996). Additionally, off-grid ZEB has to ensure self-sufficiency even when system failure occurs, which will involve additional capital costs and energy losses arising from the utilization of large storage system. Due to the above mentioned disadvantages, it was reported that an on-grid ZEB with renewable energy can deliver better performances than an equivalent off-grid ZEB (Feist, 1997; Vale & Vale, 2002). Consequently, the on-grid ZEB had been given special preference due to its promising potential in the near future (Hermandez & Kenny, 2010).

However, regardless of whether it is an on-grid or off-grid ZEB, energy self-sufficiency without any reliance on external grid has been given high emphasis from the viewpoint of security of supply in the building sector (National Renewable Energy Laboratory, 2015), especially after the Great East Japan Earthquake and Fukushima disaster. While 1.45 million corporations had to stop their operation due to the planned power cut conducted by the Japanese government after the Fukushima disaster (Ministry of Economy, Trade and Industry (METI), 2011a), some buildings such as Mori Building Co. did not only managed to meet its own electricity demand but had even exported power to the

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http://dx.doi.org/10.1016/j.scs.2017.03.023
Received 11 October 2016; Received in revised form 23 February 2017; Accepted 30 March 2017
Available online 05 April 2017

Nomenclature

X	Computed values of indicator
$R.$	Correlation matrix
λ	Eigenvalues
I	Normalized values of indicators
A	Eigenvector
P	Principle Components
F	Factor loading
v'	Variance

List of subscript

p	List of indicators
i	PV-battery capacity combination
j	Order of eigenvalue

List of Acronyms

CO_2	Carbon Dioxide
FiT	Feed in Tariff
NEDO	New Energy and Industrial Technology Development Organization
PV	Photovoltaic
TOU	Time of Use
ZEB	Zero Energy Building
ZEBI	ZEB performance index
ZEH	Zero Energy House

grid (Japan for Sustainability (JFS), 2011). In addition, few residential buildings using on-site renewable energy and backup storage technology had also helped to supply electricity to neighboring households after meeting the energy demand within its own building. The nature of building stock by utilizing both on-site renewable sources and backup storage is a key determining factor for the self-sufficiency capability (Iqbal, 2004; Miller, 2015).

Given that the sustainability of the ZEB relies heavily on both the on-site renewable sources and battery, both their capacities had to be carefully selected to ensure that the ZEB meets the intended performance goal. As such, a project is initiated in this paper to first establish the framework for evaluating the ZEB performance. Subsequently, the established ZEB performance framework is used to optimize the on-site renewable sources and battery capacities. In this paper, ZEB refers to the building which uses electricity from both on-site renewable energy and storage technology connected with the external grid. A zero energy house in Japan is selected as a case study.

The paper is structured as follows. Firstly, Section 2 establishes both framework and methodology for evaluating the ZEB performance. Subsequently, a composite index based on ZEB framework in the case of Japan is derived in Section 3. Finally, Section 4 concludes this paper.

2. Research Method

The methodology in this research consisting of scope of study, development of ZEB performance framework and followed by evaluation of the ZEB performances is presented in this section.

2.1. Scope of research

A zero energy house (ZEH) in Kyoto, Japan, which is also a variant of ZEB, is considered in this project to reduce the energy utilization and enhance the demand and supply balance in the residential sector in Japan. The Japanese Ministry of Economy, Trade and Industry has established a ZEH roadmap for standard new houses to be zero energy by 2020 (Ministry of Economy, Trade and Industry (METI), 2015). The house receives its power from the onsite solar photovoltaic (PV) and battery storage as well as the external grid (Iqbal, 2004). In this project, the capacities of both the on-site solar PV and the installed battery can be varied which will delivery different ZEB performances. As such, a framework will be established in the next section to evaluate the ZEB performances under the different on-site renewable sources and battery capacities.

2.2. Development of ZEB performance framework

Owning to the promising potential in ZEB, Various indicators for ZEB performance optimization have been proposed by different authors in recent years. Economical aspect has been developed as an indicator to evaluate the ZEB performance (Hamdy, Hasan, & Siren, 2013; Nolte, Ralf, Staniaszek, & Faber, 2013) with the inclusion of peak load tariffs and feed in tariff (Lindberg et al., 2016). Subsequently, CO_2 emissions have been analyzed in building optimization studies to propose the environmental indicator (Atanasiu et al., 2011). The combination of both economic and environmental impacts has been also developed as a multi-objective indicator (Cao & Siren, 2015; Georges, Massart, Moeseke, & De Herde, 2012; Ren & Gao, 2010). Given that one of the foundation principals for designing energy saving buildings is the enhancement of indoor environment quality, Huws and Jankovic had also proposed comfort as another indicator to investigate social conflicting constrains (Huws & Jankovic, 2014). In addition, the external interaction of ZEB with the electricity grid has also recently been proposed as another indicator (Marszal et al., 2011). The external interaction has been analyzed from both load matching and grid interaction. Load matching refers to the amount of local energy generation that meets the building load, while grid interaction refers to the energy exchange between the building and a power grid (Voss et al., 2010). Pertaining to load matching, self-consumption factor has been widely proposed to represent the ratio of on-site generation such as solar PV to the building load (Castillo-Cagigal et al., 2010; Lindberg et al., 2016; Widen & Munkhammar, 2013). In contrast, grid interaction refers to the electricity exchange between ZEB and the external electricity grid (Lindberg et al., 2016; Salom et al., 2011).

It can be observed that the indicators proposed for ZEB performance framework are diverse and addresses a variety of needs. However, most of the proposed ZEB performance frameworks are not comprehensive, which may be short run and unsustainable (Ang, Choong, & Ng, 2015). Sustainable energy policy in the long run should ideally be the policy containing the overarching principle covering a broader sustainability issue. As such, the construction of ZEB performance framework from a more holistic viewpoint, incorporating the concept of energy trilemma is of significant importance to achieve a sustainable energy policy in the long run. Given that the performance of ZEB had not been evaluated from energy trilemma perspective until now, therefore, the ZEB performance framework in this paper will be evaluated from energy trilemma perspective, which encompasses the energy security, environment issues and economic aspect.

Besides the indicators proposed for ZEB performance frameworks presented above, a wide variety of indicators had been proposed for the evaluation of other performance framework, particularly related to global energy security including economic and environmental aspects. The authors in (Sovacool & Mukherjee, 2011) presented 200 indicators for evaluating national energy security policies and performance. Numerous indicators had also been proposed by other authors (Vivoda, 2010). From these established performance frameworks, indicators that are related to energy trilemma are first identified. Subsequently, the set of chosen indicators are then used to develop a new ZEB performance framework, which had not been proposed by any