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

Shoki Kosai\textsuperscript{a,b}, ChiaKwang Tan\textsuperscript{b}

\textsuperscript{a} Graduate School of Energy Science, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
\textsuperscript{b} UM Power Energy Dedicated Advanced Centre (UMPEDAC), University of Malaya, Kuala Lumpur, 59990, Malaysia

\begin{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.
\end{abstract}

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 off-grid ZEB had been given special preference due to its promising potential in the near future (Hernandez & 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...
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 deliver 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, Staniszezrk, & Faber, 2013) with the inclusion of peak load tariffs and feed in tariff (Lindberg et al., 2016). Subsequently, CO2 emissions have been analyzed in building optimization studies to propose the environmental indicator (Atanasie 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, Moeke, & 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...
paper.

The contribution of generated power from the ZEB to the external grid had been identified as one of the important indicator for energy trilemma. The authors in (Jewell, Cherpi, & Riahi, 2014) proposed that the energy security risks include the incapacity of an electricity infrastructure system to meet growing load demand, which highlights the importance of power contribution from other sources. Similarly, the authors in (ÖLZ et al., 2007) suggested the increase share of on-site renewable energy is required to mitigate this security risk, being considered as an indicator of energy security (Institute for 21st Century Energy, 2012; Yao & Chang, 2014). Especially, daytime when electricity is generated by on-site solar PV matches with the time of peak grid demand.

Subsequently, the mitigation of dependence on external grid electricity to increase self-sufficiency had been also recognized as one of the important indicator. The concept of self-sufficiency has been highlighted in the discussion of global energy security indicators (Ang et al., 2015; Cherpi and Jewell, 2011; Sovacool, 2011; Wu, Liu, Han, & Wei, 2012) due to the risk of a temporary supply interruption on the grid. Council of European Energy Regulations reported the duration of electricity supply interruption which are from 20 minutes to 500 minutes in Europe in 2012 (Council of European Energy Regulators (CEER), 2014). Decreasing reliance on the external grid and increasing self-sufficiency can mitigate the impact of temporary supply interruption on the grid and improve security of continuous electricity supply in the individual building (Sovacool, 2013; U.S. Department of Energy (DOE), 2015).

In addition, saving electricity by reducing the energy loss from energy conversion into and out of the battery can be considered as another important indicator for energy trilemma. Energy loss has been identified as a concern of energy security (Wang, Wang, & Zhao, 2008). Even though the electricity transmission and distribution loss has been mostly utilized as an indicator of energy security (Sovacool, 2013; Sovacool & Mukherjee, 2011), the utilization of battery also causes a significant loss. It would be better option for electricity generated on-site to be exported to the grid, since more energy loss is generated by energy conversion into and out of the battery rather than by transmission and distribution of electricity through the external grid (Cao, 2016). Meanwhile, the energy loss through the battery utilization has only been scarcely integrated in the ZEB performance indicator so far.

Furthermore, de-carbonization of electricity generation is particularly associated with environmental issues (Marchamadol & Kumar, 2012; Sovacool, 2013; Wu et al., 2012). The individual ZEB has a potential of management of local climate change (Marszal et al., 2011; Santamouris, 2016), successively contributing to a low carbon society (Pohlmann, 2011).

Finally, the reduction of electricity cost in the individual building is related to the economic aspect of energy trilemma from the perspective of the affordability of electricity utilization (Intharak et al., 2007; Marchamadol & Kumar, 2012). The approach to reduction of electricity cost including both Feed in Tariff (FiT) and the multiple electricity payment method can assist the better affordability of electricity market (Sovacool & Mukherjee, 2011).

In summary, a new ZEB performance framework was developed including a set of 5 indicators, which are related to the energy trilemma. The five indicators are listed below:

a) Contribution – Contribution of electricity generated by on-site renewable sources to the grid
b) Dependence – Mitigation of dependence on external grid electricity to increase self-sufficiency
c) Energy loss – Saving electricity by reducing the energy loss from energy conversion into and out of the battery
d) Total CO2 emissions – De-carbonization of the electricity generation in order to make the whole energy system less sensitive to global climate change
e) Electricity cost – Reduction of electricity cost by reducing import from grid and increasing export to the grid

The first three indicators are associated with energy security, while the fourth and fifth indicators are related to environment issues and economic aspect respectively. This approach based on energy trilemma can be easily applied to the national energy scheme since energy trilemma has been widely acknowledged as the sole performance goal for all countries. These indicators will be used to evaluate the ZEB performance under the varying combinations of on-site renewable energy capacity and battery capacity.

2.3. Evaluation of the ZEB performance

In this section, ZEB modelling will be constructed to compute the established five indicators so that the ZEB performance can be evaluated.

2.3.1. ZEB modelling

The ZEB is modeled using system dynamics as shown in Fig. 1, which is also called ZEB electricity demand and supply model. The building receives its power from 3 sources, which are the intermittent renewable source, backup storage supply and external infrastructure. The intermittent renewable source is represented by the solar PV, covering a certain portion of the roof-top. In contrast, the battery acts as the backup storage supply and the external infrastructure is considered as the external electricity grid. The summation of power from all three sources is consumed by the load demand. Surplus power that is not utilized by the building will be channeled to the battery for storage up to the maximum battery capacity. The stored energy will then be discharged during period when the load demand is greater than the power from roof-top PV. Any surplus power which cannot be stored due

Fig. 1. ZEB electricity demand and supply model.
to the limitation of battery capacity will be exported to the connected grid. Meanwhile, the building will import electricity from the grid when the combined power from both the solar PV and battery is not enough to meet the demand.

Naturally, this model will need the prerequisite data as input for solar irradiation, demand, surface area of roof-top, PV efficiency and battery round trip efficiency. The data of solar irradiation in Kyoto is taken from New Energy and Industrial Technology Development Organization (NEDO) solar radiation database in Japan (New Energy and Industrial Technology Development Organization (NEDO), 2016). In this case study, the sunny day on the 6th of August 2015 is selected to observe the balance of both demand and supply at the maximum condition of solar power output. The maximum residential daily load curve, as published by the Japanese government (Ministry of Economy, Trade and Industry (METI), 2011b), is used as input for demand to analyze the most severe case. The average dimension of Japanese house is 140 m² according to Japan Housing Finance Agency (Housing Finance Agency, 2014), which is used as input for surface area of roof-top. It is assumed the installed solar panel is of type VBHN245WJ01, which has 19% of the conversion efficiency from solar irradiation to electricity energy (Panasonic, 2016). The surface area of solar PV module is 1.26 m². 22 solar modules are expected to meet the capacity in Japan (4R ENERGY, 2014), the maximum solar PV capacity is 140 m² according to Japan Housing Finance Agency (Housing Finance Agency, 2014), which is used as input for demand to observe the balance of both demand and supply at the maximum condition of solar power output.

Although Japan has been using the flat electricity price rate and has not yet introduced tiered rate in the electricity market, deregulation and smart grid society potentially will stimulate the change of payment method in the electricity market. This paper follows one of the tiered electricity price systems, or Time of Use (TOU) (Faruqui & Sergici, 2010) which is suitable to solar PV generation pattern. The data is taken from summer price plan of Pacific Gas and Electric Company Tier 1 in California (Pacific Gas and Electric Company, 2015). Even though Japan has introduced FiT since 2012, the electricity cost should be analyzed in the same platform. This paper considers FiT as a benefit of PV using Power buy-back program of Clean Energy Authority in California (Clean Energy Authority, 2015). For simplicity, electricity can be sold at a base of 7.7 cents per kilowatt hour produced under 10-year contracts.

2.3.2. Computation of each of five indicators

Firstly, the possible capacity of both the onsite solar PV and the installed battery will be identified to evaluate the ZEB performance. The determination of both the maximum ratio of solar panel to roof top and battery capacity is of use to identify the possible range. In fact, given that 12000Wh is categorized in the maximum residential battery capacity in Japan (4R ENERGY, 2014), the maximum solar PV capacity will be computed. The identified capacity combination of both the onsite solar PV and the installed battery is hereafter referred to the PV-battery capacity combination. Subsequently, under varying the identified PV-battery capacity combination, “Contribution”, “Dependence”, “Energy Loss”, “Total CO2 emissions”, and “Electricity cost” will be computed, following the definition summarized in Table 1. The detailed models and equations for each of five indicators are described in Appendix B.

It must be noted that CO2 emission per power from the grid depends on the time. CO2 emissions from the grid per power with time are computed by constructing the demand and supply grid model based on the data taken from The Federation of Electric Power Companies (The Federation of Electric Power Companies, 2015). This calculation is explained in Appendix C.

2.3.3. Analysis of ZEB performance index

The computed five indicators are integrated into a composite index to quantify overall ZEB performance. First, the computed indicators are normalized to be expressed in the same units in the form of \( I_p \). Each of five indicators is given in the form of \( X_{pi} \).

The minimum value of \( X_{pi} \) is set to zero while the maximum value of \( X_{pi} \) is set to unity in the following manner:

\[
I_p = \frac{\text{Max}(X_{pi}) - \text{Min}(X_{pi})}{\text{Max}(X_{pi}) - \text{Min}(X_{pi})}
\]

where \( p = 1: \text{Contribution}, i = \text{the PV-battery capacity combination} \)

\[
I_p = \frac{X_{pi} - \text{Min}(X_{pi})}{\text{Max}(X_{pi}) - \text{Min}(X_{pi})}
\]

where \( p = 2: \text{Dependence}, 3: \text{Energy loss 4: Total CO2 emissions, 5: Electricity cost}, i = \text{the PV-battery capacity combination} \)

Subsequently, the weight is put on the aforementioned normalized indicator to calculate a composite index. Lindberg et al. indicated that outcomes of overall ZEB performance depend on the weighting factors between their indicators, which may make it difficult to draw the clear conclusion (Lindberg et al., 2016). Weighting method should be compared for the evaluation of ZEB performance. Two weighting methods of both principal component analysis (PCA) and equal weight are presented to analyze the difference of a composite index based on the set of five indicators. The first composite index with PCA will be explained, and then the second composite index with equal weight will be introduced subsequently.

PCA is multivariate statistical approach for the replacement of a correlated variable combination to an uncorrelated one (Shukla & Kakar, 2006). The normalized indicators \( I_{pi} \) are used to calculate the \( 5 \times 5 \) correlation matrix \( R \). And then, eigenvalues \( \lambda \) of \( R \) is obtained based on the following Eq. (3).

\[
\mathbf{R} - \lambda \mathbf{I} = 0
\]

The obtained eigenvalues is decreased in the order of \( \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \). Subsequently, the following Eq. (4) is used to calculate

---

### Table 1

<table>
<thead>
<tr>
<th>ZEB performance indicators</th>
<th>Components of indicators</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy security</td>
<td>Contribution (Wh)</td>
<td>Energy transferred from ZEB to the grid for one day</td>
</tr>
<tr>
<td></td>
<td>Dependence (Wh)</td>
<td>Energy transferred from external electricity grid to ZEB including transmission loss for one day</td>
</tr>
<tr>
<td>Environment</td>
<td>Energy loss (Wh)</td>
<td>Power loss through residential battery utilization</td>
</tr>
<tr>
<td></td>
<td>Total CO₂ emissions (gCO₂)</td>
<td>The amount of CO₂ emissions from solar PV as well as from the external grid for one day</td>
</tr>
<tr>
<td>Economic</td>
<td>Electricity cost ($)</td>
<td>The total electricity cost for one day</td>
</tr>
<tr>
<td></td>
<td>Electricity price ($)</td>
<td>The price a house pays to the utility</td>
</tr>
<tr>
<td></td>
<td>FIT ($)</td>
<td>The price with which a house sells the electricity to the utility</td>
</tr>
</tbody>
</table>
eigenvectors corresponding to each of five eigenvalues.

\[(R - 
\lambda_i)A_i = 0 \]

where \(A_i = [a_{i1}, a_{i2}, a_{i3}, a_{i4}, a_{i5}]\) is a \(5 \times 5\) eigenvector corresponding to \(\lambda_i\) and then the five eigenvectors \(E_1, E_2, E_3, E_4\) and \(E_5\) are obtained. Based on both the normalized indicators and the five eigenvectors, the five principal components (PCs) are computed with the following Eq. (5).

\[P_i = I_pA_1, P_2 = I_pA_2, \ldots, P_5 = I_pA_5\]

Finally, the variance of \(P_i\) is calculated in the form of \(v_i\) to be used for weighting on the PCs. This first composite index using PCA is named ZEB performance index 1 (ZEB1) as follow.

\[ZEB1_i = \frac{\sum_{j=1}^{5} v_jP_j}{\sum_{j=1}^{5} v_j}\]

On the other hand, second composite index using equal weight, named ZEB performance index 2 (ZEB2), is derived as the root mean square of the five normalized indicators in the following equation

\[ZEB2_i = \sqrt{\frac{\sum_{j=1}^{5} (I_j)^2}{5}}\]

ZEB1 and ZEB2 in a given PV-battery capacity combination (ZEB1, and ZEB2) can be used as a composite quantitative measure for the evaluation of ZEB performance by taking into consideration the interactions of the set of indicators. A lower index corresponds to the better ZEB performance.

3. Result

3.1. Identification of the possible PV-battery capacity combination

The possible PV-battery capacity combination was firstly identified to evaluate the overall ZEB performance. Given that the surface area of solar PV module is 1.26m² and the minimum required solar modules to meet the annual electricity demand in an individual house is 22, the maximum ratio of solar panel to roof top is computed. This maximum ratio of solar panel to roof top corresponds to the maximum solar PV capacity.

\[\text{Maximum ratio of solar panel to rooftop} = \frac{\text{the surface area of solar PV module}}{\text{the minimum required solar modules}} \times \frac{\text{the surface area of roof - top}}{140\text{m²}}\]

\[\text{Maximum ratio of solar panel to rooftop} = 1.26\text{m²} \times \frac{22}{140\text{m²}} = 0.198\]

Where, the surface area of roof - top = 140m²

As such, the maximum ratio of solar panel to roof-top is estimated as 20%. Given that 12000 Wh can be considered as the maximum residential battery capacity in Japan, the installation of both “The ratio of solar panel to roof top” of 20% and “battery capacity” of 12000 Wh is selected as a maximum capacity combination.

It must be noted that the case of the maximum capacity combination should allow the only on-site supply to meet the residential demand. As such, the electricity demand and supply balance in ZEB installing the maximum capacity combination is analyzed to confirm its choice is applicable. ZEB demand and supply balance in the case of “The ratio of solar panel to roof top” of 0.2% and “battery capacity” of 12000 Wh is given in Fig. 2. The vertical and horizontal axis represents the power and time respectively. Table 2 indicates the results of five indicators based on the simulation under this condition. The surplus power is properly channeled to the battery for storage to utilize it when demand is greater than supply. In contrast, this case does not rely on the connected external electricity grid as \(X_2\) equals zero, which maintains 100% of self-sufficiency. Therefore, it can confirm that this condition can be considered as the maximum PV-battery capacity combination. In summary, the PV-battery capacity combination is explored here as follows: 0%, 5%, 10%, 15%, and 20% of “The ratio of solar panel to roof top” in steps of 5%, and 0Wh, 2000 Wh, 4000 Wh, 6000 Wh, 8000 Wh, 10000 Wh and 12000 Wh of “battery capacity” in steps of 2000Wh. Simulation will be conducted under the various PV-battery capacity combinations in this range to compute each of five indicators.

3.2. Normalization of each of five indicators

The computed five indicators in the form of \(X_{pi}\) is normalized in the identified possible PV-battery capacity combinations. Each of the five normalized indicators under all of PV-battery capacity combination is given in Fig. 3. It must be mentioned that the smaller value corresponds to the better performance in each of the five indicators.

Contribution of electricity generated on site to the grid is generally improved with the solar PV capacity increased and the battery capacity decreased especially in the case of “The ratio of solar panel to roof top” of both 15% and 20%. On the other hand, in the case of “The ratio of solar panel to roof top” of 5%, there is no contribution to the grid in spite of the different battery capacity, since the surplus power is not generated and battery does not operate. In the case of more than 6000Wh of battery capacity with “The ratio of solar panel to roof top” of 10%, since all of generated surplus power is channeled to the battery for the storage, ZEB does not feed electricity grid as well. Under these PV-battery capacity combinations, ZEB does not interact with the external grid. Meanwhile, under less than 6000Wh of battery capacity with 10% of “The ratio of solar panel to roof top”, the surplus power needs to be transferred to the grid in some extent due to the limitation of battery capacity.

Dependence on external grid electricity is generally mitigated with the battery capacity increased. Meanwhile there is almost no difference on Dependence by the change of the solar PV capacity under the PV-battery capacity combination which has the external interaction. This is because, in this condition of PV-battery capacity combination, the ratio of electricity generated by the solar PV to the residential demand is almost consistent notwithstanding the fact that the solar PV capacity is increased. Therefore, the contribution of the solar PV to the increase of self-sufficiency can be only observed in the case of small solar PV capacity, looking at the transition of Dependence from 0% to 5% of “The ratio of solar panel to roof top”.

Saving electricity by reducing the energy loss from energy conversion into and out of the battery can be obviously achieved by the battery capacity decreased. Energy loss corresponds to the operation of
battery. Therefore, ZEB with both no battery installation and no surplus power generation do not cause the electricity loss.

Total CO2 emissions are decreased with the battery capacity increased. The trend is similar to the case of Dependence. The increased imports of electricity from the grid contribute to the more total CO2 emissions. Meanwhile, after achieving 100% of self-sufficiency such as the case of “The ratio of solar panel to roof top” of 15% and 20% with the battery capacity of 12000Wh, CO2 emissions are slightly increased because of the more solar PV utilization.

Electricity cost is reduced with the solar capacity increased under the same battery capacity group. On the other hand, the increase of battery capacity only from 0Wh to 2000Wh has a contribution to the reduction of electricity cost, while there is not even a slight difference on electricity cost between 4000Wh and 12000Wh. The battery capacity size is not a significant matter for the electricity cost as long as the solar PV capacity is large enough to be installed.

### Table 2
The value of each indicator in the case of “The ratio of solar panel to roof top” of 20% and “battery capacity” of 12000 Wh.

<table>
<thead>
<tr>
<th></th>
<th>$X_1$ (Wh)</th>
<th>$X_2$ (Wh)</th>
<th>$X_3$ (Wh)</th>
<th>$X_4$ (gCO2)</th>
<th>$X_5$ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The ratio of solar panel to roof top: 20% battery capacity: 12000Wh</td>
<td>7261</td>
<td>0</td>
<td>828.3</td>
<td>1053</td>
<td>-0.56</td>
</tr>
</tbody>
</table>

3.3. Analysis of ZEB performance index

Based on the calculation result for each of the five normalized indicators, the composite index is derived from two different weighting methods. The ZEB performance index constructed with PCA is shown in Fig. 4 as ZEBI1, while the ZEB performance index using equal weight is illustrated in Fig. 5 as ZEBI2. Both ZEB performance index was computed under the various PV-battery capacity combinations. The vertical and horizontal axis means ZEBI1 and the PV-battery capacity combination respectively. The value of index cannot be compared here, since both ZEBI1 and ZEBI2 are derived from the different calculation method. The trend will be focused on to discuss the ZEB performance. The lower value of both ZEBI1 and ZEBI2 corresponds to the better ZEB performance.

ZEBI1 is improved with the battery capacity increased and with the solar PV capacity increased. ZEBI1 remains the same under the same solar PV capacity group such as “The ratio of solar panel to roof top” of 5% as well as “The ratio of solar panel to roof top” of 10% with more than 6000Wh of the battery capacity. This can be confirmed by the calculation result for each of the five normalized indicators. In ZEBI1 calculation, the worst ZEB performance is obtained in the case of “The ratio of solar panel to roof top” of 0% and “battery capacity” of 0Wh, while the best ZEB performance is given in the case of “The ratio of solar panel to roof top” of 20% and “battery capacity” of 12000 Wh.

On the other hand, ZEBI2 is generally improved with the solar PV capacity between 0Wh and 8000Wh of battery capacity. Meanwhile, under more than 10000 Wh of battery capacity, ZEBI2 is jeopardized with “The ratio of solar panel to roof top” increased from 10% to 15%.

Like ZEBI1, ZEBI2 is also consistent under the same solar PV capacity.
group such as “The ratio of solar panel to roof top” of 5% as well as “The ratio of solar panel to roof top” of 10% with more than 6000 Wh of the battery capacity. Under “The ratio of solar panel to roof top” of both 15% and 20%, ZEBI2 is amended with the battery capacity increased from 0 Wh to 2000 Wh, but it is subsequently deteriorated with the battery capacity increased from 4000 Wh to 12000 Wh. In ZEBI2 calculation, the worst ZEB performance is obtained in the case of “The ratio of solar panel to roof top” of 0% and “battery capacity” of 0 Wh, while the best ZEB performance is given in the case of “The ratio of solar panel to roof top” of 20% and “battery capacity” of 2000 Wh.

In summary, the installation of both the solar PV and battery has significantly a positive influence on the ZEB performance compared to buildings which do not use any of these two devices. This characteristic can be observed in both of the different weighting methods. On the other hand, the comparison of both ZEBI1 and ZEBI2 shows a different trend in terms of installation capacity. This different trend from the two weighting methods will be discussed below.

The main difference of proposed two weighting methods is the consideration of variance between each of the five indicators. The correlation of each indicator will be analyzed to find out what causes this difference of ZEB performance indexes.

The eigenvalues are plotted in the descending order of \( \lambda_1, \lambda_2, \lambda_3, \lambda_4, \) and \( \lambda_5 \) in Fig. 6 called a scree plot. This scree plot visually indicates components which explain most of variability. The scree plot normally has a common pattern in which a steep curve is followed by a bend and a flat line. \( \lambda_1 \) and \( \lambda_2 \) are the components in the steep curve before the first point (\( \lambda_3 \)) that starts the flat line. These two components are taken for factor loadings since successive factors \( \lambda_3, \lambda_4, \) and \( \lambda_5 \) accounts for the less amount of total variance. Factor loading \( F_1 \) and \( F_2 \) are calculated as a following equation:

\[
F_1 = \sqrt{\lambda_1} A_1, \quad F_2 = \sqrt{\lambda_2} A_2
\]

Subsequently, the communality is obtained based on factor loadings, which indicates the extent of correlation of a component with all of four other components.

\[
\text{communality} = F_1^2 + F_2^2
\]
in ZEBI2, which would cause the different trend. In summary, the comparison of different weighting method reveals that utilization of battery has an influence on the determination of ZEB performance index. In addition, the impact of 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 variance and the principle components of five indicators. 

4. Conclusion

This paper has identified indicators that are related to energy trilemma for the evaluation of ZEB performance. Subsequently, the new ZEB performance framework has been developed based on the set of chosen indicators; Contribution of electricity generated by on-site renewable sources to the grid; Mitigation of dependence on external grid electricity to increase self-sufficiency; Saving electricity by reducing the energy loss from energy conversion into and out of the battery; De-carbonization of the electricity generation in order to make the whole energy system less sensitive to global climate change; Reduction of electricity cost by reducing import from grid and increasing export to the grid. And then, each of the proposed five indicators has been computed and normalized under varying the capacity combination of both the onsite solar PV and the installed battery. Finally, using the normalized indicators, ZEB performance index has been derived and analyzed based on two different weighting methods of both principal component analysis (PCA) and equal weight. 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 variance and the principle components of five indicators.

In summary, an algorithm to evaluate ZEB performance from energy trilemma perspective has been developed to select the appropriate capacity combination both the on-site renewable sources and battery, which ensures that ZEB meets the sustainable performance goal.

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.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A

Each component of ZEB electricity demand and supply model can be computed as follows:

(A-1) \( \text{SolarPV} = \text{surfacearea of rooftop} \times \text{PV efficiency} \times \text{solar irradiation} \times \text{the ratio of solar panel to rooftop} \)

(A-2) \( \text{SurplusPower} = \text{IF THEN ELSE}(\text{Power delivery} - \text{Demand} < = 0, 0, \text{Power delivery} - \text{Demand}) \)

(A-3) \( \text{Energy Stored in battery} = \text{IF THEN ELSE}(\text{Energy stored in battery} > \text{battery capacity}, - \text{Power from battery/battery round trip efficiency}, \text{Surplus Power} - \text{Power from battery/battery round trip efficiency}) \)

(A-4) \( \text{Exporting power} = \text{IF THEN ELSE}(\text{Energy stored in battery} > \text{battery capacity}, \text{Surplus Power}, 0) \)

(A-5) \( \text{Power from battery} = \text{IF THEN ELSE}(\text{Energy stored in battery} < = 0, 0, \text{IF THEN ELSE}(\text{Actual Demand} - \text{SolarPV} < 0, 0, \text{Actual Demand} - \text{Solar PV power})) \)

(A-6) \( \text{Battery} = \text{Power from battery} \)

(A-7) \( \text{IF THEN ELSE}(\text{Actual Demand} - \text{Battery Power} - \text{SolarPV} < 0, 0, \text{Actual Demand} - \text{Battery Power} - \text{SolarPV}) \)

(A-8) \( \text{Power delivery} = \text{External electricity grid} + \text{Battery} + \text{SolarPV} \)

(A-9) \( \text{Electric Power} = \text{Power delivery} - \text{Demand} - \text{Surplus Power} \)

---

Table 3

<table>
<thead>
<tr>
<th>Indicator</th>
<th>F1</th>
<th>F2</th>
<th>Communality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution</td>
<td>-0.29</td>
<td>-0.95</td>
<td>0.98</td>
</tr>
<tr>
<td>Dependence</td>
<td>-0.98</td>
<td>0.11</td>
<td>0.97</td>
</tr>
<tr>
<td>Energy loss</td>
<td>0.89</td>
<td>-0.33</td>
<td>0.88</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>-0.95</td>
<td>0.21</td>
<td>0.94</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>-0.92</td>
<td>-0.36</td>
<td>0.96</td>
</tr>
</tbody>
</table>

---

The result of both factor loading and communality are presented in Table 3. The less communality corresponds to the less correlation with the ZEB performance index. The communality of each of five indicators is decreased in the order of Contribution, Dependence, Electricity cost, Total CO₂ emissions and Energy loss. As such, contribution of electricity generated by on-site renewable sources to the grid can be considered to significantly contribute to the determination of ZEBI1. Meanwhile saving electricity by reducing the energy loss from energy conversion into and out of the battery has the least impact on ZEBI1 calculation. According to the normalized indicators in the case of “The ratio of solar panel to roof top” of both 15% and 20% in Fig. 3, the energy loss is obviously reduced by the decreasing battery capacity. Besides that, under “The ratio of solar panel to roof top” of 15% and 20% with the larger battery capacity such as 8000 Wh, 10000 Wh and 12000 Wh, the normalized energy loss represents the worse performance than the other 4 indicators in the same condition. Therefore, the impact of energy loss is not observed in ZEBI1, although it significantly contributed to the deteriorated ZEB performance with the battery capacity increased under “The ratio of solar panel to roof top” of 15% and 20%.

---

Fig. 6. Scree plot.
Appendix B

The equations for each of five indicators are summarized in Table B1. The models for each of five indicators are given as well in Figs. B1–B5.

Table B1
The equations for each of five indicators.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution</td>
<td>Contribution = ( \int \text{Exporting power} ) (B-1)</td>
</tr>
<tr>
<td>Dependence</td>
<td>Dependence on external electricity grid ( = \text{Externaelelectricitygrid} \times \text{transmissionlossrate} ) (B-2)</td>
</tr>
<tr>
<td>Energy loss</td>
<td>Power loss = Power from battery/battery round trip efficiency ( - \text{Power from battery} ) (B-4)</td>
</tr>
<tr>
<td>Total CO(_2)</td>
<td>CO(_2) emissions = dependence on external electricity grid ( \times \text{CO}_2) emissions from grid ( + \text{SolarPV} \times \text{CO}_2) emissions from PV ( (B-6) )</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>Electricityprice = ( \int \text{Externaelelectricitygrid} \times \text{Electricitypricerate} ) (B-8)</td>
</tr>
<tr>
<td></td>
<td>TotalCO(_2)emissions = ( \int \text{CO}_2)emissions (B-7)</td>
</tr>
<tr>
<td></td>
<td>FIT = ( \int \text{Exportingelectricity} \times \text{FiTrate} ) (B-9)</td>
</tr>
<tr>
<td></td>
<td>Electricity cost = Electricityprice ( - \text{FIT} ) (B-10)</td>
</tr>
</tbody>
</table>

Fig. B1. Contribution.

Fig. B2. Dependence.

Fig. B3. Energy loss.

Fig. B4. Total CO\(_2\) emissions.
Appendix C

CO₂ emission per power from the grid depends on the time due to the grid electricity configuration. The grid electricity demand and supply model is constructed as shown in Fig. C1. The subject of this model is Kansai area, where Kyoto is located. The basic structure is almost the same as ZEB electricity demand and supply model. The grid demand consumes electricity generated by oil, LNG, coal, nuclear, hydro and pumped-storage hydro power plants. The surplus power will be used for storage as pumped storage hydro through which the feedback loop can be seen. The use of pumped storage hydro is illustrated in Fig. C2.

![Fig. B5. Electricity Cost.](image)

![Fig. C1. The grid electricity demand and supply model.](image)

**Table C1**
The installed capacity of each electricity component.

<table>
<thead>
<tr>
<th>Electricity component</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>9760</td>
</tr>
<tr>
<td>Oil</td>
<td>6220</td>
</tr>
<tr>
<td>Coal</td>
<td>1800</td>
</tr>
<tr>
<td>LNG</td>
<td>8010</td>
</tr>
<tr>
<td>Hydro</td>
<td>3320</td>
</tr>
<tr>
<td>Pumped storage hydro</td>
<td>4880</td>
</tr>
</tbody>
</table>

![Fig. C2. CO₂ emissions from grid per power.](image)
storage hydro can be recognized as the large scale storage system and modeled here as such. Oil, LNG and hydro are considered as an operation-controlled power. Reference daily load curve for maximum demand day in Kansai area published by the government (Ministry of Economy, Trade and Industry (METI), 2011b) is used as input for grid demand. The installed capacity of each electricity component uses the data before the Great East Japan Earthquake given in Table C1. The parameter “CO₂ emissions from grid” per power with time is computed based on the simulation of the grid demand and supply model with the data of CO₂ emissions from different sources (The Federation of Electric Power Companies, 2015). The result is given in Fig. C2.

References


