Zero Energy Potential of High-Rise Residential Buildings

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Abstract
This study aims to determine the zero energy potential of high-rise residential buildings based on the energy use of recently occupied apartments. Among the 33 newly built apartment complexes which were occupied from 2008 to 2010, the 5 complexes whose scale, type and energy consumption rate were similar were analyzed in terms of energy consumption during the year 2012. For renewable energy, optimally tiled rooftop PV panels on the rooftops of residential buildings and PV panels in four directions with the PV system as a basis were used. The zero energy potential and strategy for residential buildings based on PV panels are suggested in this study.

Keywords: zero energy building; solar energy production; actual energy consumption; high-rise residential building

1. Introduction
1.1 Background: Literature Review of Previous Research Papers
At the 6th meeting of the Global Green Growth Institute held in November 2009, the mid/long-term road map for building energy saving was established. In the case of residential buildings, it was announced that 60% energy saving at the level of passive houses up to 2017 and zero energy by 2025 be obligatory. The U.K. government announced the Building Regulations of 2006 levels compared to 25% reduction by 2010, 44% reduction by 2013 (Passive House Level) and the obligation of NZEB (Nearly Zero Energy Building) by 2016. The German government announced the EnEV 2007 levels compared to 30% reduction by 2009, the EnEV 2009 levels compared to 30% reduction by 2012 and the obligation of NFFB (Buildings to operate without fossil fuels) by 20201), with the specific practical strategies and plans being established.

Since more than ten years ago, various researches have been conducted on zero energy single-family homes that operate only on renewable energy without relying on fossil fuels; some houses have already proved the economic benefits.

In Korea, researches on building design methods and the thermal performance evaluation for energy independent houses are in progress. Zero energy homes require an effective combination of energy conserving and renewable energy production technologies. Thus, an integrated design process with proper technical priorities is the key to success.

Previous studies on zero energy buildings were geared to single family homes or small-size office buildings.

There has yet to be a study on the feasibility analysis of zero energy high-rise residential buildings. Furthermore, most studies on zero energy buildings were based on simulated building energy demands. To achieve a higher level of validity, it is of great importance to assess the feasibility using actual energy consumption data of existing buildings.

As such, this study investigated the actual energy consumption of high-rise residential buildings for one year in 2012. To this end, apartment complexes constructed and occupied from 2008 to 2010 were studied.

2. Research Design
This study examined the feasibility of high-rise residential buildings that incorporate photovoltaic (PV) panels as the on-site energy production system. For the purpose of estimating the energy demands of high-rise residential buildings, we compiled the energy consumption data of existing apartment complexes.

It also analyzes the possibilities in terms of climate, technology, and economy as well as the possible building scale and possibility of energy self-sufficiency.
It also examines the roof and sides of the test building where solar panels could be installed as well as the potential of zero energy houses by means of solar energy, and also the realistic scale of zero energy houses is estimated based on PV energy production.

2.1 Test Building

The test building is a high-rise residential building. To identify a representative South Korean high-rise residential building, more than 100 housing complexes recently built in Gwang-ju were investigated. The test building was selected based on the building shape, unit size and planning, and the combination of unit size. The selected test building houses multistory flats, each floor consisting of two symmetrical apartment units, which is the most popular high-rise apartment type. The units contain common step-up structures and an elevator hall. The floor plan is approximately 30m wide and 10.4m deep. (See Fig.1.)

The floor area of each unit of the test building is 85m$^2$. The floor area on each floor including the core and corridor is 309.0m$^2$. The total floor area of the building is 6,798.0m$^2$.

The floor-to-floor heights of the piloti, 2nd floor, and standard floor were different. The piloti was 3.6m high, the 2nd floor 2.9m, and the standard floor 2.8m respectively. The total height up to the rooftop was 68.7m, and that up to the edge of the rooftop tower was 74.6m. The physical features of the test building are presented in Table 1.

Table 1. Overview of High-Rise Residential Buildings

<table>
<thead>
<tr>
<th>Contents</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather Data</td>
<td>Gwang-Ju</td>
</tr>
<tr>
<td>Unit Area</td>
<td>85.0m$^2$</td>
</tr>
<tr>
<td>Floor Area</td>
<td>Unit Area: 85.0m$^2$</td>
</tr>
<tr>
<td></td>
<td>Floor Area: 309.0m$^2$</td>
</tr>
<tr>
<td></td>
<td>Total Floor Area: 6,798.0m$^2$</td>
</tr>
<tr>
<td>Height</td>
<td>Pilotis Height: 3.6 m</td>
</tr>
<tr>
<td></td>
<td>2nd Floor Height: 2.9 m</td>
</tr>
<tr>
<td></td>
<td>Typical Floor Height: 2.8 m</td>
</tr>
<tr>
<td>Direction</td>
<td>South</td>
</tr>
</tbody>
</table>

The test building has four major vertical surfaces. The front facade faces south and has three windows: balcony window (A), living room front window (B), and small-bedroom window (C). The living room and small bedroom windows are in direct contact with the open air, and their heat transmission coefficient is 1.178 W/m$^2$k. Windows (A) and (B) are made of 22mm thick multi-layered glass of which the heat transmission coefficient is 2.80 W/m$^2$k.

The rear north facade has four windows: dressing room window (a), multi-purpose room window (b), kitchen window (c), and boiler room window (d). Both (a) and (c) are in direct contact with the open air. The heat transmission coefficient of the windows is 1.178 W/m$^2$k. Both (b) and (d) are made of 22mm thick multi-layered glass, and their U value is 2.80 W/m$^2$k. There are no windows on the east or west facade.

2.2 Potential Area of PV Panels on Building Facades

The exterior surfaces where PV panels could be installed are the roof and the four facades (south, north, east, and west). It was assumed that PV panels were installed on the flat area of the roof excluding sloped surfaces. The area on the roof where panels could be installed is 204.78 m$^2$, and is indicated by the dashed lines in Fig.3.

On the south facade, in consideration of the design characteristics, PV panels were installed in opaque walls between, above and below windows. On the north facade, similar with the south facade, PV panels were arranged horizontally in the upper and lower wall surfaces between windows. Installation of PV panels on the elevator and staircase enclosure surfaces were
The PV panels were arranged horizontally in rectangular patterns (See Fig.4.). The PV installation area of each surface of the test building is presented in Table 3. below.

Table 3. Each Elevation Area of PV Panel Installation

<table>
<thead>
<tr>
<th>Position of Installation</th>
<th>Area</th>
<th>Position of Installation</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>204 m²</td>
<td>Canopy</td>
<td>30.1 m²</td>
</tr>
<tr>
<td>Canopy</td>
<td>23.4 m²</td>
<td>Top floor</td>
<td>9.6 m²</td>
</tr>
<tr>
<td>Top floor</td>
<td>19.1 m²</td>
<td>Typical floor</td>
<td>15.0 m²</td>
</tr>
<tr>
<td>Typical floor</td>
<td>18.9 m²</td>
<td>East</td>
<td></td>
</tr>
<tr>
<td>Lowest floor</td>
<td>30.6 m²</td>
<td>Top floor</td>
<td>52.1 m²</td>
</tr>
<tr>
<td>The whole face (22 floors)</td>
<td>488.9 m²</td>
<td>Typical floor</td>
<td>376.8 m²</td>
</tr>
<tr>
<td>Canopy and top floor</td>
<td>15.3 m²</td>
<td>Lowest floor (3 floors)</td>
<td>9.6 m²</td>
</tr>
<tr>
<td>Typical floor</td>
<td>24.8 m²</td>
<td>The whole face (22 floors)</td>
<td>15.0 m²</td>
</tr>
<tr>
<td>Lowest floor</td>
<td>35.8 m²</td>
<td>Lowest floor (3 floors)</td>
<td>52.1 m²</td>
</tr>
<tr>
<td>The whole face (22 floors)</td>
<td>596.7 m²</td>
<td>The whole face</td>
<td>376.8 m²</td>
</tr>
</tbody>
</table>

The whole face (22 floors)| 488.9 m²| Canopy | 30.1 m²|

3. Building Energy Demand
3.1 Energy Consumption of High-Rise Apartment Buildings in Korea

It is the intention of this study to assess the feasibility of a zero energy building based on the actual energy demands of an existing high-rise residential building in Gwang-ju, South Korea. To this end, we needed to collect energy consumption data for high-rise apartment buildings. We sampled five apartment complexes built during 2008 and 2010 consisting of a similar apartment unit size of 85 m². The energy consumption data of the sample high-rise apartment complexes were derived from two sources. First we obtained the gas energy bill from the Apartment Management Information Systems being administered by the Korean Ministry of Land, Infrastructure and Transportation. The Ministry mandates all apartment complexes to report their maintenance costs including gas and electricity bills and publish them in the Information Systems. Using an on-line calculator that converts gas bills to the quantity of gas consumption, we could determine the amount of gas consumption of the sample apartment complexes.

The electricity consumption data of the sample apartment complexes were derived using electricity bills from the Apartment Management Information Systems. From the Information systems, the electricity bills of the five sample apartment complexes were obtained. Using a table published by the Korea Electric Power Corporation (KEPCO) that shows electricity bills and the corresponding quantity of electricity consumption, we were then able to determine the electricity consumption of the sample apartment complexes.

The electricity consumption data of the sample apartment complexes were derived using electricity bills from the Apartment Management Information Systems. From the Information systems, the electricity bills of the five sample apartment complexes were obtained. Using a table published by the Korea Electric Power Corporation (KEPCO) that shows electricity bills and the corresponding quantity of electricity consumption, we were then able to determine the electricity consumption of the sample apartment complexes.

Taking into account the graduated rates, the KEPCO table correlates electricity bills and the amount of electricity consumed in Kwh. Table 4. shows the annual gas, electricity and total energy consumption per unit floor areas (m²) of the sample apartment complexes. The highest total energy consumption was 109.1 Kwh/m²-yr, the lowest 87.91 Kwh/m²-yr, and the average 95.8 Kwh/m²-yr, of which electricity consumption was 38.1 Kwh/m²-yr and gas consumption 57.5 Kwh/m²-yr. From this analysis, it was found that gas energy for heating and cooling takes a majority, 60% of energy consumption in high-rise residential complexes, and electrical energy for plug-in loads and cooling takes a minor portion of 40%. Applying the method described above, monthly average gas and electricity...
consumptions of the five sample apartment complexes were calculated (See Table 5).

Monthly energy consumption by fuel type reveals that the fluctuation of energy consumption during the year is due primarily to gas energy consumption. According to the monthly energy consumption, the highest heating season is in February and the lowest cooling season is in July. On the other hand, electricity consumption during the course of a year was remarkably constant at approximately 3.1 Kwh/m²·yr. Only in August and September, did electricity consumption increase slightly due to air-conditioning. The ratio of gas to electricity energy consumption during the year was 6:4.

4. Onsite Renewable Energy Production

Electricity produced from PV systems is a function of solar radiation incident on PV panels and the efficiency of PV systems as:

\[ E_p = E_s \times \eta \]

where, \( E_p \) is electricity produced from PV systems, \( E_s \) is global solar radiation incident on solar panels, and \( \eta \) is the efficiency of PV systems including the PV cell efficiency and the efficiency of all system components including the inverter. Thus, in order to calculate electricity production from on-site PV systems, solar irradiance data for each PV panel installed on the test building must be estimated and the efficiency of PV systems must be determined.

4.1 Solar Radiation Availability

The test building has PV panels installed on four vertical surfaces and on the roof. The ones on the roof are facing south but are tilted optimally for the test city, Gwang-ju Korea, whose latitude and longitude are 35.1° and 126.8° respectively. According to NASA (reference), the optimum tilt angle of non-tracking solar panels in Gwangju is 30.8°. Thus in order to calculate electricity production from the building, solar irradiance data for four vertical surfaces facing east, west, south and north and a south-facing surface whose...
A tilted angle is 30.8° must be determined. The annual average solar irradiance on the optimally tilted surface in the test city is readily available as 4.69 Kwh/m²/day. However, because of the absence of available data, the vertical irradiance data on the four surfaces were calculated using Ecotect, which is capable of determining both direct, diffuse and reflected solar irradiance. The solar radiation is the global normal radiation in Ecotect. Table 6. shows monthly and yearly average solar irradiance on the four vertical surfaces and the optimally tilted south-facing surface.

4.2 Onsite Energy Production

The efficiency of a PV system is affected by a variety of factors. The energy conversion efficiency of a PV cell is the foremost significant factor for a PV system. According to 'the renewable energy technology cost analysis series' published by IRENA (International Renewable Energy Agency), the average efficiency of PV cells in the year 2011 was 14%, and it is expected that this will increase to 20% by 2015. This study assumes two PV system efficiencies: 14.0% and 17.0%. Thus, the system efficiency refers to the efficiency of the total system including all losses associated with the inverter, dirt accumulation, aging, etc. The variation of the conversion efficiency of PV cells due to air temperature was disregarded.

5. Zero Energy Potential

According to the domestic Building Act, 'a high-rise residential building' means a building with 5 or more floors of housing units among various types of residential buildings (apartment, townhouse, and multiple housing). Hence, when it comes to the potential of zero energy of high-rise residential buildings, it is assumed that the building is at least a 5-story building.

5.1 Zero Energy Potential as PV Efficiency

When the PV panel efficiency is 14.0%, it is possible to generate electric power as much as 151.3% in the case of a 22-story building, which is 60.2% of the entire energy consumption. As for the number of floors in the building, 'zero energy' would be possible in a 7 to 8-story building. When PV panels are installed only on the rooftop, the number of floors that can be covered for electricity consumption is 7 to 8. It would be impossible to cover the entire energy consumption regardless of the number of floors. When PV panels are installed only on the rooftop, it is possible to cover 13.6% of the total energy consumption and 34.3% of the electricity consumption. (See Fig.7. and Fig.8.)

When PV panel efficiency is increased to 17.0%, it is possible to achieve 'zero energy' for a higher building. In the case of a 22-story building, it is possible to generate power as much as 183.8% of the entire consumption and to cover 73.1% of the entire energy consumption. The number of floors of a residential building in which 'zero-energy' would be possible was 10 to 11. (See Fig.9.)

When PV panels are installed on the rooftop only, the power generation will be similar to the electricity consumption in the case of a 9 to 10-story building. 'Zero-energy' would be impossible with panels on the rooftop only regardless of the number of floors. (See Fig.10.)

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hori</td>
<td>2.45</td>
<td>3.44</td>
<td>4.44</td>
<td>5.37</td>
<td>5.51</td>
<td>5.13</td>
<td>4.76</td>
<td>4.92</td>
<td>4.29</td>
<td>3.71</td>
<td>2.67</td>
<td>2.22</td>
</tr>
<tr>
<td>South</td>
<td>2.21</td>
<td>2.46</td>
<td>2.47</td>
<td>2.24</td>
<td>1.79</td>
<td>1.49</td>
<td>1.58</td>
<td>1.84</td>
<td>2.20</td>
<td>2.85</td>
<td>2.51</td>
<td>2.16</td>
</tr>
<tr>
<td>East</td>
<td>1.11</td>
<td>1.43</td>
<td>1.86</td>
<td>2.25</td>
<td>2.52</td>
<td>2.15</td>
<td>2.20</td>
<td>2.01</td>
<td>2.04</td>
<td>1.73</td>
<td>1.29</td>
<td>1.00</td>
</tr>
<tr>
<td>West</td>
<td>0.89</td>
<td>1.18</td>
<td>1.56</td>
<td>1.93</td>
<td>2.20</td>
<td>1.87</td>
<td>1.93</td>
<td>1.92</td>
<td>1.62</td>
<td>1.44</td>
<td>1.01</td>
<td>0.84</td>
</tr>
<tr>
<td>North</td>
<td>0.60</td>
<td>0.78</td>
<td>0.94</td>
<td>1.01</td>
<td>1.29</td>
<td>1.36</td>
<td>1.43</td>
<td>1.36</td>
<td>0.97</td>
<td>0.74</td>
<td>0.63</td>
<td>0.57</td>
</tr>
<tr>
<td>Opt</td>
<td>3.81</td>
<td>4.53</td>
<td>5.10</td>
<td>5.55</td>
<td>5.51</td>
<td>5.10</td>
<td>4.74</td>
<td>4.98</td>
<td>4.60</td>
<td>4.75</td>
<td>3.95</td>
<td>3.66</td>
</tr>
</tbody>
</table>
According to a report from IRENA, the PV panel efficiency of Super Mono Crystalline Silicon was 20.0% as of 2011. In this case, 'zero-energy' would be possible between the 13th and 14th floors of the residential building.

When the PV panel efficiency increases to 24.0%, 'zero-energy' will be possible even on the 22nd floor. The PV panel efficiency as of 2011 was 14.0%, and has recently increased to 17.0%. It is assumed that as the PV panel efficiency increases, the possibility of 'zero energy' will increase accordingly.

As PV panel efficiency increases to 24.0%, zero energy housing will be possible in 22 floors. In addition, when the PV panels are installed on the rooftop only, it is possible to generate power up to 58.8% of the entire electricity consumption.

As PV panel efficiency increases even up to 24.0%, it will be possible to generate power up to 23.4% of the entire energy consumption. When PV panels were installed on the rooftop only, it increased to 25.0%, which is one fourth of the entire consumption in 22 floors. (See Fig.11.)

5.2 Monthly Energy Trade-Off

The data of each month was analyzed for a 10-story zero-energy residential building with a PV efficiency of 17.0%.

In January, February and March during which heating energy consumption is high, the quantity of remaining energy (energy consumption – energy generation) was negative while in the other months, it was positive. The greatest deficit took place in January, during which the loss reached 4,933Kwh. The greatest amount of remaining energy was 14,036Kwh in July. The total remaining energy during the year was 75,653Kwh. (See Fig.12.)

When PV panels are installed on the rooftop only, 91.6% of the entire electricity consumption will be produced.

In January, February, August, September, November and December, the remaining energy was negative while in the other months, it was positive. The entire electricity consumption was 64,770Kwh and energy production was 59,049Kwh. Therefore, the deficit of energy each year would be 5,721Kwh. (See Fig.13.) This is more than the electricity consumption per month in one residential building. When PV panels are installed on the roof only, it will be required to pay the electricity bill for only one month during the year.

The power generation of PV panels installed on the rooftop and all four sides (south, east, west, and
north) is presented in Fig. 15. From April to August, the production of PV panels on the rooftop was the largest, and in the other months, that on the southern side was the largest. The production on the northern side was more than on the eastern and western sides in June, July and August. In the remaining months, the production on the western and northern sides was similar. (See Fig. 14.)

Although there was a risk of production drop in the case of the northern side, the solar radiation would be constant because the area of panel installation was large and there was no influence from shade, etc. (See Fig. 15.)

6. Conclusions

The possibility of realizing a zero-energy residential building was determined based on the actual energy consumption during the year.

The possibility of realizing a zero-energy residential building through solar energy generation by means of PV panels on the rooftop and sides of the building (front, rear, right and left sides) was examined in this study. The efficiency of PV panels considered in the study was 14.0% on average in the year 2011 and 17.0% in the year 2014. In the former case, it turned out that zero-energy consumption would be possible in a 7-story building when the panels were installed on the rooftop and on all the sides. When installed only on the rooftop, electricity consumption was saved in a 7-story building. In the case of the latter, zero energy will be possible in a 10-story building when panels are installed on the rooftop and sides. When they are installed on the rooftop only, electricity consumption will be saved in a 9-story building. When the PV panel generation efficiency reaches 24.0%, it will be possible to realize zero-energy when all panels are installed on the rooftop and sides. In a 10-story building capable of zero energy housing, compared with the energy consumption rates per month, the remaining energy was negative in January, February and March. In the other months, it was positive.

The results of this study suggest that this is an important way of improving the performance of heating rather than cooling to satisfy a zero-energy high-rise residential building. So on the demand-side, the current levels of building energy demands must be drastically reduced, employing energy conserving building strategies such as high insulation of walls and windows, shading of windows, high efficiency lighting fixtures and heating systems. The pairing of energy demand reduction with onsite renewable technologies is an essential strategy for zero energy buildings.
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