# An Analysis of Energy Efficiency of a Smart Envelope Package in Residential Buildings

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ABSTRACT: In the 1980s and 90s, the construction codes of South Korea did not require substantial insulation, which resulted in a large amount of cooling and heating energy uses in high-rise residential complexes. About 3.6 million residential units were constructed during that period. Since 2014, the Korean government initiated an incentive program to remodel the aged residential units, and only about 2,000 units have taken advantage of the incentive in the last 3 years. Over the last two to three decades, residents have extended living spaces to the balcony areas which were designed to serve as a sun space using passive solar principles. The energy consumption has consequently increased significantly due to the loss of thermal buffer area and an addition of the conditioned space. This study proposes a Smart Envelope Package that can replace an existing exterior window enclosing the living room area of such residential units. This smart envelope package is designed to reduce building's energy use functioning as a Double Skin Façade, and comes with Building Integrated Photovoltaics (BIPV) to generate electricity, an Energy Storage System (ESS), an A/C condenser, sun-shading devices, automated operable windows and an air filtration system. The Smart Envelope Package aims to reduce cooling and heating energy consumption and to produce electricity during daytime as well, which will be stored in the ESS and used during peak hours and nighttime. The trend of adopting prototype floor plans with very little modifications 20-30 years ago makes the package possible to be modularized and pre-fabricated. This paper discusses optimal sustainable design strategies for the development of the Smart Envelope Package system. The main goal and result of this paper is to find a new product to reduce the energy consumption in old high-rise residential building in South Korea.

KEYWORDS: Smart Envelope Package, Energy Efficiency, High-rise residential building, EnergyPlus

## INTRODUCTION

Buildings use 40% of total energy in the world, and this is steadily increasing due to industrial development (EIA, 2017), which means, to reduce the total energy consumption, building energy has to be reduced. In order to reduce it, researchers and governments take advanced approaches through innovative design and smart controls. High-efficiency equipment has been introduced to improve energy efficiency and reduce energy consumption of existing buildings. South Korea made a dramatic economic growth (Chang, 2006), and in terms of the residential spaces, high-rise building became one of the most dominant types of housing (Yuen, 2011). Research shows that in South Korea there are 10 million multi-family residential units (called "apartment" in South Korea), which is 60.1% of all the housing. Out of the total apartments today in South Korea, 36.2% or 3.6 million apartments were built 20 years ago or earlier (Statistics Korea, 2016). New buildings consume relatively less energy than buildings built in the past due to the added efforts such as utilizing highly efficient insulation, lighting and equipment. At the time of construction of the old buildings, the construction codes were not strict enough to require good insulation, which resulted in a large amount of cooling and heating energy uses. Out of the 3.6 million residential units constructed about 20 years ago or earlier in South Korea, only very few (about 2,000 units) have been remodeled through a government incentive program since 2014. In terms of the energy sources, South Korea ranked 7th for $CO_2$ emissions per person in 2016. To reduce the $CO_2$ emissions, each country has to use and develop renewable energy following an effort in making high-performance buildings. Unfortunately, South Korea ranked 8th for electricity production from fossil fuel, non-ranked for solar power production and ranked 10th for other renewable energy in 2016 (Olivier et al., 2017). To reduce the $CO_2$ emissions, South Korea revised its policies in 2001 for enhanced building regulations and policies; and apartment buildings were required to be energy-efficient buildings. As a result, 1,380 residential buildings have received preliminary Building Energy Efficiency Certification from 2001 to 2014. In 2001, however, only one residential building was able to get it. After that, the number of certified buildings increased every year, and 267 new residential buildings obtained this certificate in 2014 (Park et al., 2015).

This paper presents the development of a Smart Envelope Package (SEP) that integrates multiple passive and active strategies that aim to reduce $CO_2$ emissions and increase renewable energy market.

Various research projects are underway to reduce the building energy uses and $CO_2$ emissions by using high efficiency heating, ventilation, and air-conditioning (HVAC) systems, high performance insulation, and optimal control systems. Even if high efficiency equipment is used, high efficiency would not be readily realized without optimal control. Optimal control algorithms can be developed by utilizing Artificial Intelligence (AI) technologies. An AI control system will be developed and used to control the devices and equipment installed in the SEP, such as window, blind and ESS. This paper is focused on confirming the potential of building energy savings through SEP itself and control strategies. The application of optimal control to achieve the maximum energy efficiency will follow in the future.

## 1.0 LITERATURE REVIEW

The significance and prevalence of the reduction of building energy consumption and $CO_2$ emissions enabled a number of studies to be carried out. In order to reduce building energy consumption and $CO_2$ emissions, a number of studies suggested remodeling or retrofitting of existing housing. Morelli et al. conducted research on three ways of retrofit-measures, which were implemented in a test apartment using practical experiences. The three types were i) changing interior insulation, ii) hanging exterior window, and iii) installing a decentralized mechanical ventilation system with heat recovery in an old Danish multi-family building to make a nearly-zero energy building. The results of this study were that it is difficult to achieve a nearly-zero energy building without generating renewable energy on site, although these methods could reduce 68% of building energy. Dallo et al. (2012) conducted research about the methodology for evaluating the energy saving from retrofitting residential buildings. This methodology, which contained a survey, changing windows, roof, insulation, and facades, could reduce energy used by residential buildings in European Union (EU) up to 24.8% by 2020. Arumagi and Kalamees (2014) analyzed building energy use for historic wooden apartment buildings. The results of this study were that building energy use could be reduced by 20% to 65% with an improvement of HVAC system and building envelope.

Most of the studies have been conducted to reduce residential building energy use by means of improving the efficiency of building envelope and HVAC system. Remodeling by changing the envelope and the HVAC system is time consuming, and residents might not be able to use their rooms while the remodeling takes place. The proposed SEP is a new style of Double Skin Façade (DSF). There is no such study directly related to SEP, but there are many studies about DSF. Most of the studies about DSF focused on reducing building energy consumption. Gelesz and Reith (2015) compared DSF with triple glazing. They found that DSF could reduce 9% to 12% of cooling energy without increasing heating energy in Central Europe. However, the DSF system in the study was used only for buffer effect. Gratia and Herde (2007) conducted simulation study to analyze heating and cooling energy depending on whether DSF was installed (south, north, east and west). They found that the amount of decrease in energy was different. Heating load decreased but cooling load increased regardless of the installed direction. The DSF system was not the best way to reduce building energy. They reported that weather and building conditions had to be considered before the application of DSF systems. This was a simple DSF system where only a window was attached on the exterior. It did not combine BIPV, ESS or other systems for multi-functional DSF system like SEP.

The objective of this study is to make a new style of DSF system and investigate the heating and cooling load variation caused by this new SEP which includes BIPV and ESS. The DSF system will act as a thermal buffer area and a new exterior envelope of apartment. It is expected that the DSF system with a window control (On/Off) has potential to improve energy efficiency of building. The BIPV will generate electricity, which will be stored in the ESS. The electricity stored in ESS will be used to reduce peak heating and cooling loads and supplement the energy required in building.

## 2.0. RESEARCH SCOPE

This paper presents the results of an early-stage research that develops a SEP for building energy savings of old high-rise residential buildings and proposes an optimal control of the envelope interacting with the residents. This paper lays out the initial design of the SEP and an analysis of how much energy can be saved through this SEP system. This paper focuses on old high-rise residential buildings built more than 20 years ago in South Korea. The 2016 Population and Housing Census (2016), which is an annual report published by Statistics Korea, reported that an average area of high-rise residential units built before 1979 is 80.4m$^2$, the one from 1980 to 1989 is 65.6m$^2$, and the average built during 1990 to 1999 is 70.0m$^2$. Seoul Housing & Communities Corporation, founded by Seoul Metropolitan Government (SMG), provides three common floor plans of high-rise residential buildings as 59m$^2$, 85m$^2$, and 115m$^2$. This study used a common high-rise residential building floor plan (59m$^2$) to analyze building energy use. These areas do not include the balcony, the area to which many residents have extended their living room. Since this study focuses on the SEP system to be installed in this extended balcony area or an additional floor space of an apartment, the total floor area of the simulation model is 69.3m$^2$ which became the Base Model. Then a design model was developed with SEP being attached without BIPV and ESS for comparison of building energy use and the impact by SEP itself. After that, the BIPV and ESS were integrated with SEP to know how much electricity it generated and how much building energy and peak energy could be reduced by the generated electricity from the BIPV.

## 3.0. SIMULATION MODELING OF SEP

## 3.1. Simulation program

The EnergyPlus program (version 8.8) was used to create a sophisticated simulation model, which is a robust building energy simulation program developed by Department of Energy (DOE) in United States (Wall and Bulow-Hube, 2003). EnergyPlus is capable of dynamic analysis of thermal conduction, radiation, and convective heat transfer, and it can mathematically verify the energy and thermal environment of the building that changes according to building envelope and indoor and outdoor weather conditions. EnergyPlus uses a heat balance method which is recommended by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). EnergyPlus can calculate and analyze building energy, and it is possible to accurately predict and analyze the amount of building energy to be reduced through the SEP that is covered in this study. EnergyPlus also has PV and ESS modules (U.S. DOE, 2017a), which is suitable for this study. In addition, the basic control of window opening (On/off control) can be performed since the user can input the desired control.

## 3.2. Simulation model development

A middle unit was selected out of a multi-story apartment complex shown in Figure 1. Based on the most common floor plan of old residential units in South Korea, a simulation model was made using EnergyPlus version 8.8. To avoid the effect from the ground and external roof, the SEP was applied to the middle floor as shown in Figure.1. In order to analyze in more detail, this study considerd four cases as shown in Table.1.
Case 1 was the base model, Case 2 was the SEP case without window opening control, BIPV or ESS to analyze the reduction of building energy consumption through the passive effect from the SEP itself. Case 3 added a window opening control to see the change in building energy use. Case 4 was the final case of this study with BIPV and ESS being added to the Case 3 to know how much electricity was generated and how much building energy could be covered by the BIPV and ESS.
The size of this package was 6.6m (W) x 0.8m (D) x 2.2m (H). There were total 12 windows, 4 of which were set on the top of the wall that were motorized and another 4 were set in middle of the wall operable by occupants. Four large windows were fixed with double glazing in the Case 2 and 3, and BIPV in the Case 4.

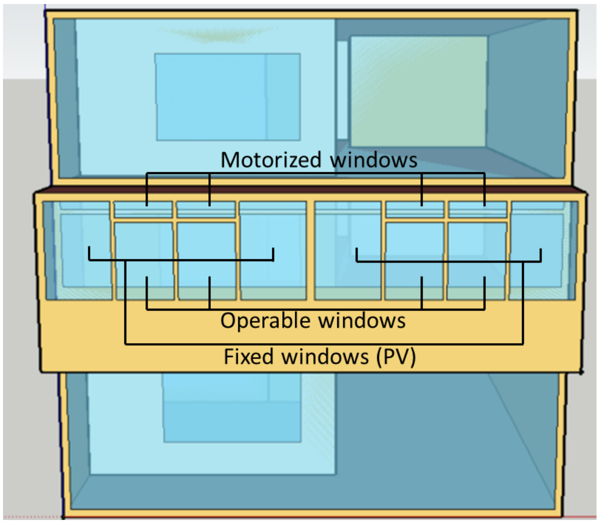

**Figure 1**: Simulation model

**Table 1**: Description of the cases

| | |
|---|---|
| *Case 1* | *Base model* |
| *Case 2* | *Smart Envelope Package* |
| *Case 3* | *Case 2 + window opening control* |
| *Case 4* | *Case 3 + BIPV and ESS* |

To make the simulation model, building materials provided by “Energy Technology Transfer and Diffusion” which was published by Korea Institute of Energy Research in 2007 were used. This report provided common building materials and construction of the residential units in South Korea. Tables 2 and 3 show the building construction and characteristics of materials used to develop the simulation model. All windows were double glazed of which each pane is 6 mm. The blind, which was set between SEP and building, has a slat width of

25 mm, slat separation of 25 mm, slat thickness of 1 mm, and the solar reflectance for both front and back side of 0.5 which are default values in the EnergyPlus simulation program.

**Table 2**: Construction of simulation modelling

| | Layers | | | |
|---|---|---|---|---|
| Interior wall | Gypsum | air | Gypsum | |
| Exterior wall | Stucco | Concrete | Insulation | Gypsum |
| Floor | Carpet | Concrete | | |
| Roof | Roof membrane | Insulation | Metal Decking | |
| Window | 6mm clear | air | 6mm clear | |

**Table 3**: Characteristics of building materials

| Material | Conductivity (W/m·K) | Density (kg/m³) | Specific Heat (J/kg·K) |
|---|---|---|---|
| Stucco | 0.6918 | 1858 | 837 |
| Concrete | 1.729 | 2243 | 837 |
| Insulation | 0.0432 | 91 | 837 |
| Gypsum | 0.16 | 784.9 | 830 |
| Roof membrane | 0.16 | 1121.29 | 1460 |
| Metal Decking | 45.006 | 7680 | 418.4 |

## 3.3. Simulation conditions

A TMY3 weather file was used for the weather condition of Incheon, South Korea. The internal heat gain and cooling and heating setpoints are shown in Table 4 which is also provided by Energy Technology Transfer and Diffusion 2007 report. Schedule of each internal heat gain also follows Energy Technology Transfer and Diffusion 2007, and the cooling and heating in the building were in operation all day.

**Table 4**: Internal heat gain and cooling and heating setpoints

| | | |
|---|---|---|
| Internal heat gain | People | 22.4 $m^2$/person |
| | Lighting | 4 $W/m^2$ |
| | Equipment | 14 $W/m^2$ |
| Set-point | Cooling | 26℃ (May-Oct.) |
| | Heating | 22℃ (Nov.-Mar.) |

## 4.0. Analysis

Before analysis of building energy consumption of all cases, to confirm the energy efficiency of the SEP itself, a comparison of the heating and cooling energy between Case 1 and Case 2 was carried out. Figure 2 shows the results. When the SEP was set on the southern exterior wall (Case 2), the heating and cooling loads were decreased. The annual heating and cooling loads for Case 1 and Case 2 were 65.24 kWh/m²·year and 49.77 kWh/m²·year respectively. This means the heating and cooling loads can be reduced by 23.71% by the SEP itself. As mentioned above, Case 2 is the SEP without any control, BIPV, and ESS, which implies the reduction of the heating and cooling energy will probably be larger through the use of control, BIPV, and ESS.

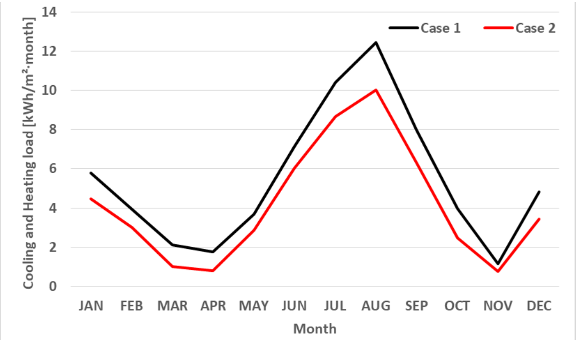

**Figure 2**: Comparison of cooling and heating loads between Case 1 and Case 2

Figure. 3 shows the hourly temperature of zones where the SEP is applied and the living room. The living room was a conditioned zone of which temperature changes were based on the heating and cooling schedule. In terms of the package zone temperature, it was an unconditioned zone of which range of temperature was higher than the living room. During the daytime, the package zone temperature was higher than the living room temperature, and it was lower than the living room during the nighttime. Based on this result, the window opening schedule was created. EnergyPlus does not have a function for the control of the window, thus it is always closed in the modeling.

To solve this problem, this study made use of “Zonemixing” and “Air Flow Network” to create a window opening control. The Air Flow Network model is able to simulate the heat transfer of airflow caused by wind pressure or thermal pressure (Wang et al., 2017). This model was used to assume the window opening control. But the Air Flow Network could be used for exterior windows of the double skin only. Therefore, “Zonemixing” function was used for the interior window control. “Zonemixing” function was used for indoor air mixing between two or more zones. The Air Flow Network model removed the heated air from the package to reduce the cooling load during the summer. This study assumed that “Zonemixing” function could be used for opening control of interior window, and “Air flow network” function could be used for exterior window opening control.

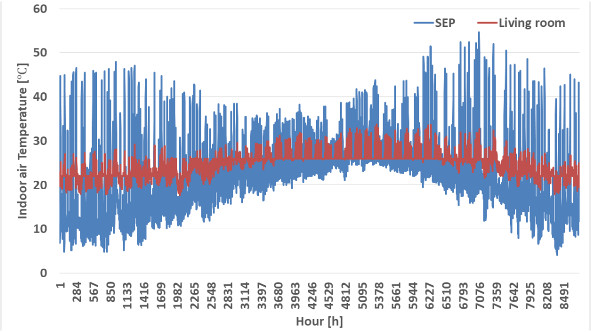

**Figure 3**: Zone temperatures of the SEP and the living room.

Table 5 shows the window opening schedule. “$T_{OA}$” means Outdoor air temperature, “$T_{LR}$” is the living room temperature, “$T_{PKG}$” is the package temperature, “*Window-*$_{Ex}$” is exterior window opening schedule, and “*Window-*$_{In}$” is interior window schedule.

When outdoor air was higher than indoor temperature, if the package zone temperature was higher than both the living room temperature and outdoor air temperature, both interior and exterior window would close. If the package zone temperature was higher than living room temperature and lower than outdoor air temperature, exterior window would open and interior window would close. If package zone temperature was lower than living room temperature and higher than outdoor air temperature exterior window would close and interior window would open. And if the package zone temperature was lower than both living room temperature and outdoor temperature, both exterior and interior window would open.

**Table 5**: Window opening schedule

| | | $T_{PKG} > T_{LR}$ | $T_{PKG} > T_{LR}$ | $T_{PKG} < T_{LR}$ | $T_{PKG} < T_{LR}$ |
|---|---|---|---|---|---|
| $T_{OA} > T_{LR}$ *(Cooling)* | *Window-*$_{Ex}$ | *Close* | *Open* | *Close* | *Open* |
| | *Window-*$_{In}$ | *Close* | *Close* | *Open* | *Open* |
| $T_{OA} < T_{LR}$ *(Heating)* | *Window-*$_{Ex}$ | *Open* | *Close* | *Open* | *Close* |
| | *Window-*$_{In}$ | *Open* | *Open* | *Close* | *Close* |
| | | $T_{OA} > T_{PKG}$ | $T_{OA} < T_{PKG}$ | $T_{OA} > T_{PKG}$ | $T_{OA} < T_{PKG}$ |

When outdoor air temperature was lower than indoor temperature, if the package zone temperature was higher than both the living room temperature and outdoor air temperature, both interior and exterior window would open. If the package zone temperature was higher than the living room temperature and lower than outdoor air temperature, exterior window would close and interior window would open. If package zone temperature was lower than the living room temperature and higher than outdoor air temperature exterior window would open and interior window would close, if package zone temperature was lower than both living room temperature and outdoor temperature, both exterior and interior window would close.

In this study, only “Close” (or “0”) and “Open” (or “1”) are used for the control, which means the value here are fractions. To make more detailed control, the “Schedule:File” object in the EnergyPlus is used. A one-year control schedule was created in the MS Excel program by comparing the temperatures, then that schedule was used for the simulation model.

Figure. 4 shows a comparison among Case 1, 2, and 3. By using the window opening control, the heating and cooling loads were reduced even more than Case 2. As mentioned above, by installing the SEP, the heating and cooling loads were reduced by 23.71%. Annual heating and cooling load of Case 3 is 44.10 kWh/m²·year, 32.40% less than Case 1 and 11.39% less than Case 2. It can be seen that the load reduction is possible by a simple window opening control. When an advanced control algorithm such as control by Artificial Intelligence (AI) technology is implemented, more load reductions are expected.

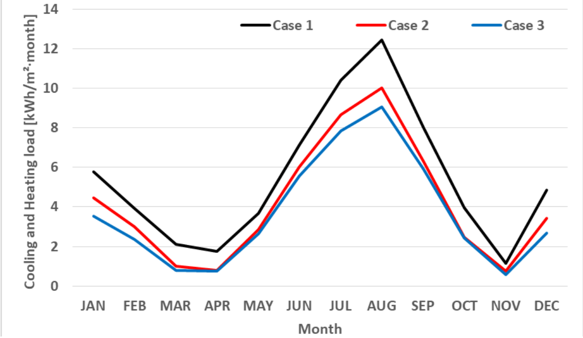

**Figure 4**: Comparison of cooling and heating loads among Case 1, 2 and 3.

To implement the BIPV and ESS to the SEP, the basic information is available in the EnergyPlus simulation program. An amorphous silicon photovoltaic (a-Si PV) window was used for its aesthetic value. EnergyPlus offers three different PV options to predict the electricity generation produced by solar electric PV panels (U.S. DOE, 2017b). They are Simple, Equivalent One-Diode and Sandia model and each type has a different algorithm and an equation. This study used Sandia model which was developed by Sandia National Laboratory (U.S. DOE, 2017b). All data and schedule for the Sandia model was derived from the Schedules Library issued with the BLAST program (U.S. DOE, 2017c). For a-Si PV module power generation, Sandia Array Performance Model (SAPM) was chosen to simulate the electricity generated by PV modules. The SAPM model can simulate power generation accurately although it is empirically based because all the 39 coefficients in the SAPM model are from experimental tests of the same a-Si PV module (Peng et al., 2015). The properties of the a-Si PV are U-Factor of 2.725 W/m²·K and Solar Heat Gain Coefficient of 0.398 (Martellotta et al., 2017). The efficiency of a-Si PV is 5.3% which is not a laboratory but a simulation result. A-Si PV was installed on four fixed windows of the SEP. The size of each window was 0.85m by 1.2m. This study used a 3.3 kW Electric storage system which is suitable for the residential unit. The efficiency of ESS used was 90% (International Electrotechnical Commission, 2011). Figure 5 and Table 6 showed the comparison of the cooling and heating loads for all four cases. Case 4 showed the lowest heating and cooling loads of 43.57 kWh/m²·year. Case 4 showed 33.21% less heating and cooling loads than the base model, 12.46% less than Case 2, and 1.2% less than Case 3. Due to the change in the window from double glazed window to the BIPV window, the heating load was increased by 2.75%, while the cooling load was decreased by 2.33%.

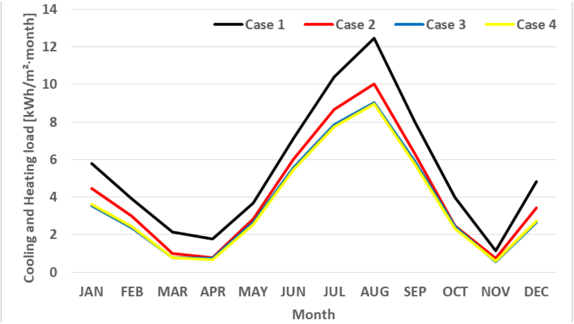

**Figure 5**: Comparison of the cooling and heating loads among Case 1, 2, 3 and 4

**Table 6**: Comparison of the annual Heating and cooling load among cases

| *Case* | *Heating and cooling load [kWh/m²·year]* | *Percentage [%]* |
|---|---|---|
| *Case 1* | *65.24* | *100* |

| | | |
|---|---|---|
| *Case 2* | *49.77* | *76.29* |
| *Case 3* | *44.10* | *67.60* |
| *Case 4* | *43.57* | *66.79* |

Figure. 6 shows electricity production by a-Si PV. The production of electricity in heating season (Nov – Mar) was higher than cooling season (May – Oct). As shown in Figure 7, beam solar radiation on the surface where PV was installed was higher during the heating season than the cooling season. Based on the equation of electrical power produced by BIPV in EnergyPlus, the solar radiation and the electrical power produced are proportional (U.S. DOE, 2017a).

Annual electric power production by the BIPV was 132.74 kWh from 4.08 m² of BIPV area. The electricity consumption of the apartment per year was 5,199.95 kWh. So, the produced power by BIPV could cover 2.55% of electricity and lighting energy need of the apartment. It is not a large portion of the total electricity consumption of the apartment unit, but it can be increased by making the optimal ESS control logic, or using more high-efficiency PV, or changing from a-Si PV to crystalline (c-Si PV) which has higher efficiency than a-Si PV, and the produced electricity can be used more efficiently such as lower peak load. These aspects will be studied in more detail in the future.

The vertical installation of the BIPV is disadvantageous compared to horizontal or tilted in terms of the electricity production because properly tilted surfaces get more solar radiation than vertical. Installation of the BIPV in this study does not mean covering all the electric energy requirement but it can be used effectively when the building is at high demand or as a temporary electricity supply to electric equipment such as refrigerator during power outage.

By installing a-Si PV and ESS in the SEP, 33.21% of heating and cooling load was reduced when compared to base model, and 2.55% of lighting and equipment electricity could be covered by electricity produced by BIPV.

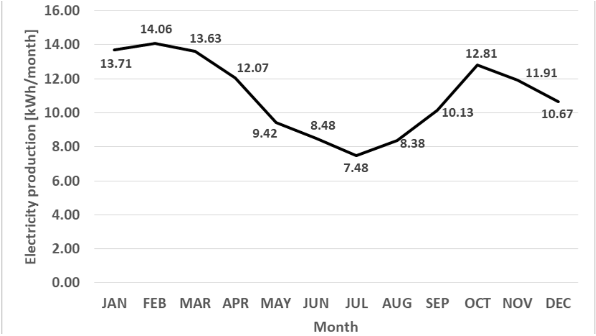

**Figure 6**: Electricity production by a-Si PV.

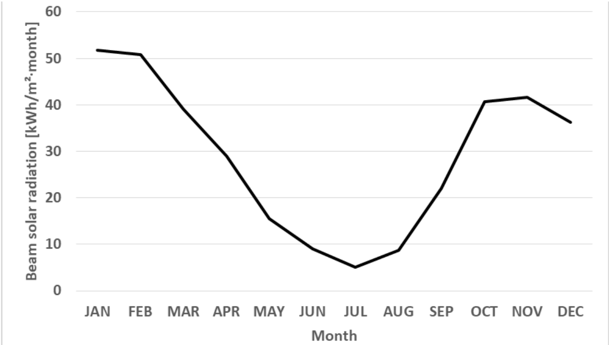

**Figure 7**: Beam solar radiation on the Southern wall

## CONCLUSION

This paper presents the results of an early-stage research. The ultimate goal is to develop a fully functional SEP optimized to achieve maximum energy savings from old high-rise residential buildings. An initial design of the SEP was proposed to analyze how much energy could be saved through the SEP unit. Key results of this study are as follows:

- Comparison between base model and SEP shows that the base model showed 65.24 kWh/m²·year for heating and cooling and the SEP (Case 1) 49.77 kWh/m²·year. This indicates that installing the SEP into the old high-rise residential unit could reduce 23.71% of the heating and cooling loads.
- The SEP with window opening control (Case 3) showed the heating and cooling loads of 44.10 kWh/m²·year. Case 3 showed 12.45% less heating and cooling loads than Case 2 and 32.40% less than the base model. This means when the SEP is used for residential units, control is an important part and needs to be developed further to achieve more energy efficiency.
- Case 4 showed the lowest heating and cooling loads of 43.57 kWh/m²·year. Case 4 had 33.21% less heating and cooling loads than base model, 12.46% less than case 2, and 1.2% less than case 3. Due to change in window from double glazed window to BIPV window, heating loads were increased by 2.75%, but cooling loads were decreased by 2.33%.
- Annual electric power production from BIPV was 132.74 kWh. This amount was 2.55% of total electricity requirement.

In future studies, we will develop an optimal design of the SEP with considerations, including optimal controls of windows corresponding to the outdoor conditions, automated blind control, and higher efficiency BIPV. To make simulation models more accurate, the CFD analysis results will be integrated with the EnergyPlus simulation processes. Another future study will be along the lines of application of the SEP, its marketability, and appeal to the occupants of the apartments.

## ACKNOWLEDGEMENTS

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