A Comparative Study on the Energy Performance of Movable Insulation and Triple-Glazed Windows

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Abstract

Windows account for around 30% of the total heating and cooling loads in buildings. The development of windows with better energy performance has always been a hotspot in building technology research. However, the improvement of static properties of windows is expensive and restricted. Dynamic windows, on the other hand, show a great potential for energy saving with possibly lower cost. Movable insulation is a technology proposed a long time ago but has not been studied systematically. This paper proposes an automatic control method for movable insulation with a control accuracy of 95%. Through building energy simulation, it is found that the energy performance of movable insulation is better than triple-glazed windows in all climate zones tested and its energy savings increase with the extremity of climate. A net present value analysis is also conducted for the building designers and owners’ information.

Introduction

In 2017, residential buildings account for 20.4% of the total energy consumption in the US, the portion for commercial buildings being 18.5% (Energy Information Administration, 2018). Together, they make building the largest energy consumption sector in the US. Reducing the heating and cooling loads with high-performance envelope is one of the most important ways of building energy conservation. According to Arasteh et al. (2006), the heating and cooling loads induced by windows make up roughly 30% of the total heating and cooling loads of buildings. Therefore, improving the performance of windows can be an effective way of saving energy.

The most critical window properties related to energy use are U-factor, solar heat gain coefficient (SHGC), window-to-wall ratio (WWR), and orientation. The U-factor of a window depends on the U-factor of the glazing (Ug), the U-factor of the frame (Uf), the U-factor of the spacer and the configuration of the window (International Organization for Standardization, 2006), and similarly for the SHGC. Hereinafter, the U-factor and SHGC refer to the U-factor and SHGC of the whole window, except where noted. Generally speaking, for residential buildings in heating dominated climates, medium-sized windows facing south and small-sized windows facing other directions (for the Northern Hemisphere) with a U-factor as low as 0.6 W/(m²·K) and an SHGC as high as 0.45 is conducive to the reduction of heating load (Persson et al., 2006; Gasparella et al., 2011; Arasteh et al., 2003; Arasteh et al., 2006; Karlsson and Roos, 2001). It should be noted that 0.45 is not a high value in itself, but a U-factor of 0.6 W/(m²·K) requires triple-glazing as well as double or even more low-e coatings, which makes it hard for the SHGC to get above 0.45 (Karlsson and Roos, 2001; Jelle et al., 2012). However, this window configuration may increase the cooling demand during the summer unless proper shading is used. For residential buildings located in cooling dominated areas, it is necessary to apply shading to small-sized windows facing directions other than north with a low U-factor and a low SHGC in order to receive beneficial effects from windows (Gasparella et al., 2011; Arasteh et al., 2003; Arasteh et al., 2006). The size and SHGC of the windows facing north are not restricted in this case, as long as their U-factor is low enough.

The energy saving potential of varying the static U-factor and SHGC of windows is limited by the material properties. In addition, one value that is advantageous in one season may be disadvantageous in another. Minimizing window size to achieve energy goal is also out of the question because architects and occupants are usually in favor of large windows to have better views, let in more daylight, and realize aesthetic purposes. In light of these reasons, we try to find an alternative method in which the U-factor and SHGC of the windows can have different values according to the need. Windows with dynamic properties can be realized through different ways. The simplest one is to use louvers or shutters to reduce the unwanted solar heat gain. There have been numerous simulation and experimental studies on using louvers to reduce the cooling load and glare (Palermo-Marrero and Oliveira, 2010; Alawadhi, 2016; Hammad and Abu-Hijleh, 2010; Montier et al., 2013). The SHGC can also be varied using thermo-, photo- or electro-chromic materials (Jelle et al., 2012). Simulation results have shown that windows with dynamic SHGCs are especially appropriate for climates with two distinct heating and cooling seasons, and the energy saving potential is on the same level as windows with much superior properties (Arasteh et al., 2003; Arasteh et al., 2006).

Another way of endowing windows with dynamic properties is to use movable insulation. Movable insulation is an opaque insulation layer which can be either attached to or removed from the window according to need. The moving mechanism can be sliding, folding,
or rolling, and the installation position can be either the inside or outside of the glazing. Movable insulation can change not only the SHGC but also the U-factor of the window. Numerous movable insulation application cases have been summarized in Langdon (1980) and Shurcliff (1980). Figure 1 shows a possible configuration of the sliding insulation on the exterior side of the glazing. The main difference between movable insulation and dynamic louvers is that the use of dynamic louvers emphasizes on the control of the SHGC alone, the associated U-factor change being unintended and uncontrolled. Therefore, automatically controlled louvers are mostly applied to office buildings only to reduce solar heat gain (Hammad and Abu-Hijleh, 2010). While movable insulation controls both the U-factor and SHGC of windows, and it is mainly applied to residential buildings to reduce both cooling and heating loads.

However, no systematic research has been done on the impact of movable insulation yet. Firstly, no dynamic whole building simulation has been conducted to answer if movable insulation can save energy compared to baseline windows, how much it can save, and what climate zones it is most appropriate for. Hammad and Abu-Hijleh (2010) and Montier et al. (2013) studied the energy saving potential of louvers and shutters with a commercial building simulation software, IES-VE. However, due to the limitation of the software, their simulation is not really dynamic. Secondly, no control method for movable insulation has been proposed. Thirdly, a comparison study between baseline windows plus movable insulation and advanced triple-glazed windows is required to provide designers and house owners suggestions. Lastly, the benefits of energy saving measures should be weighed against their costs. A net present value (NPV) analysis is required to justify any design or renovation decision. In the following sections, these problems will be discussed.

Methods

Model

A typical single-family house model was chosen, as shown in Figure 2. The house has a floor area of 200 m². The WWR is 30%, which is a typical design value in the US. A basic overhang with a width of 20 cm is added to the windows. The indoor environment is controlled by a packaged unit with electric cooling and gas heating.

A family with four members, two adults and two children, live in the house. The metabolic rate of the adults is set as 80 W/person, and that of the children is set as 60 W/person. During the weekdays, the family leave home at 8:00 a.m. and return home at 5:30 p.m. On Saturdays, the family would go out together at 8:00 a.m. and return home at 12:00 p.m. On Sundays, the family stay at home all day. The loads of lighting and appliances are 2 and 7 W/m² respectively, and they both follow their respective schedules.

Figure 2: The dimensions of the single-family house model

Scenarios

Minneapolis (MN), San Francisco (CA), Atlanta (GA), and Phoenix (AZ) were chosen as representative cities. For each city, three scenarios were studied: baseline window (double-glazed), baseline window plus movable insulation, and advanced window (triple-glazed, TG). In order to make the buildings in different climate zones comparable, the properties of the wall, roof, and baseline window except the SHGC were chosen according to the requirements for climate zone 6A from ASHRAE 90.2 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007). The SHGC of the baseline window was set as 0.6 for Minneapolis and San Francisco and 0.4 for Atlanta and Phoenix. The SHGC of the triple-glazed window was set as 0.45 for Minneapolis and San Francisco and 0.4 for Atlanta and Phoenix. Some of the best low-e triple-glazed windows have a Uₜ close to 0.50 W/(m²K). Combined with the best frame and spacers, the whole window U-factor can be as low as 0.6 (International Organization for Standardization, 2006; Jelle et al., 2012). However, this is the lowest value that current technology can get. To be more representative of the market products, we chose 0.7 W/(m²K) as the advanced window U-factor.

We placed the insulation layer on the outside of the glazing because the thermal resistance of the insulation is far higher than the glazing. If we place the insulation on the inside of the glazing, moisture would enter the space between the insulation and the glazing and condensate, thus causing mold problem. The insulation layer used in this study comprises from outside to inside a layer of aluminum foil, a 4-cm-thick extruded polystyrene layer, a 1-cm-thick gypsum board, and a layer of latex paint. The aluminum foil not only protects the insulation layer from...
where $U_{W1}$ is the U-factor of the window with insulation, $W/(m^2\cdot K)$; $U_W$ is the U-factor of the original window, $W/(m^2\cdot K)$; $R_I$ is the R-value of the insulation layer, $m^2\cdot K/W$. The calculated total U-factor of the window with insulation is 0.50 $W/(m^2\cdot K)$. Its SHGC is 0.

The infiltration rate of the house is set as 0.5 air changes per hour (ACH) for the baseline scenario and 0.4 ACH for the triple-glazed scenario. The assumption is that the triple-glazed window is an advanced choice that not only has better properties but also has lower infiltration rate. For the movable insulation scenario, the infiltration rate is 0.5 when all the movable insulations are open and reduces to 0.4 ACH when all the movable insulations are closed.

Control

Windows on different façades are controlled independently. The diagram of the automatic control system is shown in Figure 3. The outdoor and indoor thermometers measure the outdoor and indoor temperatures respectively. The pyranometer measures the incident solar radiation (both direct and diffuse) on the window. The black bulb temperature sensor measures the mean radiant temperature of the environment surrounding each window. When the sun is shining, the black bulb temperature sensor should be shaded from the sun or just simply disabled. The infrared detector detects the presence of occupants. When the house is occupied, the cooling set point is 26°C and the heating set point is 20°C. The access to daylight is given priority over building load reduction. Thus, the movable insulation will remain open as long as the house is occupied and the incident solar radiation on the window exceeds 20 $W/m^2$. When the house is unoccupied, the cooling set point is 30°C and the heating set point is 16°C. The user input information, including the cooling and heating set points, window U-factor, window average transmittance, window average absorptance, and window outside face emissivity, is used to calculate the energy balance of the window. If the window average transmittance and window average absorptance are not available, the user can simply input the SHGC and the system will estimate these values using the method explained in Arasteh (2009). The control step is set as 10 minutes in the study.

The control algorithm is based on the energy balance of the window. The method employed in this work is similar to that used by EnergyPlus (U.S. Department of Energy, 2018). In this model, we consider the glazing system as an equivalent single layer. The equivalent thermal conductance $k$ is calculated according to Arasteh (2009). The portion of incident solar radiation absorbed by the glazing system is split equally and added to surface 1 and surface 2, where surface 1 is the exterior surface of the equivalent layer and surface 2 is the interior surface. The heat balance equations for surface 1 and surface 2 are

\[
Q_{o1} = k(T_1 - T_2) + h_i(T_1 - T_2) + h_o(T_o - T_1) + \frac{1}{2} \alpha S = 0 \tag{2}
\]

\[
h_i(T_1 - T_2) + k(T_2 - T_1) + \frac{1}{2} \alpha S = 0 \tag{3}
\]

where $h_{rad}$ is the equivalent radiation heat transfer coefficient and is calculated by $h_{rad} = \sigma \varepsilon_1 (T_{rad}^2 + T_{rad}^2)(T_{rad} + T_1)$, $W/(m^2\cdot K)$; $T_{rad}$ is the mean radiant temperature of the exterior environment, $K$; $T_o$, $T_1$, $T_2$, $T_i$ are the temperatures of the outdoor air, surface 1, surface 2, and indoor environment respectively, $K$; $\alpha$ is the solar absorptance of the glazing system; $S$ is the incident solar radiation, $W/m^2$; $h_i$ is the outside surface convection heat transfer coefficient, $W/(m^2\cdot K)$; $h_o$ is the inside surface heat transfer coefficient, which takes both convection and radiation into account, $W/(m^2\cdot K)$. From Equations (2) and (3) we can solve for the temperatures of surface 1 and surface 2 and then the conduction heat flux through the window is calculated by

\[
Q_{co} = k(T_1 - T_2) \tag{4}
\]

The solar radiation transmitted through the window is calculated by

\[
Q_{t0} = \tau S \tag{5}
\]

where $\tau$ is the solar transmittance of the glazing system. The total heat transfer rate through the window when the movable insulation is open is

\[
Q_0 = Q_{co} + Q_{t0} \tag{6}
\]

When the movable insulation is closed, the transmittance of window is reduced to 0. All the absorbed solar radiation should be added to surface 1. The conduction heat flux through the window in this case, $Q_c$, can be calculated using similar heat balance equation.
When $T_{in} > 25^\circC$, the control system will compare $Q_0$ and $Q_1$ and choose the smaller one as the movable insulation status to reduce heat gain through the window. When $T_{in} < 21^\circC$, the control system will choose the greater one of $Q_0$ and $Q_1$ as the movable insulation status to increase heat gain through the window. The reason why the control of movable insulation uses 21°C and 25°C instead of 20°C and 26°C as thresholds is that with the heating ventilating and air conditioning (HVAC) system working properly, the indoor temperature will fluctuate slightly around 20°C when heating is on and 26°C when cooling is on. The adoption of 21°C and 25°C as thresholds will ensure that load reduction is always effective as long as the HVAC system is on. It should be noted that the movable insulation only has two statuses, on and off. This is because partially opening the movable insulation will make it lose its airtightness, in which case the movable insulation becomes an ordinary shutter.

**Simulation**

The building energy simulation is conducted by EnergyPlus, which is a whole building energy simulation program developed by the National Renewable Energy Laboratory (NREL) (U.S. Department of Energy, 2018). It has been widely validated and verified. The control algorithm is written in Matlab. The co-simulation of EnergyPlus and Matlab is realized by a co-simulation tool, Building Controls Virtual Test Bed (BCVTB), developed by Lawrence Berkeley National Laboratory (LBNL) (Wetter and Nouidui, 2016). The time step of simulation is 10 minutes. At each time step, EnergyPlus sends the outdoor dry-bulb temperature, sky temperature, indoor temperature, incident solar radiation rate per area on each window surface, outside radiation heat transfer coefficients (including to air, to sky, and to ground) of each window and the occupancy schedule to Matlab via BCVTB. After the processing of the control algorithm, Matlab sends the status of each movable insulation and the resultant infiltration rate back to EnergyPlus. Then, EnergyPlus performs building energy simulation. The infiltration rate for the movable insulation scenarios changes according to the statuses of the movable insulations.

**Results**

**Proving the control algorithm is accurate**

When calculating the energy balance of the window, static outdoor convection heat transfer coefficient, glazing system absorptance and glazing system transmittance are used. For the heat transfer between the window and the indoor environment, a single static heat transfer coefficient is used to include both convection and radiation effects. These simplifications make it possible to control the movable insulation with only a few measured variables. However, we need to prove that these simplifications will not compromise the control accuracy too much.

We ran the cases with constantly closed and open movable insulation and let EnergyPlus report the window net heat transfer rates for these cases. If the difference between them is positive ($Q_0 > Q_1$), opening the window at this time step will lead to more heat gain through the window. If the difference is negative ($Q_0 < Q_1$), opening the window at this step will lead to more heat loss through the window. In general, there are only five scenarios for the expected movable insulation status as shown in Table 1. If the control status of the movable insulation matches the expected status, the control algorithm is reckoned to be accurate at this time step.

**Table 1: The five scenarios if the control algorithm is accurate**

<table>
<thead>
<tr>
<th>Indoor temperature (°C)</th>
<th>Window net heat transfer rate difference (W/m²)</th>
<th>Occupancy</th>
<th>Daylight</th>
<th>Expected movable insulation status</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;21</td>
<td>+</td>
<td>Occupied</td>
<td>Yes</td>
<td>Open</td>
</tr>
<tr>
<td>&lt;21</td>
<td>+</td>
<td>Occupied</td>
<td>Yes</td>
<td>Open</td>
</tr>
<tr>
<td>&gt;25</td>
<td>-</td>
<td>Occupied</td>
<td>No</td>
<td>Open</td>
</tr>
<tr>
<td>&gt;25</td>
<td>+</td>
<td>Occupied</td>
<td>No</td>
<td>Closed</td>
</tr>
</tbody>
</table>

Taking the southern window of Phoenix as an example, out of a total of 52,560 simulation steps in a year, the control algorithm made the right decision in 49,828 steps. The accuracy is 94.8%. The inaccuracy mainly comes from two sources. Firstly, due to the inherent limitations of BCVTB, there is a two-timestep lag between the measurement of the input variables and the implementation of the control decision (one for data transmission from EnergyPlus to Matlab and the other for data transmission from Matlab to EnergyPlus). Secondly, during summer nights when the outdoor temperature is close to indoor temperature, the difference between $Q_0$ and $Q_1$ is very small and closing or opening the movable insulation does not make a difference. Therefore, the real control accuracy should be higher than 95%, and the inaccurate timesteps have little impact on the energy consumption. It is reasonable to reckon that the control algorithm is accurate.

**The energy performance comparison**

Figure 10 shows the monthly cooling/heating energy for the three scenarios in different locations. The cooling/heating energy for the movable insulation scenario is always much lower than that for the baseline scenario. The heating energy reduction effect of the movable insulation is more significant than its cooling energy reduction effect. In the transition seasons of Phoenix and the whole cooling season of Atlanta, the cooling energy for the triple-glazed scenario is close to or even higher than that for the baseline scenario. This is probably because triple-glazed windows prevent the use of free cooling during the night.

Figure 4 shows the annual cooling/heating energy for the three scenarios in different locations. The number on each column indicates the percentage of energy saved by movable insulation compared to that scenario. If the number is negative, it means that the energy consumption for the movable insulation scenario is actually higher than the compared scenario. For example, the annual heating energy for the movable insulation scenario in Atlanta is 40% lower than that for the baseline scenario and 3%
percent higher than that for the triple-glazed scenario. The annual heating energy for the movable insulation scenario is 31%, 49%, and 40% lower than that for the baseline scenario in Minneapolis, San Francisco, and Atlanta respectively. The heating energy of Phoenix is too small to be meaningful in comparison. The heating energy for the movable insulation scenario is almost the same as that for the triple-glazed scenario. The cooling energy for the movable insulation scenarios is 23%, 18%, and 14% lower than that for the baseline scenario, and 3%, 11%, and 17% lower than that for the triple-glazed scenario in Minneapolis, Phoenix, and Atlanta respectively. In general, the movable insulation has similar performance to triple-glazed window in terms of reducing heating energy and outperforms triple-glazed window in terms of reducing cooling energy.

Figure 4: The annual heating/cooling energy comparison

Illustration of how movable insulation saves energy
Figure 5 shows the hourly heating energy profile on two typical winter days for Minneapolis. Figure 6 shows the movable insulation status of each window for the same time period. From Figure 5 we can see that, after the occupants return home at 5:30 p.m., the heating energy of the HVAC system first rises dramatically to raise the indoor temperature from 16°C to 20°C, then drops a little, and rises again as the outdoor temperature decreases until 6:00 a.m. The heating energy for the movable insulation scenario is the lowest throughout the night because the window with movable insulation has the lowest U-factor. During the day, however, the heating energy of the movable insulation scenario is a little higher than that of the triple-glazed scenario, because some of the windows are opened to let in sunshine, which increases the infiltration rate.

From Figure 6 we can see that, the insulation layers on the southern and eastern windows are opened first in the morning and the insulation layers on the western windows are closed last at dusk. The insulation layer on the northern windows remains closed all the time because the diffuse solar radiation transmitted through the north window is not enough to compensate for the convective heat loss. So, opening the insulation layer on the northern windows will always lead to a negative net heat gain.

Figure 5: The heating energy profile on two typical winter days for Minneapolis

Figure 6: The movable insulation status of each window on two typical winter days for Minneapolis (the presence of the colour bar indicating that movable insulation is closed.)

Figure 7 shows the hourly cooling energy profile on two typical summer days for Phoenix. Figure 8 shows the movable insulation status of each window for the same time period. From Figure 7 we can see that, during the first day there are two cooling energy peaks at 8:00 a.m. and 7:00 p.m. respectively. They are the typical breakfast and dinner time which has large internal load. During these two periods, the cooling energy of the movable insulation scenario is larger than that of the triple-glazed scenario, because the insulation layers are opened to provide daylight. During the unoccupied hours of the day, the cooling energy of the movable insulation scenarios is prominently lower than the other two, because the insulation layer not only reduces the convective heat gain but also blocks solar heat gain. During the night, the cooling load of the movable insulation scenario is only slightly lower than that of the triple-glazed scenario, because the difference between the outdoor temperature and indoor temperature during the night is quite small. In the afternoon of the second day, the cooling energy of the movable insulation scenario is markedly higher than that of the triple-glazed scenario, because it is Saturday and the building is occupied in the afternoon.

In Figure 8, all the insulation layers are opened at 6:50 a.m. for daylight. Actually, they should be opened at 6:30 a.m. when the residents just get up, but there is a two-timestep lag in the implementation of the control decision as mentioned before. At 8:30 a.m. (should be 8:10 a.m.),
all the insulation layers are closed because the residents left the building. All the insulation layers remain closed to reduce the heat gain until the residents return home. One interesting thing to mention is that the movable insulation on the southern window is closed before that on the northern window at sunset, because the sun actually rises and falls in the north in the summer in the Northern Hemisphere.

The reduction of peak heating load

Figure 9 shows the heating load profile that contains the peak heating load for Minneapolis. There are two peaks when the occupants just return home. However, these peaks are trivial to our study, because they are only transient peak loads to raise the room temperature from the unoccupied setpoint (16°C) to the occupied setpoint (20°C). If the control logic is changed to allow the room temperature to gradually warm up, these peaks can be easily removed. The true peak heating load of concern occurs in the early morning of the second day when the outdoor temperature is the lowest. This peak load cannot be removed using some simple control strategy. The peak loads of the baseline scenario, triple-glazed scenario, and movable insulation scenario at this time are 13.702 kW, 10.213 kW, and 9.744 kW respectively. The movable insulation has the potential to reduce the peak heating load by 28.9% compared to the baseline scenario and 4.6% compared to the triple-glazed scenario. Since the peak heating load is lower, a smaller heating system can be selected, and less initial investment is required.

NPV analysis

An NPV analysis has been conducted for the triple-glazed and movable insulation scenarios. Table 2 shows the energy bills for different scenarios in different cities. The heat content of natural gas (1037 Btu/ft³), electricity price ($0.13/kWh) and natural gas price ($12.6 kft³) are the U.S. national average values from Energy Information Administration (EIA) website (Energy Information Administration, 2018).

Table 2: The energy bills for different scenarios in different cities

<table>
<thead>
<tr>
<th>City</th>
<th>MIN</th>
<th>SFO</th>
<th>PHX</th>
<th>ATL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Cooling</td>
<td>Baseline</td>
<td>108.89</td>
<td>10.71</td>
<td>710.98</td>
</tr>
<tr>
<td></td>
<td>TG</td>
<td>85.86</td>
<td>6.27</td>
<td>649.67</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>84.25</td>
<td>9.11</td>
<td>579.81</td>
</tr>
<tr>
<td>Electricity Bill $</td>
<td>TG</td>
<td>23.03</td>
<td>4.44</td>
<td>61.31</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>24.64</td>
<td>1.60</td>
<td>131.17</td>
</tr>
<tr>
<td>Saving</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Heating Natural Gas</td>
<td>Baseline</td>
<td>899.64</td>
<td>150.48</td>
<td>29.70</td>
</tr>
<tr>
<td></td>
<td>TG</td>
<td>637.43</td>
<td>83.08</td>
<td>9.75</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>624.47</td>
<td>76.31</td>
<td>9.00</td>
</tr>
<tr>
<td>Bill $</td>
<td>TG</td>
<td>262.21</td>
<td>67.40</td>
<td>19.95</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>275.17</td>
<td>74.17</td>
<td>20.70</td>
</tr>
<tr>
<td>Saving</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Energy Bill Saving $</td>
<td>TG</td>
<td>285.24</td>
<td>71.85</td>
<td>81.26</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>299.81</td>
<td>75.77</td>
<td>151.86</td>
</tr>
</tbody>
</table>

The costs of the baseline window and movable insulation system are estimated based on the data from RSMeans Building Construction Cost Data 2016 (Plotner et al., 2015). The estimated price of a double-glazed window with a size of 1.83 m × 1.22 m is $725 (U.S. Dollars). The house model in question needs 24 such windows in total. The estimated price of the insulation layer is $47.79 per square meters, and the total price of the control system is $704. Based on the price data from multiple sources (Pikas et al., 2014; Menzies and Wherrett, 2005), it is reasonable to assume that the price of the triple-glazed considered in this study is 20–30% higher than that of the double-glazed window. Two scenarios in which the price...
of the triple-glazed window is 20% and 30% higher than that of the baseline window respectively are considered in the NPV analysis. The initial costs are the premium prices of the movable insulation and triple-glazed window on top of the baseline window. The discount rate used is 3% which is the DOE discount rate for projects related to energy conservation, renewable energy resources, and water conservation (Lavappa and Kneifel, 2018). The results are shown in Figure 11.

In Figure 11 we can see that, in Minneapolis the pay back periods for movable insulation and triple-glazed window with a price 20% higher than the baseline window are 14 and 16 years respectively. In all other scenarios, the investment will not pay off in 25 years. Therefore, in terms of saving money, it is only reasonable to add movable insulation to the baseline window or replace the baseline window with triple-glazed window in places with extremely harsh winters like Minneapolis. However, it should be noted that some energy saving measures have already been taken in the house considered. In light of this, installing movable insulation may also be economic in Phoenix.

Conclusion

A control method has been proposed for movable insulation. The control method, which is based on the energy balance calculation of the window, ensures the access to daylight and is proven to have sufficient accuracy.

Movable insulation is effective in reducing cooling energy and especially heating energy compared to double-glazed windows in all climate zones. In places with extreme climates (hot summer or cold winter), the load reduction effect of double-glazed windows plus movable insulation is more prominent than that of triple-glazed windows.

Movable insulation can reduce the peak heating load which occurs in the early morning of cold days compared to both double- and triple-glazed windows. This helps reduce the initial investment on heating equipment.

It is profitable to install movable insulation or replace double-glazed windows with triple-glazed windows only in places with extremely harsh winters like Minneapolis.

References


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Figure 10: The monthly cooling/heating energy comparison

Figure 11: The NPVs of movable insulation and triple-glazed windows in different cities