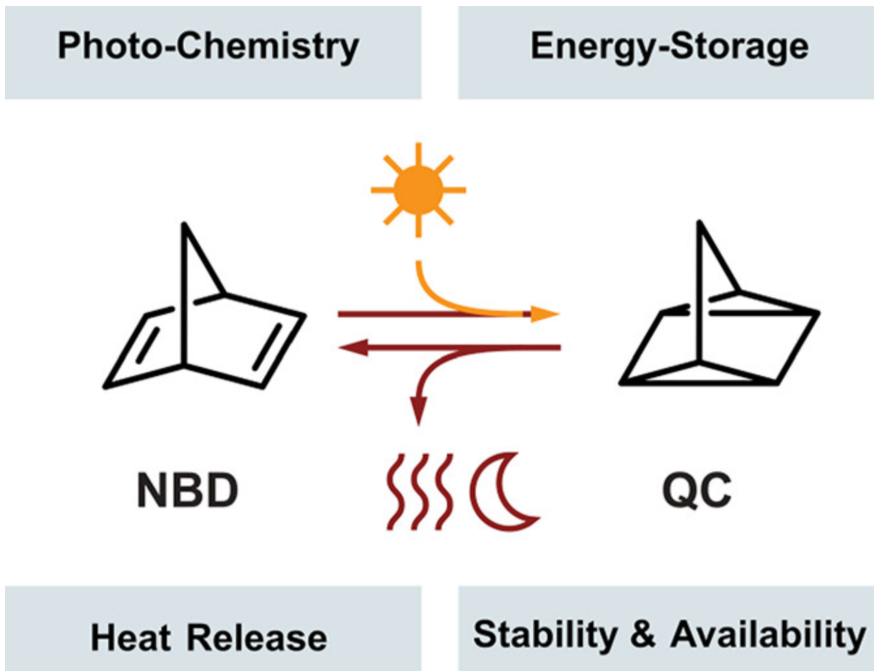

MOST film applied to windows and the effect on space heating

Master of Science in Engineering thesis in the Master's programme Sustainable Energy Systems

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Chalmers University of Technology
Gothenburg, Sweden 2022
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MASTER'S THESIS

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Abstract

A study was performed in Matlab simulink to observe the effect a molecular solar energy storage (MOST) film placed on windows have on the space heating and cooling of a room given the weather data from 2019 in gothenburg, sweden. As well as the half-life of the photoisomer's effect on the efficiency. The study concluded that the MOST film was not an effective application in the Gothenburg climate. Though it showed that the lower half-times of the MOST molecules actually had a positive impact on the efficiency.

Contents

1 Background

Even though the demand of renewable and sustainable energy sources have increased in recent years.[1][2] The fact remains that in 2019 around 84% of primary energy and 64% of electricity comes from fossil fuels.[3] The consumption of primary energy in the form of space heating or the use of electricity to either cool or heat obviously differs depending on geographical location, Though the share of household energy for space heating was 63.3% in the EU in 2018 [4]. Both the share of the energy production for space heating and cooling can be seen in figure 1.

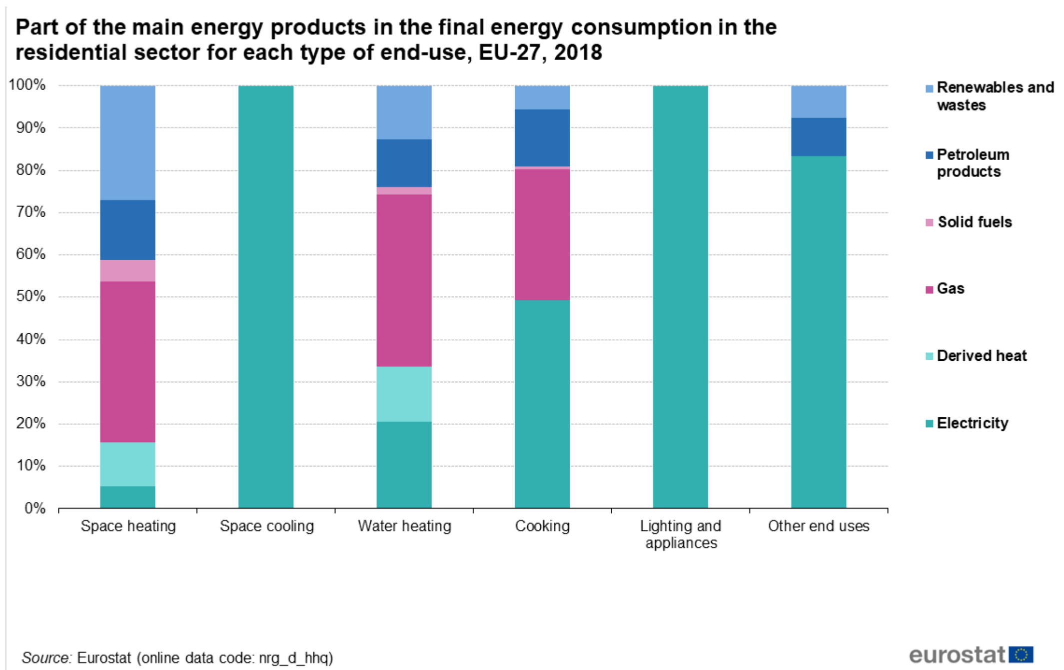


Figure 1: The share of main energy product in the final consummation of each type of end use in the residential sector of the EU in 2018.

As figure 1 illustrates, a big portion of the energy sources for heating were gas (around 40%), which is still largely fossil based [5]. While 12% is petroleum products. This, combined with the generally low renewable energy share of electricity[2] shows that a large portion of the European energy use was fossil based.

Heating has the largest energy consumption in a household because how easily it can disappear from the building, in which windows is generally the least isolated part of the building compared to the opaque portions of the building. If it would be possible to mitigate the need of heating and cooling, then a large amount of energy could be saved. One possible solution could be through Molecular solar energy storage (MOST). MOST is made of molecules that has the property to change to an isomer after getting exited by a photon, thus called photoisomer [6] [7]. The photoisomer has the ability to perform a spontaneous back conversion to the original molecule (the parent); consequently releasing energy during the back conversion. Which would be the photonic energy that had been stored by the molecule. The benefit of the method of energy storage is that it does not involve any phase changes and can therefore be integrated into a transparent film that enable absorption of photons, which could then be integrated into different room surfaces.

2 Introduction

2.1 Aim of the work

The focus of this paper is to simulate the placement of a MOST film on top of a window glass panel facing the interior of the room and then simulate the heating and cooling demand of a room over the span of a year (2019) in Gothenburg. This will then be compared with to the same year without the MOST film on the windows of the simulated room. Through this study it can then be observed how efficient the film is and what kind of properties that are best suited for the film. This will be achieved by first looking at the kinetics of the MOST system and then apply it to a windows heat transfer, which will then be considered in the overall heat transfer of the room.

2.2 Methods

Three reference cases will also be tested, single-glazed, double-glazed and triple-glazed windows. Then the cases with the MOST film will be tested on single, double-glazed and triple-glazed. There will also be a simulation of so-called low-emissivity (low-E) windows as they are an established technology which would compete with the MOST film. Also three additional cases will be tested where the half-life $t_{1/2}$ for the triple-glazed case will be changed to observe the effect.

The simulation will first simulate the kinetics of the MOST molecules. This is done through using the photon flux at the wavelength of the isomersation, which is given for every hour of the simulated year. Through the kinetics the amount of energy realised and absorbed by the film can be calculated. The absorption of solar irradiation by the glass window is also taken in account for these calculations. This will then be used in the rooms energy simulation to be able to calculate the heat and cooling demand.

The data will be divide into days that only are in need of heating, days with only cooling and days that are both in need of heating and cooling in order to better understand how the MOST film affect different space heating conditions and to understand in which climate or season it would effective.

2.3 Limitations

This paper will not study the effects of the MOST film on low-E windows. As the point of the LOW-E windows is to be more reflective of photons it would run counter to how the MOST film works. No cases of different half-lives on windows other then the triple-glazed will be studied because the triple-glazed is the better windows for the Gothenburg climate. Lastly this study will not observe the efficiency of any other climate then the Gothenburg one for the reason that to many test would have to be performed then.

3 Theory

3.1 Photoisomerization

The way the MOST film will operate is through photoisomerization, which is a process of isomerization induced by photons. A parent molecule will be exited by a photon of a specific wavelength and will either return to its original state or convert to its photoisomer, the ratio of this is called the quantum yield Φ, which can range from 1 (full conversion) to 0 (no conversion) depending on the molecule in question.

The photoisomer has two ways to convert back to the parent molecule by either undergoing its own photoisomerization or by a thermal driven backconversion. Ideally the photoisomerization of the photoisomer is usually negligible compared to parent. Therefore, the main way for the photoisomer to convert back to the parent molecule is through thermal driven conversion. All of this is illustrated in figure 2.

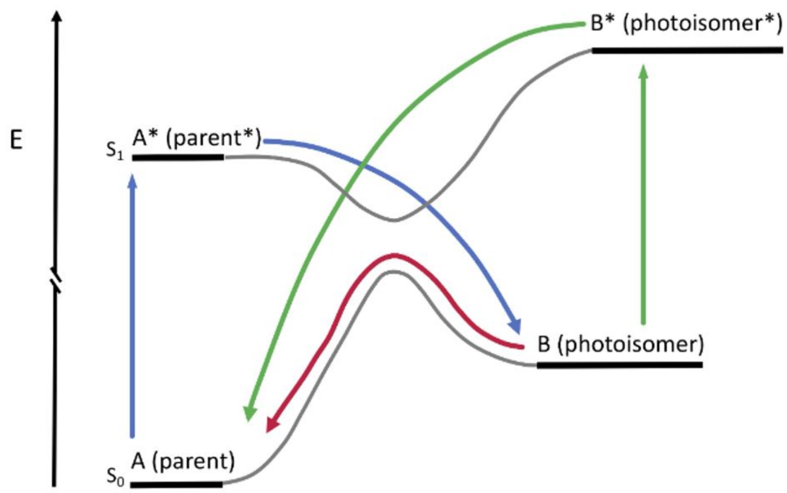


Figure 2: An energy scheme to illustrate the different processes between isomers A(parent) and B(photoisomer). The blue path is the photoisomerization of A to B. Green is photoisomerization of B to A. Red is the thermal driven conversion of B to A.

The energy difference between the photoisomer and the parent molecule is the energy that is stored $\Delta H_{storage}$. While the difference in energy needed to excite the parent and the energy difference of grounded parent and the photoisomer is thermal losses to the environment.

The mass balance is modeled in equation 1, where [A] is the parent molecule's concentration $[\frac{mol}{m^3}]$, [B] is the photoisomer concentration $[\frac{mol}{m^3}]$, n is the photon flux of the isomerisation wavelength $[\frac{1}{m^2 s}]$, N_a is Avogadro's constant $[\frac{1}{mol}]$, β_A is fraction of photons absorbed by the parent molecule, d_{MOST} is the depth of the MOST film [m] and k_b is the back conversion constant $[\frac{1}{s}]$.

$$\frac{d[A]}{dt} = -\frac{\Phi \cdot n \cdot \beta_A}{N_a \cdot d_{MOST}} + k_b \cdot [B] \tag{1}$$

β_A is given by equation 2, where ϵ is the molar extinction coefficient $[\frac{1}{mol,cm}]$and Abs is the absorbance at a given time which is given by equation 3.[8]

$$\beta_A = \frac{[A] \cdot \epsilon_A}{[A] \cdot \epsilon_A + [B] \cdot \epsilon_B} \cdot (1 - 10^{-Abs(t)}) \tag{2}$$

$$Abs(t) = [A] \cdot \epsilon_A \cdot d_{MOST} + [B] \cdot \epsilon_B \cdot d_{MOST} \tag{3}$$

While β_{B}, the fraction of photons absorbed by the photoisomer, is derived by equation 4.

$$\beta_B = \frac{[B] \cdot \epsilon_B}{[B] \cdot \epsilon_B + [A] \cdot \epsilon_A} \cdot (1 - 10^{-Abs(t)}) \tag{4}$$

3.2 Window heating and solar absorption

The heat transfer of a window is a complex process. As the glass of the window is a transparent material, solar radiation goes through the glass but some of it is also reflected by the window. Simultaneously, heat conducts through the glass by the temperature difference of the exterior and interior of the room. Because the frame of the window also absorbs solar radiation and conduct heat, it will then have an effect in the thermal transmittance (U $\frac{W}{K,m^2}$) of the window see equation 5. Figure 3 illustrates all of previously mentioned energy transfer of the window.

$$U_{windows} = \frac{A_{frame} \cdot U_{frame} + A_{edge} \cdot U_{edge} + A_{center} \cdot U_{center}}{A_{windows}} \tag{5}$$

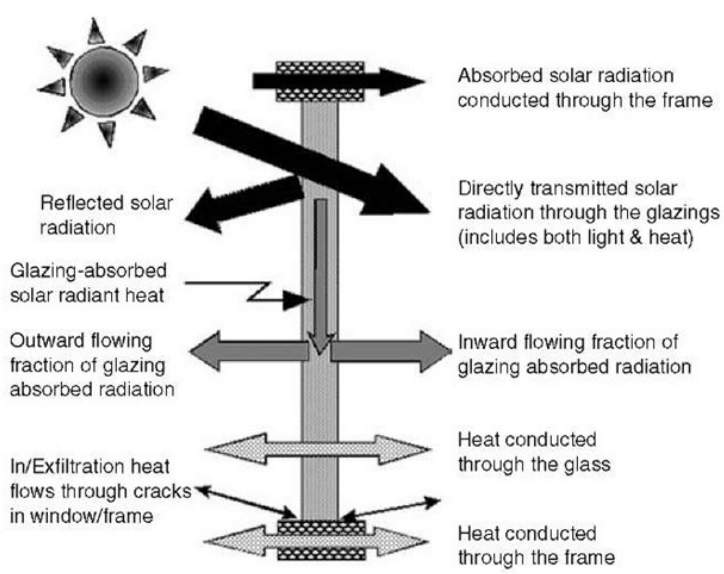


Figure 3: A complete schematic of the energy transfer through a window [9]

All the different ways energy can be transferred makes windows less thermal resistant than the rest of the room. There are measures on how to minimize the heat transfer of the window such as: insulating the frame, Using multiple, normally 2 or 3, panels alongside with an insulting gas to reduce conduction. Additionally, a film or coating can reduce the radiation transfer by lowering the emissivity of infrared and ultraviolet light so called Low-E. The methods are shown in figure 4

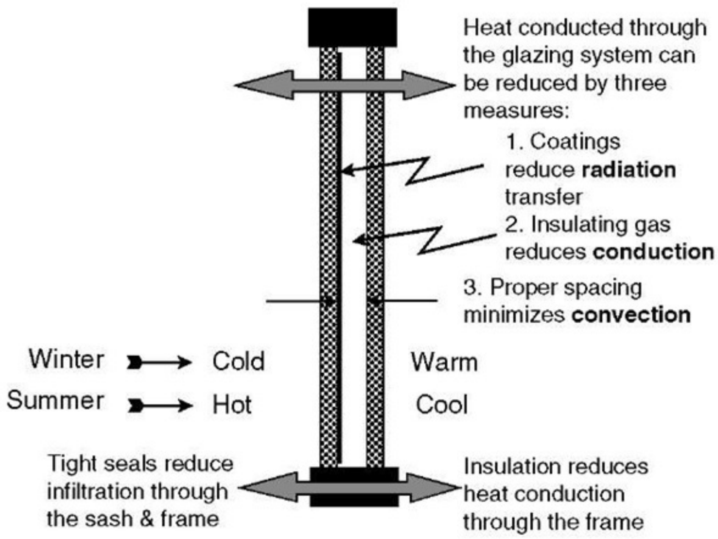


Figure 4: Measures to limit the energy transfer of the window [9]

The heat transfer of the interior and exterior of the room through the window is in normal circumstances equation 6, A is the area of the window (m^2), T_e is the temperature of the exterior (C^o) and T_i is the interior temperature.

$$q = U_{window} \cdot A \cdot (T_e - T_i) \tag{6}$$

The heat transfer from the windows' surface to the interior of the room that is given by equation 7, where h_i is the surface heat transfer coefficient between the surface of the window an the interior ($\frac{W}{K,m^2}$) and T_s is the temperature of the windows surface, would in normal condition be equal to the heat transfer between the exterior and interior.

$$q = h_i \cdot A \cdot (T_s - T_i) \tag{7}$$

With the MOST film the surface temperature of the windows is given by equation 8. Where ρ is the density of the film $[\frac{kg}{m^3}]$, c_p is the specific heat capacity of the film $[\frac{J}{kg,K}]$, Δq is the internal heat transfer of the film $[\frac{W}{m^3}]$ and S is the source term $[\frac{W}{m^3}]$.

$$\rho \cdot c_p \cdot \frac{dT}{dt} = -\Delta q + S \tag{8}$$

The temperature of the film is assumed to be homogeneous in length and height, only the depth of the film is of interest. Which concludes with Δq having the form shown in equation 9, where K is the thermal conductivity of the film $[\frac{W}{m,K}]$.

$$\Delta q = K \cdot (\frac{d^2T}{dx^2}) \tag{9}$$

The source term S is given by equation 10.

$$S = Q_{most} + Q_{glass} \tag{10}$$

Q_{most} is calculated by equation 11, I_{incident} $[\frac{W}{m^2}]$ for is given by equation 12 , where G is the spectral solar irradiation $[\frac{W}{m^2,nm}]$ and α is the spectral absorption, which is given by equation 13.

$$Q_{most} = k_b \cdot [B] \cdot \Delta H_{storage} - \frac{\Phi \cdot n \cdot \Delta H_{storage} \cdot \beta_{A,photo}}{N_a \cdot d_{MOST}} + \frac{I_{incident,A}}{d_{MOST}} + \frac{I_{incident,B}}{d_{MOST}} \tag{11}$$

$$I_{incident,i} = \int_{300}^{3000} \alpha_i \cdot G \cdot \beta_i \, d\lambda \tag{12}$$

$$\alpha_i = 1 - 10^{-[i] \cdot \epsilon_i \cdot d_{MOST}} \tag{13}$$

The amount of light that is absorbed from the windows' glass must also be considered to get an accurate simulation because it will affect the amount of photons that will get through to the MOST film. Contrary to a MOST molecule, which mostly absorb UV light see figure 6, windows absorb light in the visual and infrared span, however they still absorb a small amount of UV [10]. Also the generated energy in the glass from absorbing the photons is significant for the source term of the window. Q_{glass} is calculated by equation 14.

$$Q_{glass} = \frac{I_{incident,glass}}{d_{glass}} \tag{14}$$

4 Methodology

4.1 Window model

A module for the heating and cooling needs of a room based on the weather condition over a year in Gothenburg was given in Matlab stimulink. By adding the modifications of the window heating, a comparison can be made of the demand before and after a MOST film have been added to the window for single, double and triple-glazed while no MOST case is applied to the Low-E case. The

The parent molecule of Norbornadienes (NBA), which has the photoisomer quadricyclane (QC) see figure 5, was selected for this study. Because of the fitting $t_{1/2}$ (6.5 hours) and cycle stability, how many times the molecule can be converted without loosing efficiency [11].

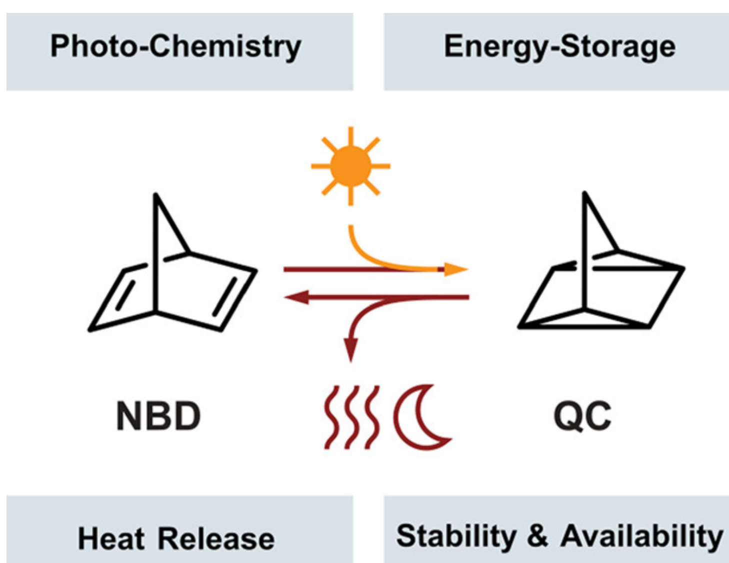


Figure 5: The parent molecule of Norbornadienes (NBA), and the photoisomer quadricyclane (QC) [12]

First, the different windows will be studied without the MOST film by calculating the heat transfer through and surface temperature of the interior facing window. This is achieved by using the U value for the specific window seen in table 1, observe that the average insulated walls U-value is 0.16-0.23 $\frac{W}{K,m^2}$ [13] . The heat transfer coefficient for the interior window (h_i) is usually a combination of radiation and convection and will be seen as 7.7 $\frac{W}{K,m^2}$ constantly for all cases. The heat gain of the solar absorption of the interior glass will also be considered. The heat gain for the exterior glass panel and middle panel (triple-glazed) by absorption will be set to zero for an easier model of the overall heat transfer, though the amount of photons that reach the interior panel is affected by the amount of glass panels and therefore the overall absorption of photons will still be taken in to account.

Windows	U-value [W/m^2K]	glass thickness [m]
Single-glazed	5.8	0.004
Double-glazed	2.8	0.008
Triple-glazed	1.3	0.012
Triple-glazed/Low-E	0.91	0.012

Table 1: U-value and total glass thickness for the different windows.

For the cases with the most film ,the concentration of the film must first be calculated by equation 15, where ρ is the density of polystyrene (1030 $\frac{kg}{m^3}$), weight% is the weight percent of the MOST molecule compared to the film (0.56%), M is the molar mass of the MOST molecule (0.33635 $\frac{kg}{mol}$). C is then equal to 17.15 $\frac{mol}{m^3}$.

$$C = \frac{\rho * weight\%}{M} \tag{15}$$

With the concentration known and with the use of equation 1 2, 3 and 11, the model can be made in simulink shown in appendix A. The surface temperature is calculated with the use of the matlab solver pdepe, which solves Partial Differential Equations (PDE), where the right and left boundary conditions are shown in equation 16 and 18.

$$-k\frac{dT}{dx}|_{x=d_{most}} = h_i \cdot (T_s - T_i) \tag{16}$$

$$-k\frac{dT}{dx}|_{x=0} = U \cdot (T_e - T_i) \tag{17}$$

$$-k\frac{dT}{dx}|_{x=0} = q'' \tag{18}$$

q" is the heat flux on the "left side" of the film. The heat flux is given by the temperature difference from the exterior and interior of the room and the U specific to the window shown by equation 19.

$$q'' = U \cdot (T_e - T_i) \tag{19}$$

Simulink will perform this calculation for every simulated second (as that is the time step) and therefore the initial conditions is the T_s calculated in the previous time step.

Similarly, the different $I_{incident,MOST}$ is calculated every time step as the α and β are dependent on the concentration of the molecule, also the spectral solar irradiance is dependent on the time of day and if the sun is out or not. Figure 6 illustrates the dependence of the wavelength for the ϵ of both NBD and QC. The values was received through absorption spectroscopy.

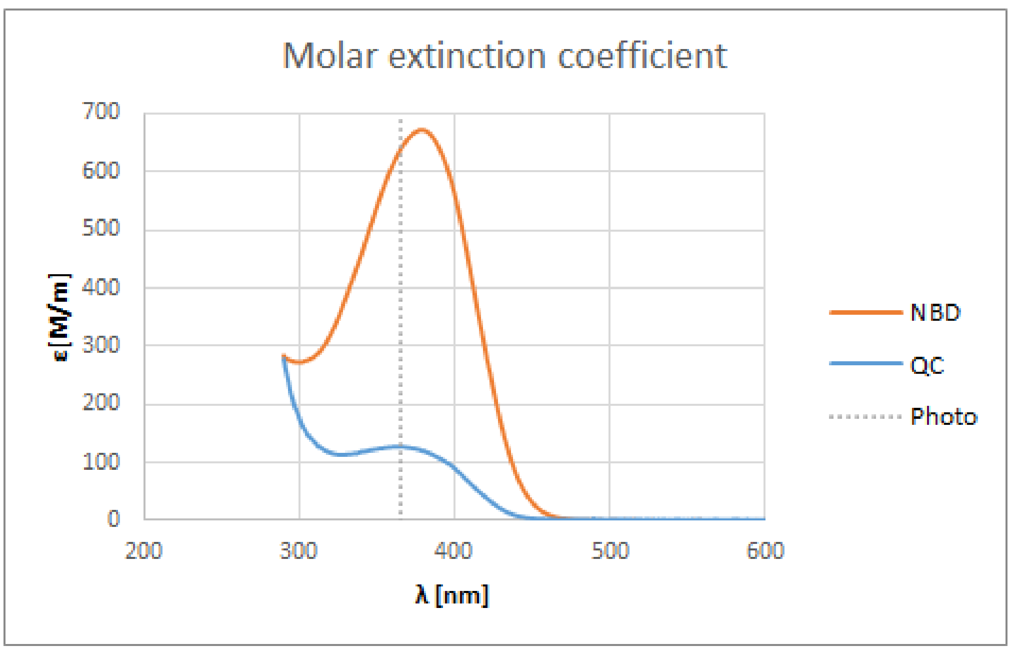


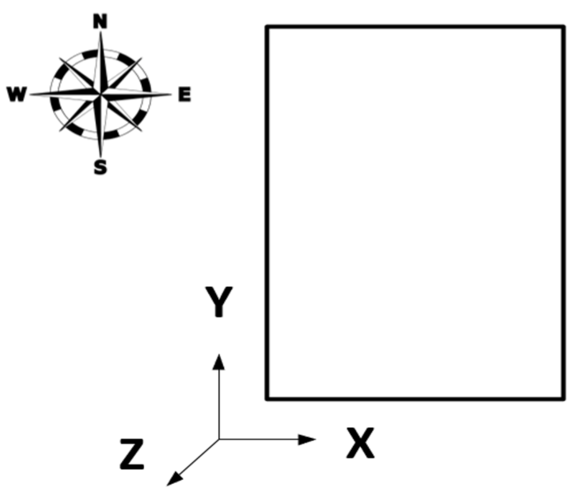
Figure 6: Extinction coefficient for NBD and QC and the wavelength where photoconversion occurs

The energy in the source term is taken from the energy in the direct solar gain, in keeping with the first law in thermodynamics.

Three other cases will be performed, where the $t_{1/2}$ will be changed to 13, 3.25 and 1.625 hours respectively to observe the effect that has on the energy savings. This will on be performed on the triple-glazed window as that is the window best suited in the Gothenburg climate.

4.2 Room energy model

The room geometry is shown in figure 7.



X	2.6m
Y	4.5m
Z	3m
Direction	**WindowArea**
North	2.25
East	0
South	0
West	2.25

Figure 7: A sketch of the room geometry

To calculate the room's interior temperature a lumped model is used as shown in equation 20. Where V_{zone} (m^3) is the volume of the room, ρ_{air} is the density of the air $[\frac{kg}{m^3}]$, $c_{p,air}$ is the specific heat capacity of the air $[\frac{J}{kg,K}]$, S_i is the power [W].

$$V_{zone} \cdot \rho_{air} \cdot c_{p,air} \cdot \frac{dT_{in}}{dt} = \sum_i S_i \tag{20}$$

The power from the different surfaces of the room is shown in equation 21, Where K_j $[\frac{W}{K,m^2}]$

is the heat transfer coefficient for the different surfaces.

$$S_1 = \sum_j K_j (T_e - T_{surface,j}) \tag{21}$$

The power from the ventilation systems can be seen in equation 22, Where n_{vent} is the ventilation rate $[\frac{1}{s}]$.

$$S_2 = n_{vent} \cdot V_{zone} \cdot \rho_{air} \cdot c_{p,air} \cdot (T_e - T_i) \tag{22}$$

The power gained for window solar gain; by direct beam and by diffuse is seen in equation 23.

$$S_3 = A_{window} \cdot [\tau(\alpha) \cdot I_{direct} + \tau_{diffuse} \cdot I_{diffuse}] \tag{23}$$

Lastly the power from the cooling and heating systems can be observed in equation 24. Which is controlled by an proportional controller with P set to 20000 for both the cooling and heating.

$$S_4 = \dot{Q}_{Heating} + \dot{Q}_{Cooling} \tag{24}$$

$$\dot{Q}_{Heating} = \begin{cases} 0, & \text{if } T_{in} > T_{heat} \\ P \cdot (T_{heat} - T_{in}), & \text{if } T_{in} \leq T_{heat} \end{cases}$$

$$\dot{Q}_{Cooling} = \begin{cases} -P \cdot (T_{in} - T_{cool}), & \text{if } T_{in} \geq T_{cool} \\ 0, & \text{if } T_{in} < T_{cool} \end{cases}$$

5 Result & discussion

5.1 U-value

By observing figure 8a the source term is at its largest around 32KW in the early hours of the day. The reason for this is that during that time NBD is being converted to QC but at the same time photons is being absorbed by NBD. As seen in figure 6 that the extinction coefficient is substantially larger for NBD then for QC. This is further illustrated in figure 8c as soon as QC have reached a steady state on the 8th of January it then reaches a plateau (around 5KW) and comparing that to the 1th of January where it had been an hour without light and QC had started it's backconversion, then the sun started to shine again and during that time the source term reached a higher peak (around 7KW) compared to the plateau of January 8th. This shows that the film will reach it highest absorption at dawn or at the first time the sun shines of the day.

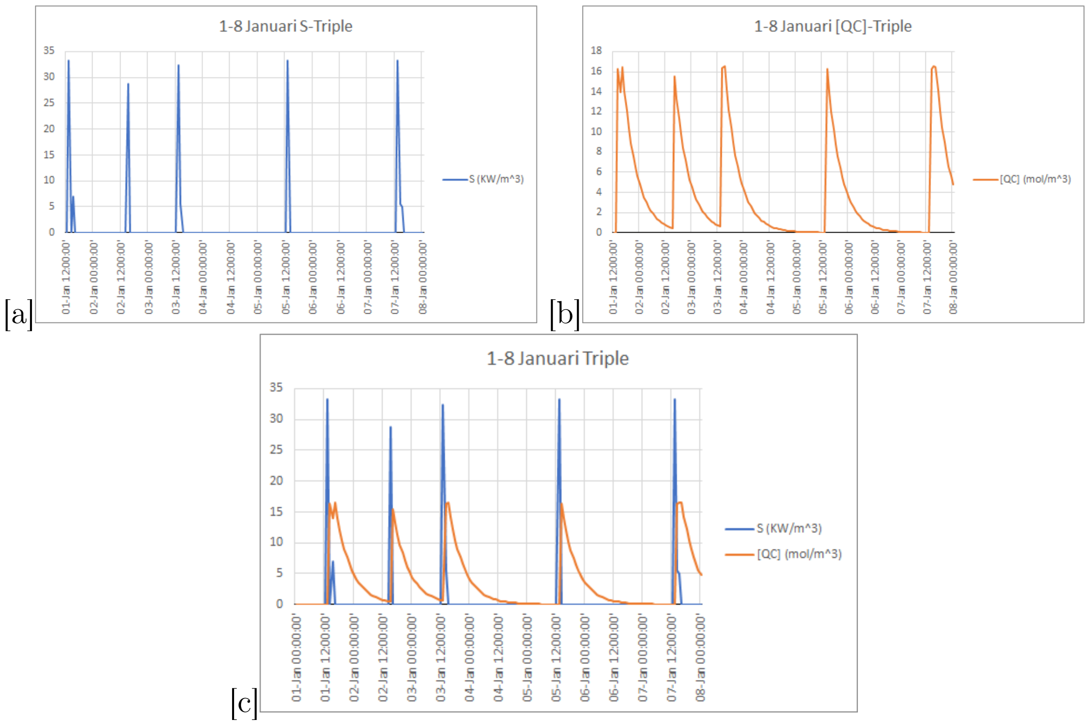


Figure 8: a) The source term for the MOST film. b) The concentration of QC in the film. c) Both the source term and the concentration in the film during 1th of January to the 8th.

Figure 9 shows the amount the back conversion contributes to the source term during the same time span as figure 8. Whats interesting to note is that in figure 8 the source term is in KW while in figure 9 it is in W. This means that the energy released during backconvertion is quite small in compared of the amount of energy that is being absorbed by the MOST film. This is further illustrated in figure 10 that the only time the surface temperature differs for the case without the MOST windows is at 13.00 which is the time the sun first shines that day otherwise the difference is negligible. Though it worth mentioning that the energy that is being used to convert NBD to QC has a somewhat larger effect on the heating demand as that happens comparably quickly to the backconvertion.

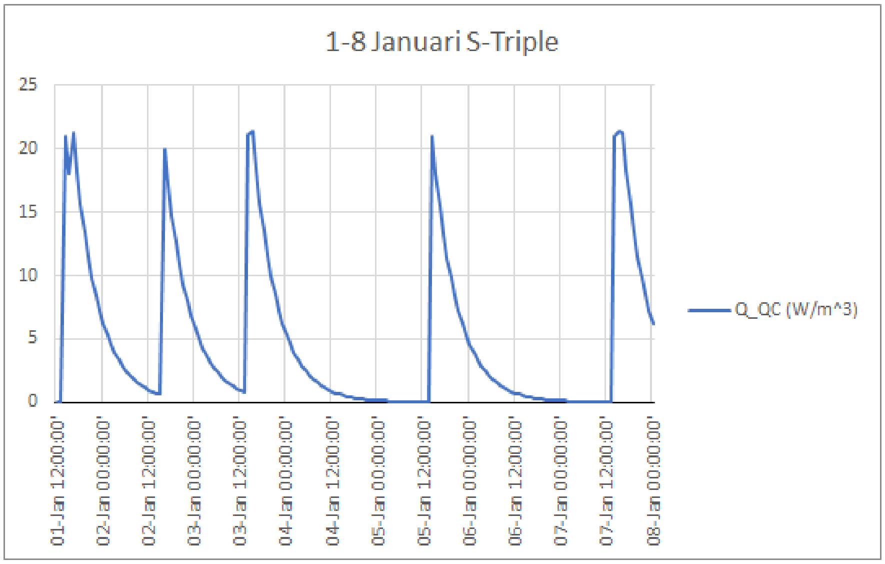


Figure 9: The amount that the energy released from the back conversion of the photoisomer QC.

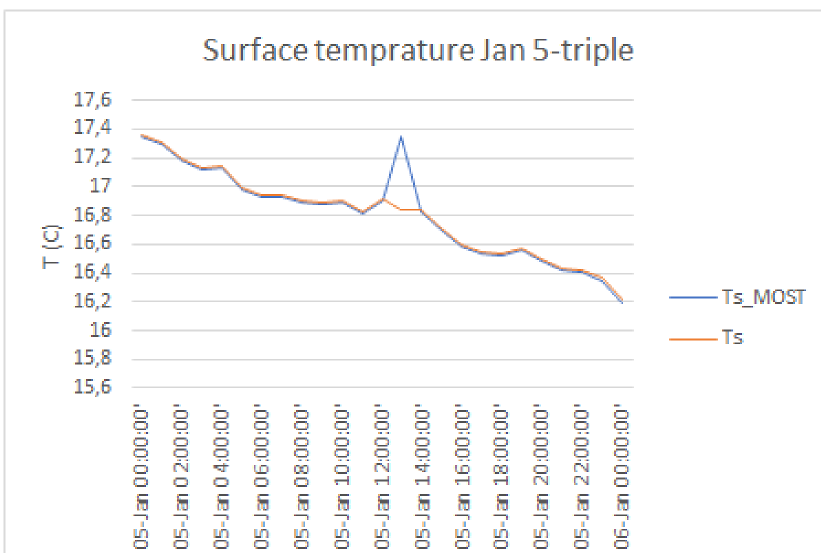


Figure 10: The surface temperature of the windows facing the interior for the triple-glazed window on January 5th with and without the MOST film.

The amount of heating and cooling needed per month can be seen in figure 11 and 12 respectively.

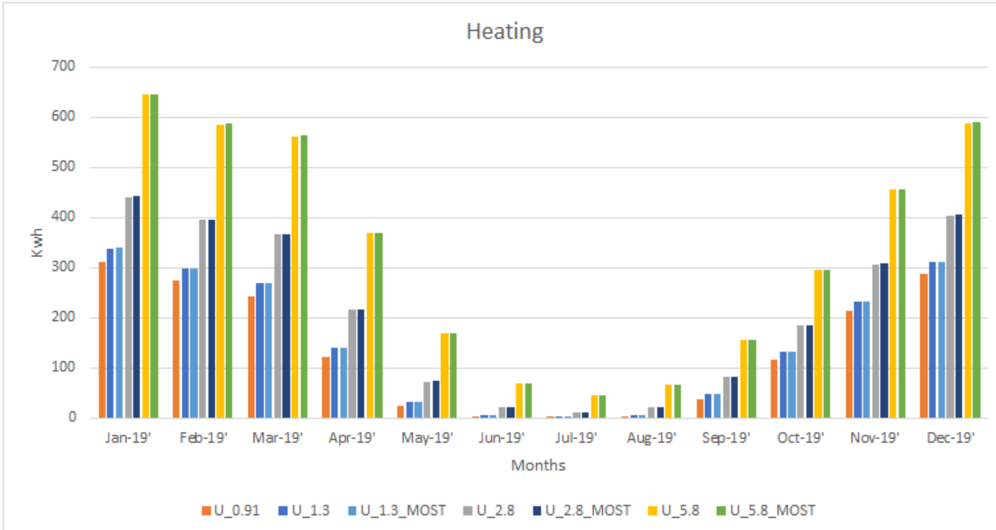


Figure 11: The total amount of energy needed for heating each month for the room

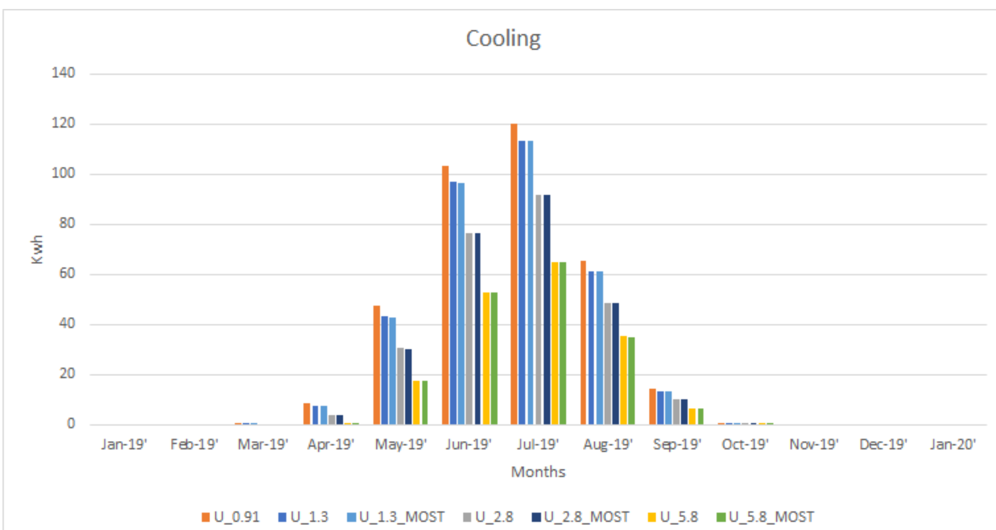


Figure 12: The total amount of energy needed for cooling each month for the room

The trend seems to be that the amount of heating has a positive correlation to the windows U value, which is not surprising. Thought the cases with the MOST film seems to be in need of more heating then the cases without. The opposite trend is observed when it comes to cooling. The total amount of heating and cooling needed for the year can be observed in table 2.

Windows	Total heating [kwh]	Total cooling [kwh]
Single-glazed	4007.3	178.16
Single-glazed/MOST	4017.7	177.35
Double-glazed	2526.4	261.77
Double-glazed/MOST	2531.5	260.84
Triple-glazed	1821.3	335.67
Triple-glazed/MOST	1823.8	334.80
Triple-glazed/Low-E	1643.7	360.26

Table 2: The total amount heating and cooling over the year for the different windows.

By separating the days of the year that only need heating, cooling and both, table 3, 4 and 5 respectively. Then the efficiency of the MOST film can be observed for the different climates.

Windows	Heating [kwh]	Days
Single-glazed	3752.4	261
Single-glazed/MOST	3761.5	261
Double-glazed	2371.8	239
Double-glazed/MOST	2376.2	239
Triple-glazed	1723.6	225
Triple-glazed/MOST	1725.8	225

Table 3: The amount of days with only heating and the total amount of heating over the year for the different windows.

Windows	Cooling [kwh]	Days
Single-glazed	64.483	14
Single-glazed/MOST	64.347	14
Double-glazed	123.99	34
Double-glazed/MOST	123.67	34
Triple-glazed	246.30	62
Triple-glazed/MOST	241.31	61

Table 4: The amount of days with only cooling and the total amount of cooling over the year for the different windows.

Windows	Heating [kwh]	Cooling [kwh]	Days
Single-glazed	254.90	113.68	90
Single-glazed/MOST	256.17	113.01	90
Double-glazed	154.63	137.79	91
Double-glazed/MOST	155.28	137.17	91
Triple-glazed	97.66	89.37	73
Triple-glazed/MOST	97.99	93.50	74

Table 5: The amount of days with both heating and cooling and the total amount of heating and cooling over the year for the different windows.

Because the MOST film effected the triple-glazed amount of days of only cooling and both cooling and heating see table 4 and 5. It would then be an interesting day to observe. As figure 13 illustrates the interior temperature at around 5 am gets below the "cooling temperature", which is not the case for the triple-glazed without the MOST film. The reason is that the MOST film store energy at the morning hours of the day as that is when the sun rises. Which then leads to less heating to the interior. This is probably the reason on why the heat demand increase when MOST is applied.

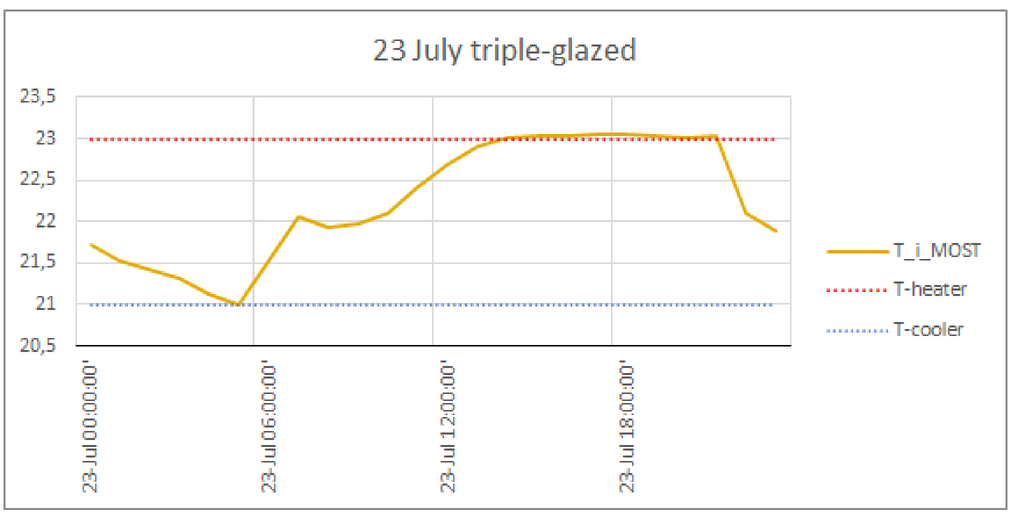


Figure 13: The interior temperature on the 23th of July

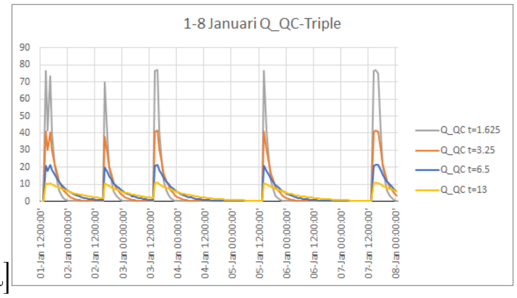
In table 6 the amount of heating and cooling that is saved in during the year can be clearly seen. What can be concluded from this data is that the % increase of heating even though it is generally lower then the days that only have cooling, the total amount of extra heating is larger then the amount of cooling saved. The reason for this is the days with only heating is the majority of days in Gothenburg as seen in table 3. Because of these facts it shows that the MOST film is not suitable for climates like Gothenburg which have a larger heating demand during the year compared to the cooling demand. Another trend that can be observed is that the lower the U value of the window, the more efficient the cooling. It could therefor be augured that the the MOST film could be an attractive option in areas where the primary need for space cooling offset the need for space heating as is more common near the equator, where less isolating windows are more common for that very reason [14].

Windows	Heating saved [kwh]	Cooling saved [kwh]	Heating %	Cooling %
Single-glazed total	-10.4	0.81	0.260	-0.455
Double-glazed total	-5.1	0.93	0.202	-0.355
Triple-glazed total	-2.5	0.87	0.137	-0.259
Single-glazed heat only	-9.1	0	0.243	0
Double-glazed heat only	-4.4	0	0.186	0
Triple-glazed heat only	-2.2	0	0.128	0
Single-glazed cool only	0	0.136	0	-0.211
Double-glazed cool only	0	0.32	0	-0.258
Triple-glazed cool only	0	0.49*	0	-0,203
Single-glazed both	-1.27	0.67	0.498	-0.589
Double-glazed both	-0.65	0.62	0.420	-0.450
Triple-glazed both	-0.33	0.37*	0.338	-0.414

Table 6: The amount of heating and cooling saved over the year for the different windows. Split into days with only heating, only cooling and both heating and cooling.
** Taking into account that 23th July changed from only cooling without MOST to both heating and cooling with the MOST film.*

5.2 $\mathbf{t_{1/2}}$

Figure 14a shows the effect of the half-life on the triple-glazed window has on the energy released where it can be seen that the lover the half-life the higher the peak and less long term realise of energy, which is to be expected.

[a] 

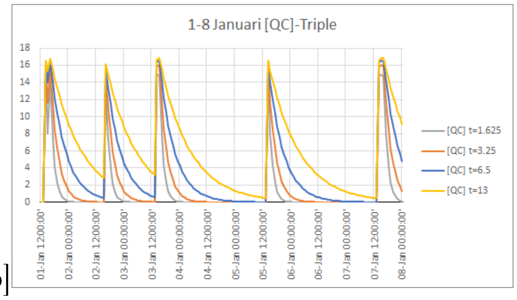
[b] 

Figure 14: a) The amount of energy released during the backconversion b) The concentration of QC in the film.

As in the previous section the space heating and cooling is divided in total heating and cooling, only heating, only cooling and both heating and cooling in table 7, 8, 9 and 10. Note that the half-life did not effect the quantity of days as shown in the previous table 3, 4 and 5.

$t_{1/2}$ [h]	Heating [kwh]	Cooling [kwh]
NA*	1821,265	335,6654
13	1823,798	334,8055
6.5	1823,801	334,8026
3.25	1823,805	334,7990
1.625	1823,810	334,7927

Table 7: The amount of total amount heating and cooling over the year for different $t_{1/2}$ for the triple-glazed case.
** No MOST film.*

$t_{1/2}$ [h]	Heating [kwh]
NA	1723,602
13	1725,812
6.5	1725,815
3.25	1725,818
1.625	1725,823

Table 8: The total amount of heating on days with only heating over the year for for different $t_{1/2}$ for the triple-glazed case.

$t_{1/2}$ [h]	Cooling [kwh]
NA	241,7919*
13	241,3091
6.5	241,3073
3.25	241,3052
1.625	241,3017

Table 9: The total amount of cooling on days with only cooling over the year for for different $t_{1/2}$ for the triple-glazed case.
** Taking into account that 23th July changed from only cooling without MOST to both heating and cooling with the MOST film.*

$t_{1/2}$ [h]	Heating [kwh]	Cooling [kwh]
NA	97,662	93,8734*
13	97,986	93,4965
6.5	97,986	93,4952
3.25	97.987	93.4938
1.625	97.989	93.4910

Table 10: The total amount of heating and cooling on days with both heating and cooling over the year for for different $t_{1/2}$ for the triple-glazed case.
** Taking into account that 23th July changed from only cooling without MOST to both heating and cooling with the MOST film.*

When observing table 11 the generally trend shows that the lower the half-life the more efficient the cooling saving and less efficient heating. This would then have the opposite correlation of the U-value where the higher the U value the more efficient cooling. Important to note that the change in efficiency for the half-life was smaller then the U-value.

$t_{1/2}$ [h]	Heating saved [kwh]	Cooling saved [kwh]	Heating %	Cooling %
13 total	-2.534	0.8597	0.1391	-0.2562
6.5 total	-2.537	0.8628	0.1392	-0.2570
3.25 total	-2.541	0.8663	0.1395	-0.2581
1.625 total	-2.548	0.8726	0.1397	-0.2600
13 heat	-2.210	0	0.1282	0
6.5 heat	-2.213	0	0.1284	0
3.25 heat	-2.216	0	0.1286	0
1.625 heat	-2.221	0	0.1289	0
13 cool	0	0.4828	0	-0.1997
6.5 cool	0	0.4846	0	-0.2004
3.25 cool	0	0.4867	0	-0.2013
1.625 cool	0	0.4902	0	-0.2027
13 both	-0.324	0.3769	0.3729	-0.3059
6.5 both	-0.324	0.3782	0.3729	-0.3073
3.25 both	-0.325	0.3796	0.3739	-0.3088
1.625 both	-0.327	0.3824	0.3759	-0.3118

Table 11: The amount of heating and cooling saved over the year for the different windows. Split into days with only heating, only cooling and both heating and cooling.

6 Conclusion

The MOST film is not suitable for colder climates. The amount of energy saved in form of cooling is offset by the extra heating demand. It could be of interest to examine how the MOST film would compare in a warmer climate where a bigger emphasis is on the cooling demand then the heating demand. The energy released in the back conversion of the photoisomer was not that substantial to have an substantial effect on the heat demand but the energy used to convert NBD to QC was substantial enough to have an effect on the heat demand, this is because of the comparably faster photoisomerization then to the thermal backconvertion. Another conclusion is that the MOST got more efficient with a lower half-life, since more of the photoisomer manage to backconvert during sunless hours.

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A

Simulink

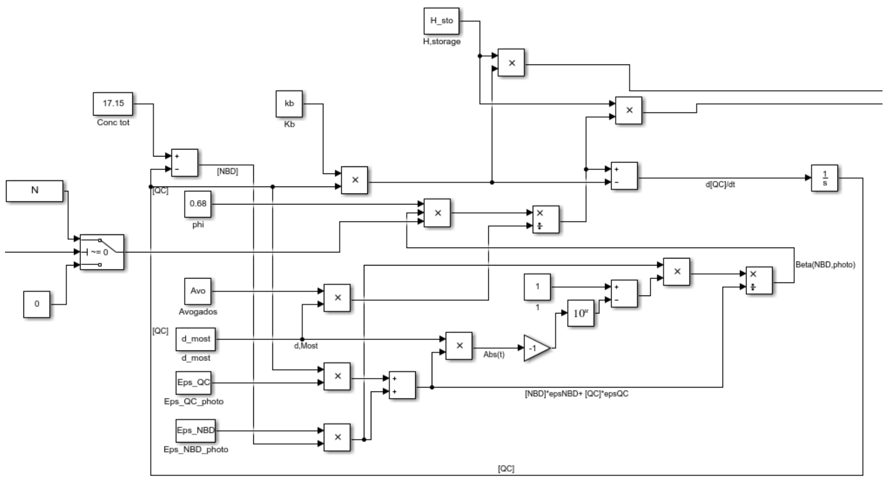

Figure 15: The simulink layout for the mass balance of the MOST molecule.

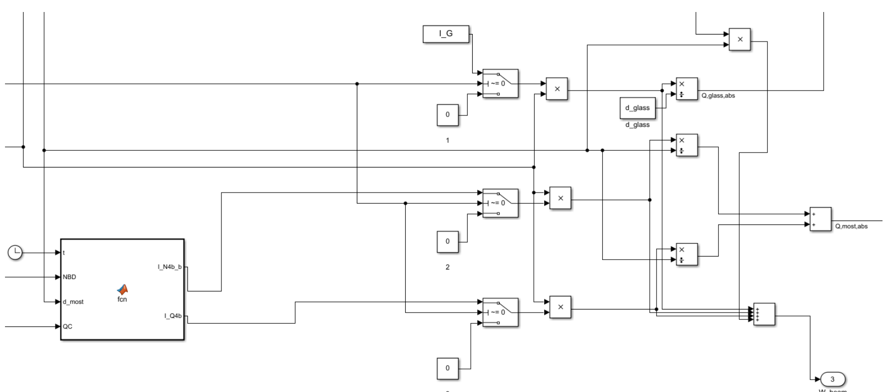

Figure 16: The simulink layout for the Incident light portion of the energy balance.

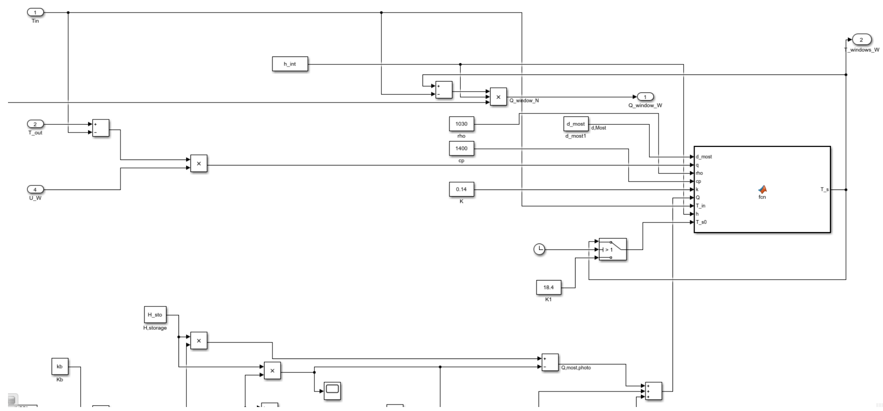

Figure 17: The simulink layout for the calculation of the surface temperature and the heat flux between the window and interior.

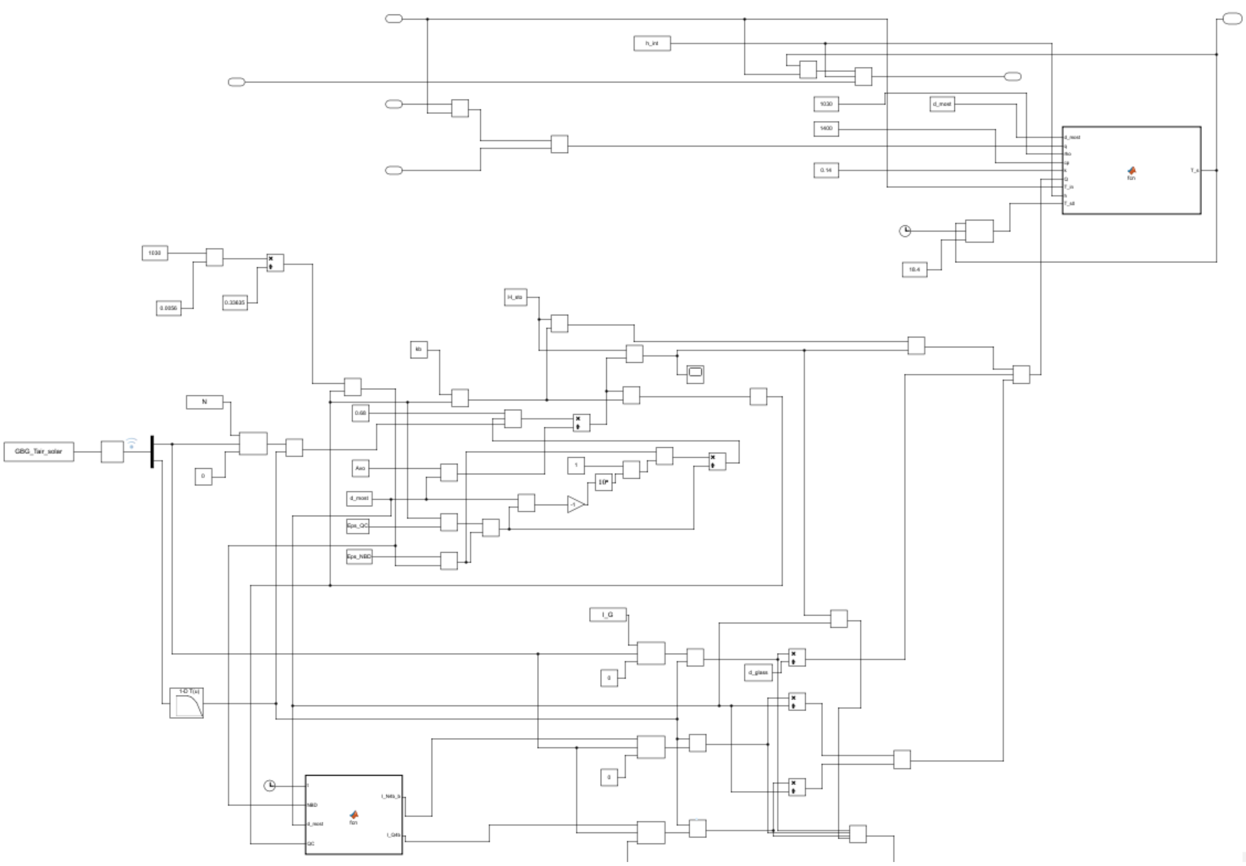

Figure 18: The full simulink layout of the window heating.