Smart Windows – Dynamic Control of Building Energy Performance

Kaitlin Allen, Karen Connelly, Peter Rutherford and Yupeng Wu*

Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, UK

Corresponding author: Tel: +44 (0) 115 74 84011; emails: Yupeng.Wu@nottingham.ac.uk, Jackwuyp@googlemail.com

Abstract

This paper will explore the potential of employing thermotropic (TT) windows as a means of improving overall building energy performance. Capitalising on their ability to dynamically alter solar and visible light transmittance and reflectance based on window temperature, they have the potential to reduce solar heat gains and subsequently reduce cooling loads when the external conditions exceed those required for occupant comfort. Conversely when the external conditions fall short of those required for occupant comfort, they maintain a degree of optical transparency thus promote the potential for passive solar gain. To test their overall effectiveness, thermotropic layers made of varying hydroxypropyl cellulose (HPC) concentrations (2wt.%, 4wt.% and 6wt.%) were firstly synthesised and their optical properties measured. Building performance predictions were subsequently conducted in EnergyPlus for four window inclinations (90°, 60°, 30° and 0° to horizontal) based on a small office test cell situated in the hot summer Mediterranean climate of Palermo, Italy. Results from annual predictions show that both incident solar radiation and outdoor ambient temperature play a significant role in the transmissivity and reflectivity of the glazing unit. If used as a roof light, a 6wt.% HPC-based thermotropic window has a dynamic average Solar Heat Gain Coefficient (SHGC) between 0.44 and 0.56, this lower than that of 0.74 for double glazing. Predictions also show that in the specific case tested, the 6wt.% HPC-based thermotropic window provides an overall annual energy saving of 22% over an equivalent double glazed unit. By maintaining the thermotropic window spectral properties but lowering the associated transition temperature ranges, it was found that the lowest temperature range provided the smallest solar heat gains. Although, this is beneficial in the summer months, in the winter, passive solar heating is restricted. In addition, with lower solar heat gain, there is a possibility that artificial lighting energy demand increases resulting in additional energy consumption.

Keywords: Thermotropic window; smart window; hydroxypropyl cellulose (HPC); building simulation; solar heat gain coefficient.

1. Introduction

Buildings are responsible for 40% of energy consumption within the EU, and consequently contribute to approximately 36% of overall carbon emissions [1]. As has been recognised for example in the UK's amendments to Approved Document L, the envelope of a building is crucial in terms of energy consumption. Attention therefore needs to be made to the design and specification of the transparent elements that comprise the building's envelope. Whilst such elements are often considered to be thermally weak, this has to be offset against the benefits to occupant comfort, health, wellbeing and productivity afforded by natural light, views and associated control over natural ventilation. A case can therefore be made to explore the application of new technologies to improve the thermal properties of these transparent elements whilst maintaining the optical properties that govern daylight availability, view and so on.

To maximise the benefits of view and daylight availability, many contemporary commercial and residential buildings employ high levels of glazing. If well designed these can lead to significant heat loss or gains when the external conditions are outside the range normally accepted for occupant comfort and as a consequence may increase the energy demands of the building. Although window technology that aims to stabilise the internal temperature of glazed buildings has improved over recent years, many are static and inflexible, such as low-emissivity (low-e) glazing. 'Switchable glazing' however is designed to regulate the amount of transmitted solar and long-wave radiation (300-3000nm) and is therefore far more adaptive in nature. By responding to an applied stimulus; heat (thermochromism), electricity (electrochromism) and light (photochromism), these technologies have demonstrated significant potential to reduce energy consumption in buildings [2].

Thermotropic (TT) windows are a type of thermochromic (TC) glazing that features reversible transmission behaviour in response to heat. By employing a manufacturing technique that allows the transition / switching temperature (T_s) to be adapted to suit various climatic forces, it provides a solution that can regulate indoor environmental conditions by controlling solar heat gain and visible light transmittance. If we consider a hydrogel and polymer based example, when the temperature of the thermotropic layer is below a designed T_s, its two main components, hydrogel and polymer, uniformly mix resulting in the layer appearing transparent. Conversely, the layer becomes translucent and diffusely reflecting when T_s is exceeded due to the two components having separated [3, 4]. As such, in its translucent state it reduces the amount of solar radiation entering a building during hot periods therefore potentially reducing overall cooling loads. In its transparent state, solar radiation is admitted to the building thus contributing to external heat gains. Whilst the exact positioning of thermotropic glazing is in the hands of those responsible for the building's design, its use is more suited to areas where an obstructed view is not considered to be important. It is suitable therefore for incorporation as high level glazing, as skylights or as roof lights, as above the transition temperature visual contact with the external environment will be lost.

Previous studies have considered the potential energy saving effects of thermochromic glazing, with some considering thermotropic glazing specifically within the built environment. General conclusions have been drawn about the performance of TC windows such as whilst they offer the potential to save energy during hot periods, the coatings can result in higher heating loads in cool periods due to low solar transmittances across both the cold and hot states [5]. Saeli et al. [6] studied the energy saving potential of TC smart windows in relation to the percentage of glazing to opaque areas, finding that when applied in London at a 25% glazing ratio, the total energy consumption was increased by 9%. This can be partially attributed to the cooler climate preventing the switching temperature of 39°C from being reached therefore the window never reaches its translucent state. Conversely, when simulated for Palermo in Italy which has higher summer time temperatures, the total energy consumption was reduced by 12%, increasing to 33% when the glazing ratio was increased to 100%, concluding that TC windows generally perform better in hotter climates where cooling is required. Hoffman et al. [7] studied the effects of switching temperature of TC smart windows for a mixed hot/cold climate and a hot, humid climate in the US. It was found that when compared to a low emissivity (LE) glazing system, a TC window with a low T_s (of between 14-20°C) reduced energy consumption by 10-17% in the south, east and west facing perimeter zones with large area windows. Warwick et al. [8] examined the effect of the thermochromic transition gradient on the energy demand characteristics of a model system (a simple model of a room in a building) in a variety of climates, these results compared against current industry standard glazing products such as silver sputtered glass and absorbing glass. It was found that in a warm climate with a low transition temperature and sharp hysteresis gradient, energy demand can be reduced by up to 51% compared to conventional double glazing.

In the project presented here, a new type of thermotropic window has been developed where the thermotropic layer is sandwiched as a membrane between two conventional glazing panes. Made from hydroxypropyl cellulose (HPC), three concentrations of HPC (2wt.%, 4wt.% and 6wt.%) were tested for solar and visible light transmittance and reflectance using a spectrometer. These data were used as input data into a series of EnergyPlus simulations based on a small office-type environment located in Palermo, Italy. These simulations sought to explore the performance of existing commercial glazing products and the newly developed window with respect to HPC concentration, plane inclination, solar gains, energy loads and overall energy performance. To do so, three sets of simulation tests were performed looking in increasing detail at glazing performance namely:

1. The effect of glazing type, inclination and HPC concentration on heat gains, heating, cooling, lighting loads and overall energy performance,
2. The effect of glazing type and membrane concentration on heat gains, heating cooling, lighting loads and overall energy performance for a horizontal plane of 0^{o} inclination,
3. The effect of transition temperature on heat gains, heating cooling, lighting loads and overall energy performance for a horizontal plane of 0^{o} inclination.

Overall, the results may be seen as offering potential advice on the design, development and use of thermotropic windows in buildings under these particular conditions.

2. Development of the thermotropic glazing

2.1 Thermotropic Membranes

Thermotropic materials can be divided into several systems based upon the mechanism by which they achieve a state of low visible and solar transmission above the T_s. Three main groups are defined namely thermotropic hydrogels, thermotropic polymer blends and embedded thermotropic polymers within fixed domains [9]. Thermotropic hydrogels are water absorbent, cross-linked polymer networks with varying degrees of both hydrophilic and hydrophobic groups within their structures. Below the lower critical saturation temperature (LCST), also referred to as the transition temperature (T_s) in this work, the polymer is hydrophilic with hydrogen bonding between polymer and water molecules dominating over hydrophobic polymer-polymer interactions. The polymer below the T_s is therefore homogeneously dissolved at the molecular level resulting in a transparent, isotropic, light transmitting state. Above the LCST, or T_s, hydrogen bonding between polymer and water is weakened resulting in hydrophobic polymer-polymer interactions dominating and subsequent polymer aggregation. Consequently phase separation occurs with water quenched out of the polymer network. With sufficient disparity between the refractive indices of these two phases, light will be scattered rather than transmitted, with a resultant ‘clouding’ of the system [9, 10].

Also dependent upon a difference in refractive index of the two components in the system are thermotropic polymer blends. However in this case the two components comprise a thermoplastic polymer embedded within a cross-linked polymer matrix. Below the T_s both polymers have a similar refractive index and therefore the polymer blend is transparent. As the temperature is increased to that of the T_s, the refractive indices of the polymers are altered and therefore light scattering occurs [11, 12]. The T_s and turbidity intensity, i.e. degree of translucence above the T_s, of both thermotropic hydrogels and thermotropic polymer blends can be adjusted by addition and ratio adjustment of copolymers, salts and tensides [9].

The third main category is thermotropic domain materials consisting of a homogeneously dispersed scattering domain statically embedded within a transparent matrix domain such as a resin [13]. The matrix domain has a consistent refractive index both above and below the T_s and remains in the solid state. Below the T_s both matrix and scattering domains have a similar refractive index whilst above the T_s the refractive index of the particles in the scattering domain is altered. This results in light scattering above the T_s and produces the translucent, ‘cloudy’ state [14, 15].

For the successful incorporation of any type of thermotropic material into a glazing unit there are a number of requirements that need to be fulfilled [9, 16, 17, 18]:

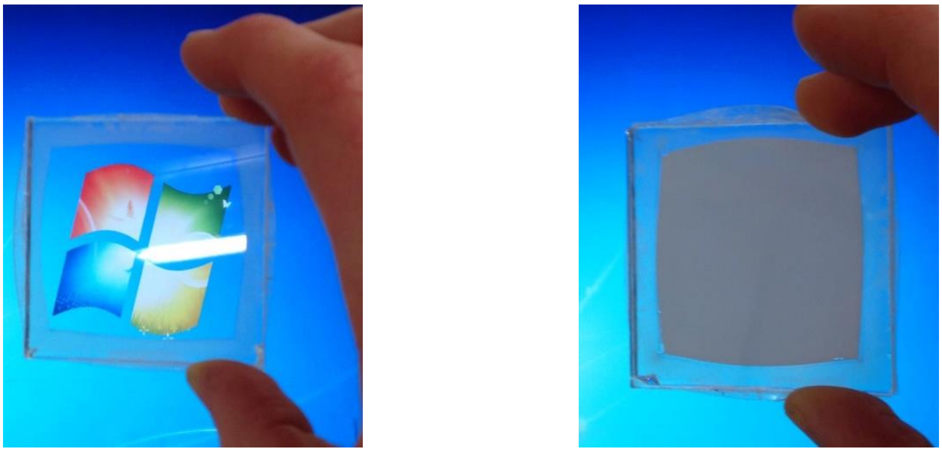
- Transmittance >85 % in the transparent state (below T_s) and transmittance <15 % in the translucent state (above T_s), however, this should be further studied by applying thermotropic windows in a building;
- Steep switching gradient within a 10 ^{o}C range;
- Reversibility of phase with low hysteresis, that is durable and reproducible over long periods of time;
- Homogeneously stable materials both above and below the T_s, i.e. no visible ‘streaking’;
- Tuneable T_s within a wide temperature range, therefore adaptable to both climatic and architectural needs ;
- Long term stability against UV-radiation and biodegradation;
- Non-freezing, non-toxic, non-flammable, preferably inert;
- Low cost and can be manufactured to cover a large area.

2.2 Hydroxypropyl Cellulose Synthesis

Based on the advantages and disadvantages of the various polymer types discussed, hydroxypropyl cellulose (HPC) was selected as the membranous sandwich layer for the thermotropic glazing unit developed. Hydroxypropyl cellulose (average Mw ~80,000 and average Mn ~10,000 where Mw refers to weight average molecular weight, and Mn refers to number average molecular weight) was purchased in the form of an off-white powder from Sigma Aldrich. The viscosity range, as reported by the manufacturer, was 150-700 cP for 10 wt.% HPC in water at 25˚C. The gelling agent used to synthesise the membrane was received as a white powder. Chemicals were used as received without any further preparation. Solutions of varying HPC concentration were prepared as follows: HPC was magnetically stirred into water heated between 50 to 60˚C for several minutes until all HPC had dissolved. The relevant volume of additional water required to produce the desired HPC wt.% was then added at room temperature and left stirring for several hours.

To synthesise the HPC membranes, the relevant amount of gelling powder required to make 1.5 wt.% in the final membrane composition was dissolved into heated water. Various concentrations of aqueous HPC were then added to the heated gelling solution whilst stirring. The HPC / gelling agent solution was cast between two 4 mm thick optical white low iron 5 x 5cm sheets of glazing using a 0.5 mm membrane as a spacer. Three types of HPC based thermotropic windows were synthesised at 2wt.%, 4wt.% and 6wt.% concentrations. The developed prototype of the thermotropic smart window and its transition states are shown in Figure 1.

Visible light and solar transmittance and reflectance data were obtained for each glazing encased membrane sample in and around the transition temperature for each HPC concentration. To do this, samples were heated on a hotplate to a defined temperature allowing 20 minutes equilibration time before taking a measurement. Four T-type thermocouples were glued to the top surface of the glazing and the resultant temperature was taken as the average of these four measurements. The sample was immediately transferred to an Ocean Optics USB200+ spectrometer connected to a FOIS-1 integrating sphere using a HL-2000 Halogen Light Source [19] and its transmittance measured. Once transmittance data had been gathered, the measurement process was repeated to obtain data on each sample's reflectance. For this, the Ocean Optics USB200+ spectrometer was used, this time coupled with an ISP-REF integrating sphere [19]. An Ocean Optics WS-1 diffuse reflectance standard was used as the reference for measuring 100% reflectance. In the case of all three HPC-based thermotropic window concentrations, the lower transition temperature was 40^{o}C, the transition complete above 50^{o}C.



(a) Window state below Ts (b) Window state above Ts

Figure 1 - Photo of the developed thermotropic smart window

3. Building energy simulation

3.1 Climatic conditions

As with the Saeli et al. [6] study, simulations were conducted for Palermo in southern Italy. Known for its hot dry summers and cool wet winters with an annual average temperature of 18.5°C, a maximum average temperature of 30°C in summer and a minimum average of 10°C in winter, this location was deemed appropriate to test the switching behaviour of the thermotropic glazing.

3.2 Construction of simulation building

A cellular office room with dimensions 5m x 4m x 3m was chosen for the simulation. The room was considered as part of a larger façade and building hence only the south wall and roof comprising the room were deemed to be exposed to external conditions. For those other room surfaces, they were assumed to be buffered by mechanically conditioned spaces and hence would not be subject to any heat transfer.

The simulations were designed to test the effectiveness of the various concentrations of TT glazing system in response to plane inclination (tilt angle). Additionally, both ordinary and solar controlled (low-e coated) double glazing units were simulated to assess their performance in relation to the TT variants. It should be noted that the purpose of the research was not to compare data across plane inclinations due to the differences in transparent to opaque area ratios between the vertical (0^o) and tilted surfaces. All models were considered to have the same roof area ($20m^2$) to enclose the space and a window of dimensions 2m x 1.5m was inserted into the plane under test. In the case of the south facing vertical surface, the window took up 25% of the total plane area. In the case of other plane inclinations, the window took up 15% of total plane area. Any additional surfaces needed to achieve this $20m^2$ were once again assumed not to be subject to additional heat transfer. To account for volumetric changes between different simulation models, these were accounted for and will be discussed in section 4: Results Analysis.

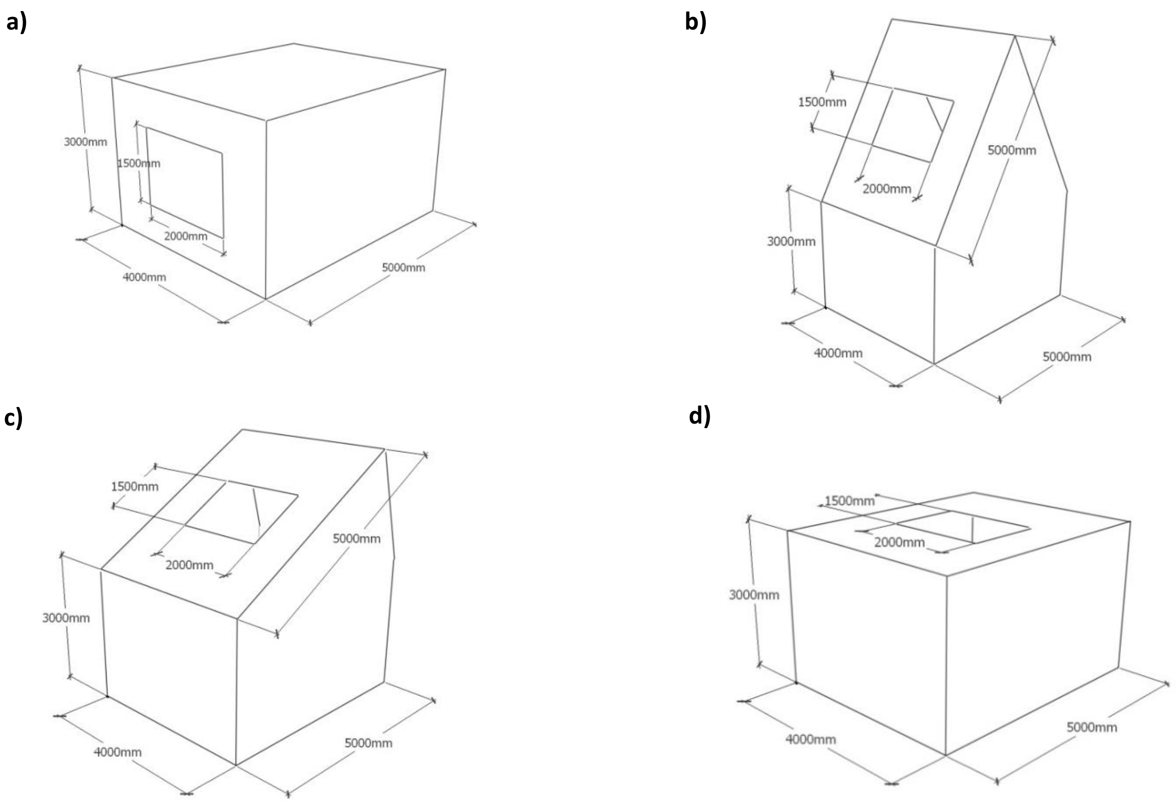


Figure 2 – Room simulations a) 90°, b) 60°, c) 30°, d) 0°, orientated window from horizontal

3.3 Properties of simulation materials

To maintain a constant U-value across a constant area, regardless of window position, the south wall and roof were assumed to have a U-value of $0.25W/m^2K$. Three types of glazing were simulated; (a) ordinary double glazing (ODG), (b) solar controlled double glazing with a low-e coating (LE) and (c) various concentrations of the thermotropic window (TT). The relevant properties for these materials can be found in Table 1.

Table 1 - Properties of the selected building components

Building component	U-Value (W/m^2K)	Solar Transmittance	Solar Reflectance
External Wall	0.25	N/A	N/A
External Roof	0.25	N/A	N/A
Double Glazing (ODG)	2.7	0.79	0.16
Solar Control Low-E Double Glazing (LE)	1.7	0.53	0.22
Thermotropic Windows (TT)	2.7	dynamic	dynamic

3.4 Occupancy, infiltration, HVAC, lighting and run time assumptions

Indoor loads including occupancy, HVAC, lighting, etc. were standardised across all simulations. The office was taken to be a private office capable of seating two people where Saturday working was the norm for the organisation (Table 2) [21]. Air infiltration was assumed to be a constant 0.085 m^3/s, this considered to be appropriate for an air 'tight' building [20, 22]. A single annual comfort set point temperature of 22^oC [22] was used and a lighting load of 12.5 W/m^2 was assumed based on a standard lighting level of 500 lux [23] where the luminous efficacy was 40 lm/W. Daylight controls were set within the simulation where artificial lights were switched on if the illuminance fell below 500 lux during working hours. A Typical Meteorological Year weather file was used for the site and the simulations were run based on 10 minute time step intervals for the entire year [26].

Table 2 - Occupancy schedule (the value of 0, 1 and 2 refers to the number of people in the office at specific time)

Time	24-7	7-8	8-12	12-13	13-17	17-18	18-24
Weekdays	0	1	2	1	2	1	0
Saturday	0	0	2	0	0	0	0
Sunday	0	0	0	0	0	0	0

4. Analysis and results

This section will present, analyse and discuss the results from both measurement and simulation tests. 4.1 will present the optical performance data as measured. 4.2 will build a general picture as to how glazing type and HPC concentration affects heat gains, heating, cooling and lighting loads and overall energy performance for four plane inclinations. 4.3 will zoom in on one particular plane inclination and explore in more detail the relationship between static and dynamic solar heat gain coefficients on beneficial and detrimental heat gains. 4.4 will take a more in-depth look at one specific HPC TT concentration (6wt.%) with a view to understanding the discrete mechanisms at play and how they affect heat gains and losses and overall energy consumption. 4.5 will undertake further simulation work with a view to exploring the impact that transition temperature has on the solar heat gain coefficients and resultant heating and cooling loads.

4.1 Measurement data

The measured transmittance and reflectance values for the three types of thermotropic window are shown in Table 3. From these data it can clearly be seen that in its transparent state, transmittance and reflectance values are identical for all concentrations. Indeed if considering the properties outlined in Table 3, solar transmittance is similar to that of a conventional double glazed unit (0.79 for ODG, 0.74 for TT). However when the HPC has transitioned into its translucent state, higher concentrations lead to lower transmittance and conversely increased reflectance, ranging from a solar transmittance of 0.20 at 2wt.% concentration to 0.11 at 6wt.%. In the case of the 6wt.% HPC concentration, solar transmittance is in the order of 5x less than that of a solar controlled low-e coated glazing unit. As a result, at higher HPC concentrations, one can expect considerably more rejection of solar heat gain in the transitioned state.

Table 3 - Measured optical properties of the developed thermotropic smart window

	2wt.% HPC Thermotropic window		4wt.% HPC Thermotropic window		6wt.% HPC Thermotropic window	
	Transparent	Translucent	Transparent	Translucent	Transparent	Translucent
Visible transmittance	0.90	0.27	0.90	0.21	0.90	0.16
Visible reflectance	0.08	0.22	0.08	0.28	0.08	0.34
Solar transmittance	0.74	0.20	0.74	0.15	0.74	0.11
Solar reflectance	0.06	0.18	0.06	0.24	0.06	0.30

4.2 Effect of window inclination, glazing type and HPC concentration on loads and energy performance

The four window inclinations as shown in Figure 2 were tested for all glazing combinations using EnergyPlus to explore their overall performance in relation to heat gains, heating, cooling and lighting loads and ultimately overall building energy consumption.

4.2.1 Window heat gain

Figure 3 shows the window total heat gains of each window type for each discrete plane inclination; a - 90°, b - 60°, c -30° and d - 0° to the horizontal. As would be expected, the ODG unit, with its higher solar transmittance consistently has the highest window heat gain irrespective of plane inclination. However with respect to the other glazing types, the ordering as a function of total heat gain changes in response to plane inclination. At 60^{o} inclination, LE glazing outperforms all but the 6wt.% TT unit but this changes as plane inclination reaches 30^{o} and 0^{o} to the horizontal where the 4 wt.% concentration begins to show an improvement over the LE unit. It can be seen therefore that with a decrease in roof gradient, TT windows with higher HPC concentrations begin to show their effectiveness over LE glazing. This can be explained due to the higher solar altitude for this particular latitude, where those windows with a lower inclination angle (i.e. moving towards the horizontal) are more exposed to increased incident solar radiation which in turn allows the window to maintain a higher temperature for a longer period of time. By being at or above T_s for longer, the windows are in their translucent state for a greater period of the day thus rejecting incoming solar radiation. This dynamic fluctuation between transparent and translucent states for HPC-based TT windows therefore positively benefits control over solar heat gain when compared to the static behaviour of LE glazing units.

This behaviour can clearly be seen when inspecting the data from the 6wt.% concentration and comparing it to the LE coated unit. In its transparent state, the HPC unit has a solar transmittance of 0.74 and in its translucent state this is 0.11. The LE unit however has a fixed transmittance of 0.53. During cooler periods the lower solar transmittance of the LE unit reduces beneficial solar gains into the space and in turn impacts on passive solar heating thus potentially increasing its heat load. Conversely, during warmer periods, the lower transmittance of the HPC unit reduces detrimental gains. This is also mirrored in the solar reflectance data. With a fixed reflectance of 0.22, the LE coated unit rejects more incoming gains in cooler periods in comparison to the HPC unit (0.06). When transitioned, the HPC unit has a solar reflectance of 0.30, 0.08 higher than the static performance of the LE unit. More incoming radiation is therefore rejected by the HPC unit during warmer spells.

When comparing across the thermotropic glazing variants, figure 3 clearly shows that TC windows with higher concentrations of HPC have the lowest heat gain. Having transitioned into their translucent state, solar transmittance at 6wt.% concentration is approximately half that at 2wt.% concentration (0.11 at 6wt.%, 0.22 and 2wt.%). This is this mirrored in the solar reflectance values which increase significantly based on concentration strength (0.18 at 2wt.% to 0.30 at 6 wt.%)

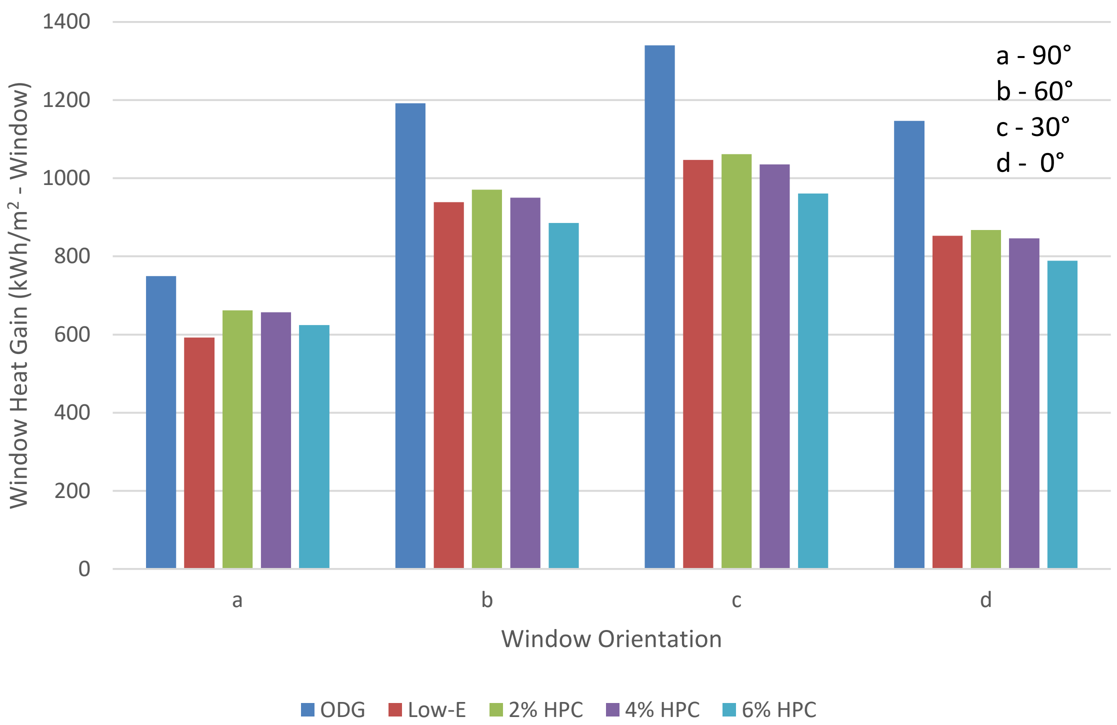


Figure 3 – Total annual window heat gain for the different glazing combinations at varying plane inclination angles

4.2.2 Room Heating/Cooling and Lighting Loads

Figure 4 shows the annual energy consumption of each window type for each of the four discrete orientations. For clarity and as mentioned in section 3.2, to account for volumetric differences in each model tested, the overall energy consumption has been standardised to kWh/m^3, where this includes the heating / cooling and lighting loads for the office space.

As with the results from 4.2.1, the data clearly shows the interrelationship between solar altitude, plane inclination and glazing type and its impact on total energy consumption. A close inspection of Figure 4 shows that in all cases, lighting loads increase as a function of glazing type; that is ODG has the lowest lighting load due to its lower visible light transmittance, this peaking where the HPC concentration is set at 6wt.%. When considering heating demand data for this particular latitude, an almost identical trend across all plane inclinations appears. In all cases, annual heating demand is lowest for ODG due to it receiving beneficial solar gains. HPC concentrations of 2 wt.% and 4wt.% result in almost identical heating demands at each plane inclination and have the next lowest demand and similarly, both LE and HPC glazing at 6wt.% concentrations have almost identical heating demands at all plane inclinations. When combined with the cooling load data, an interesting trend emerges that reinforces the conclusions from section 4.2.1. As expected, cooling load is greatest at all plane inclinations for the ODG unit; a product of its high solar transmittance and therefore high heat gains. Very little difference in cooling loads can be observed between HPC concentrations of 2wt.% and 4wt.%. However the effects of solar altitude and switching / transition behaviour can be observed when closely inspecting the LE and 6wt.%

glazing data. Here, LE glazing outperforms the 6wt.% concentration by approximately 3kWh/m^3 annually for a vertical plane (90^o). However the benefits of the increased HPC concentration can be seen as the inclination angle reduces. At 60^o inclination, cooling loads are almost identical at approximately 28.3 kWh/m^3 however by the time the plane reaches 0^o inclination (horizontal plane), the 6wt.% HPC-based TT unit outperforms the LE unit by approximately 4kWh/m^3 annually.

It is important that both heating and cooling load data are viewed with respect to the thermal transmittance (U) values of the HPC-filled units in relation to the LE unit. Indeed, for the purpose of these simulations, the U-value of the LE unit (1.7 W/m^{2}K) was 1 W/m^{2}K lower than the HPC units (2.7 W/m^{2}K). In the specific case of the 6wt.% HPC unit at 60^o, its heating and cooling performance was almost identical to that of the LE unit irrespective of the lower thermal transmittance of the LE unit, its performance improving as plane inclination decreased.

When viewed overall, it is evident that at high inclination angles (e.g. 90^o) for this particular latitude, HPC-based TC windows receive less incident radiation and therefore cannot maintain a high enough temperature to transition. This is evident in the virtually identical heating and cooling load data for all three HPC concentrations suggesting that the glazing itself has not transitioned to a translucent state. As the window's inclination decreases from 90^o to 0^o, the TT windows begin to show their energy saving potential over both ODG and LE glazing units. In this case, one can see the benefit of the glazing units switching between transparent and translucent states and the resultant rejection to incoming solar radiation. As the plane approaches 0^o inclination, its transition is maintained for a longer period of time due to its relationship with solar altitude and associated heat gains and here we can see the true benefit of the higher HPC concentration over other glazing variants.

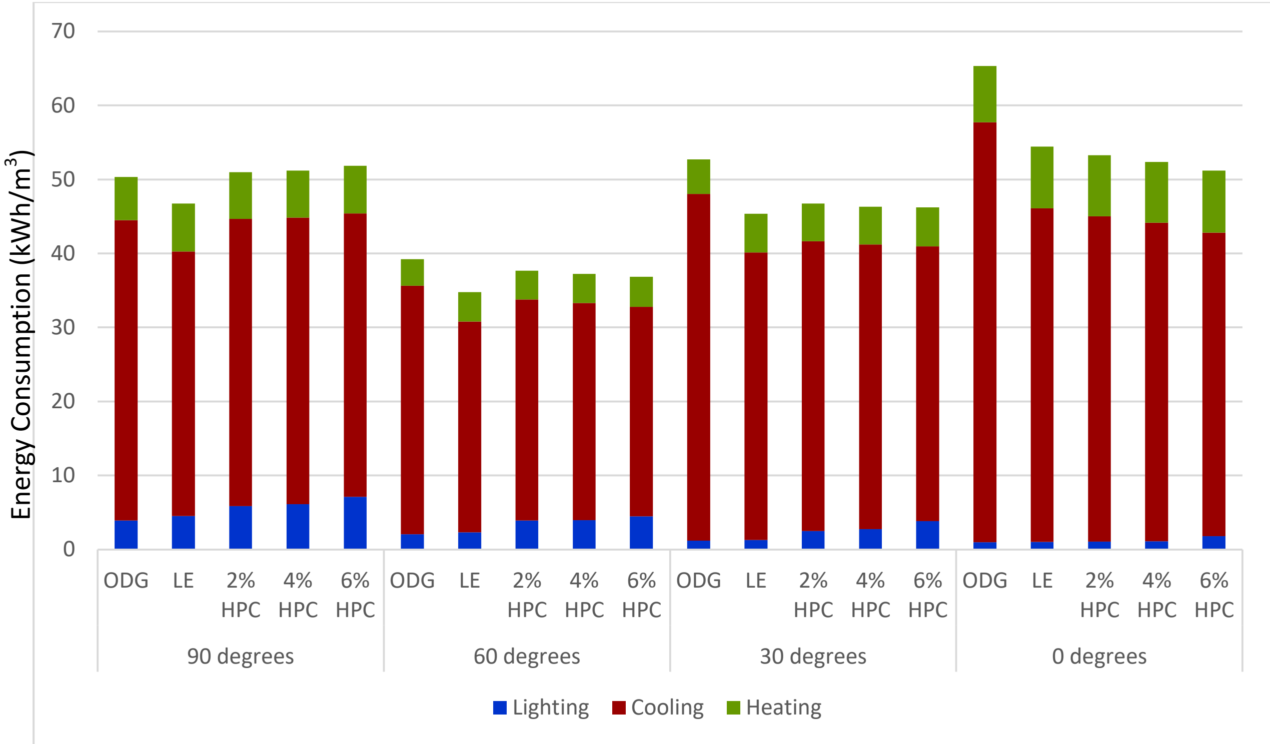


Figure 4 - Annual Energy consumption comparison between the different window combinations for discrete inclinations

4.3 Effect of glazing type and HPC concentration on Solar Heat Gain Coefficient (SHGC) and its implications on beneficial and detrimental gains.

Since the simulations showed a consistent reduction in overall energy consumption between ODG, LE coated and increased HPC concentrations at 0^{o} plane inclination, data for this plane were further analysed to identify the potential mechanisms that affected performance behaviour.

Figure 5 shows the window total heat gain plotted against incident solar radiation for the three HPC concentrations (2wt.%, 4wt% and 6wt.%). The window total heat gain shown comprises the incident radiation that enters the room in the form of transmitted radiation or as secondary heat gains due to the fraction of radiation that has been absorbed in different layers of the window and transmitted to the interior by conduction, convection and radiation. The Solar Heat Gain Coefficient (SHGC), which is the fraction of the incident solar radiation that enters the room after passing through the window [25], is determined by dividing the window total heat gain by the incident solar radiation. The hourly points are separated into the three states, before transition, transitioning and after transition, these derived from window temperature data from the output of the simulations.

As can be seen from Table 4, in their transparent state, all HPC concentrations have a SHGC of 0.56. This is a small improvement over the static SHGC for LE glazing (0.54) but considerably less than that of an ODG unit (0.74). It can therefore be expected that considerably more desirable gains will arise from an ODG unit during cooler periods (i.e. when the TT units have not transitioned). However having transitioned to their translucent state due to higher temperatures or stronger irradiance, all TT HPC concentrations have a considerably lower SHGC than their LE coated or ODG counterparts (0.50 at 2wt.%, 0.47 at 4wt.%, 0.44 at 6wt.%). As such, with a decreasing SHGC, the ability for the window to minimise undesirable heat gain increases at increased HPC concentrations due to their lower solar transmittance and higher solar reflectance. It seems therefore that the switching behaviour of the unit is a positive asset over conventional ODG or LE units, where dynamic control is exerted over incoming gains. The true benefits (or detriments) to passive heating or cooling however must be seen in light of the differences in thermal transmittance between the various units.

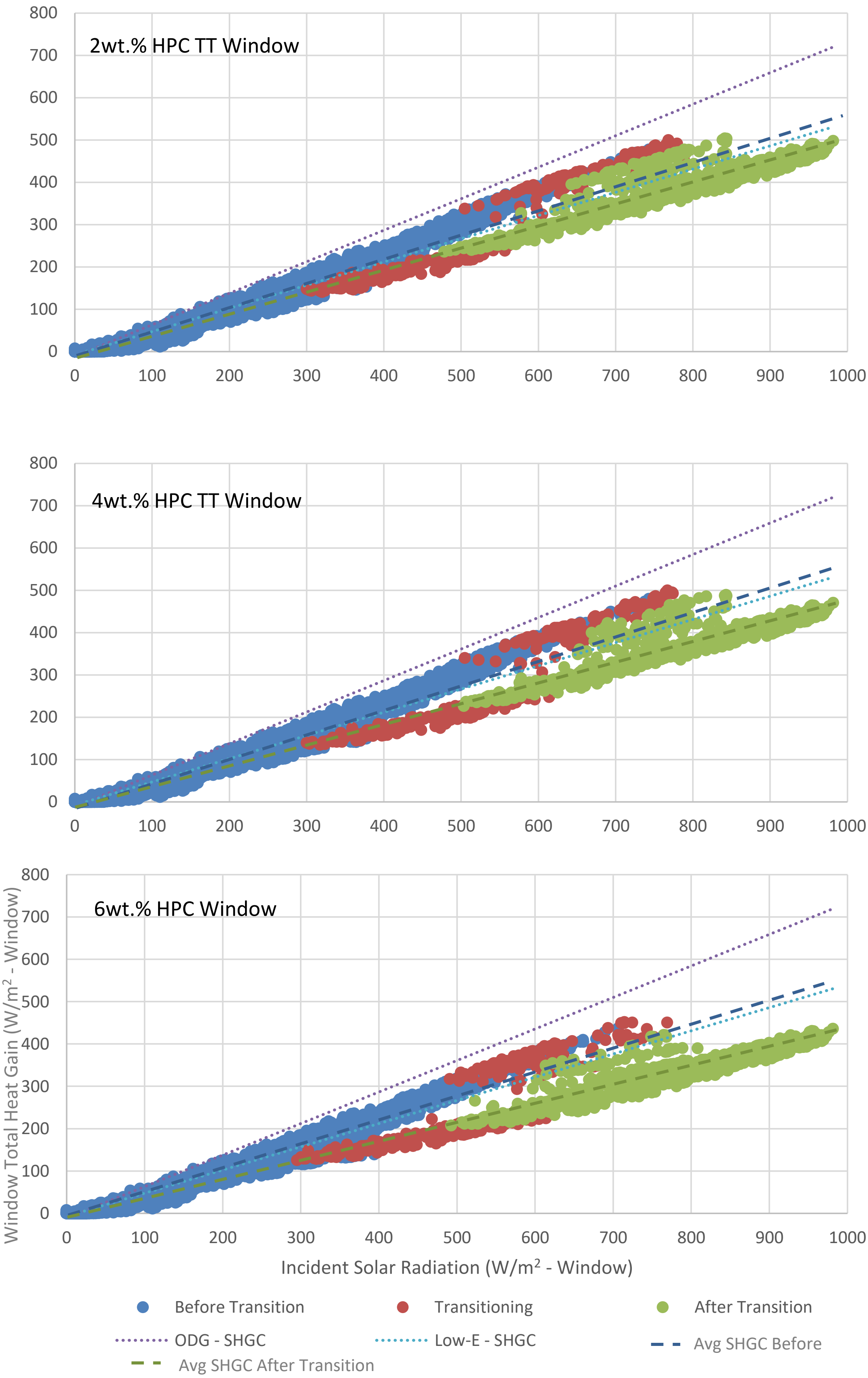


Figure 5 - Window Solar Heat Gain Coefficients for the 2, 4 and 6wt.% HPC Thermotropic (TT) Windows

Table 4 – Solar Heat Gain Coefficients for the three HPC concentrations

HPC Concentration	SHGC (Transparent State)	SHGC (Translucent State)
2%	0.56	0.5
4%	0.56	0.47
6%	0.56	0.44

4.4 Detailed Analysis of Horizontal Roof with 6 wt.% HPC TT window Installed

Since the performance of the HPC-based thermotropic window is influenced by a combination of various environmental conditions, the effects of air temperature and incident solar radiation on the temperature of the thermotropic layer and window total heat gains were explored for a representative 3 days period during both heating and cooling seasons for the 6wt.% HPC concentration. This HPC TC concentration consistently showed improved performance over all HPC glazing variants and hence was used for further study. In so doing, the combination of outdoor temperature and incident solar radiation resulting in thermotropic layer temperatures high enough to cause light scattering were considered in addition to the corresponding window heat gains. These data were considered with respect to both ODG and LE glazing units.

4.4.1 Temperatures, Incident Radiation and Window Heat Gain

Figure 6a shows the outdoor and indoor temperatures experienced during the representative 3 day period in winter and summer with the use of a HVAC system for a window inclination of 0°. Temperatures for the thermotropic layer are also plotted with corresponding incident solar radiation and window heat gains attributed to each test window type.

In Palermo the outdoor temperature during the heating season ranges between 6-12°C while the indoor temperature in every simulation is maintained at a constant temperature of 22°C by the HVAC system heating the room. Although in the simulations on each window type the incident solar radiation will be the same, the simulated window heat gains are different. As can be seen from Figure 6b and Table 5, the use of solar control LE glazing reduces the peak window heat gain by approximately 20.7% in comparison with an ODG unit during the representative heating period, while the 6wt.% HPC TT window reduces the heat gain by approximately 13.4%. The peaks in window heat gains correspond directly to the peaks in incident solar radiation and therefore window temperatures, clearly identifying that the windows had not reached their switching temperature therefore drawing a strong link between amount of incident solar radiation and ability for the thermotropic window to transition.

Given that during the heating period, any reduction in window heat gain may be undesirable as it reduces the potential for passive solar heating, the static nature of solar controlled LE windows has a constant and negative effect on solar heat gains in comparison to both ODG and HPC-based TC units, although its true effect from an energy consumption perspective will be mitigated by its improved thermal transmittance values.

The outdoor temperature during the cooling period ranges between 24-30°C with the indoor temperature again being maintained by the HVAC system cooling the room. Unlike in the heating period simulation, the TC window heat gains are now reduced further than those of the solar control LE window. Both LE and HPC TT glazing units show considerable reductions in peak heat gains over the ODG unit at 25.6% and 43.8% respectively during the representative cooling period. When comparing the HPC TT to the LE unit, the HPC TT unit reduces total heat gains by 24.5%. As expected, the peaks in incident radiation correspond to the peaks in window heat gain and TT layer temperature. As can be seen from Figure 6a, in the cooling period, the TT layer temperatures exceed 60°C at midday ensuring transition of the layer, therefore the space below can take advantage of the solar shading potential of this unit. In total, the TT window layer is in its translucent / reflective state for approximately 21 out of 72 hours during the designated simulation period. In this time, the TT glazing unit has a SHGC of 0.44 as compared to a static SHGC of 0.54 for the LE or 0.74 for ODG glazing units. The potential for savings on cooling energy that arise from solar heat gains are therefore evident.

Table 5 – Total heat gains for the three window types

	Heating Period Peak Gain (W/m^2)			Cooling Period Peak Gain (W/m^2)		
Glazing Type	~12 hours	~36 hours	~60 hours	~12 hours	~36 hours	~60 hours
ODG	211	278	245	666	699	670
LE	168	220	194	502	519	493
HPC TT 6wt.%	186	243	206	378	398	368

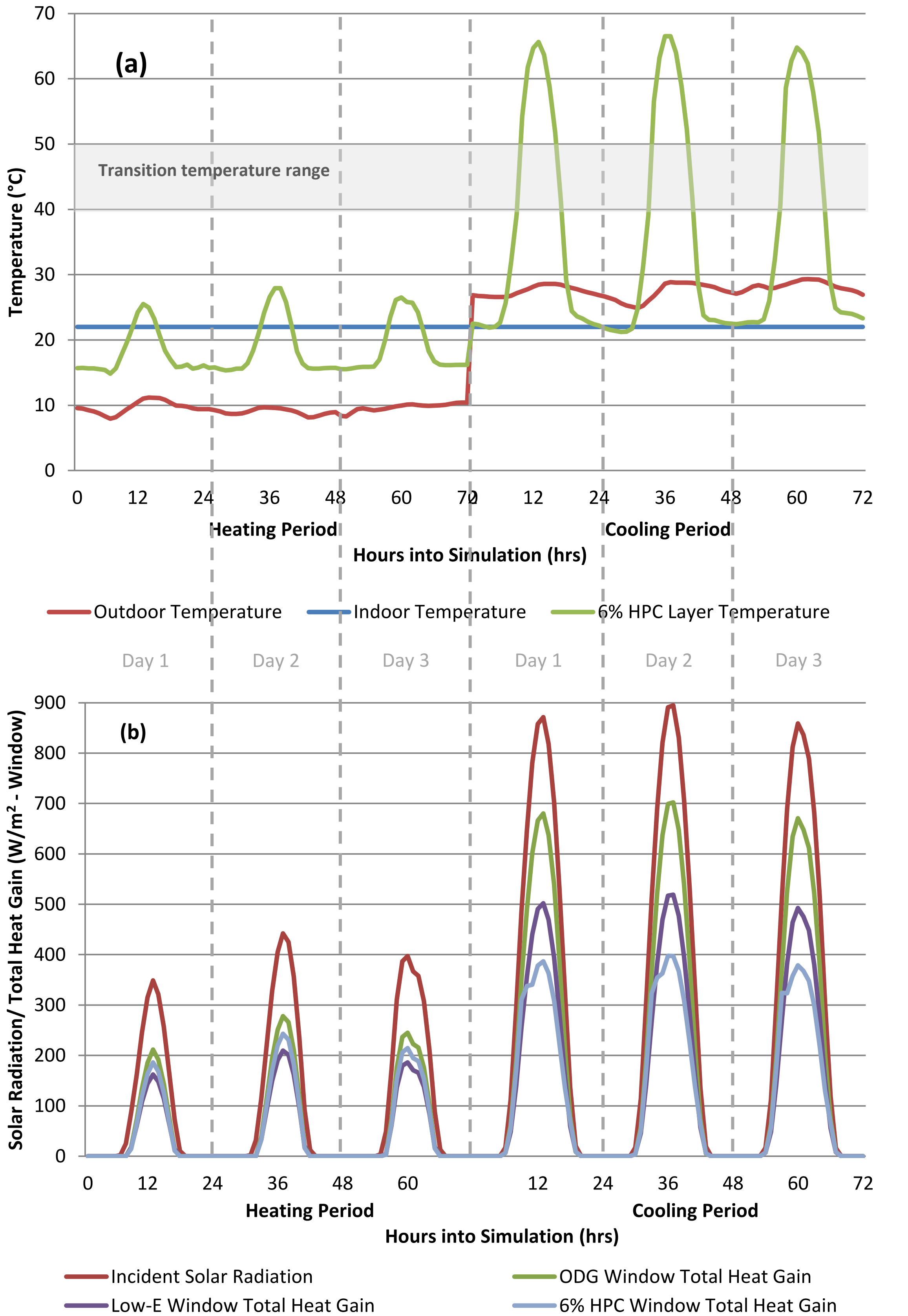


Figure 6 (a) Ambient temperatures and thermotropic layer temperature for heating and cooling period, (b) Incident solar radiation and window total heat gain for heating and cooling period

4.4.2 Temperatures and Incident Solar Radiation

It is known that there is a strong correlation between switching response to both outdoor air temperature and incident solar radiation [7]. This is evident in Figure 7 which shows hourly sets of data for outdoor air temperature plotted against solar radiation incident on the glazing, these acquired through an annual simulation. The 6 wt.% HPC TT window is in its translucent state for approximately 1056 hrs of the annual (8760 hrs) simulation. In addition, it spends approximately 396 hrs in transition. Although the outdoor temperature never approaches the transition range of 40-50°C the combination of outdoor temperature and incident solar radiation results in the HPC membrane transitioning to its translucent / reflective state. Simulation results show that transitioning takes place between the months of March and October for this location and highlights the three transition phases (Figure 7): (1) the window is transparent when the incident solar radiation is less than approximately 300 W/m^2 at temperatures lower than 30°C. (2) The transition phase itself occurs at solar radiation intensities greater than 300 W/m^2 and for temperatures higher than 14°C. (3) For lower solar radiation intensities, i.e. at approximately 500W/m^2, transition to the translucent state takes place at air temperatures around 20°C, where the required air temperature reduces as solar radiation intensity increases.

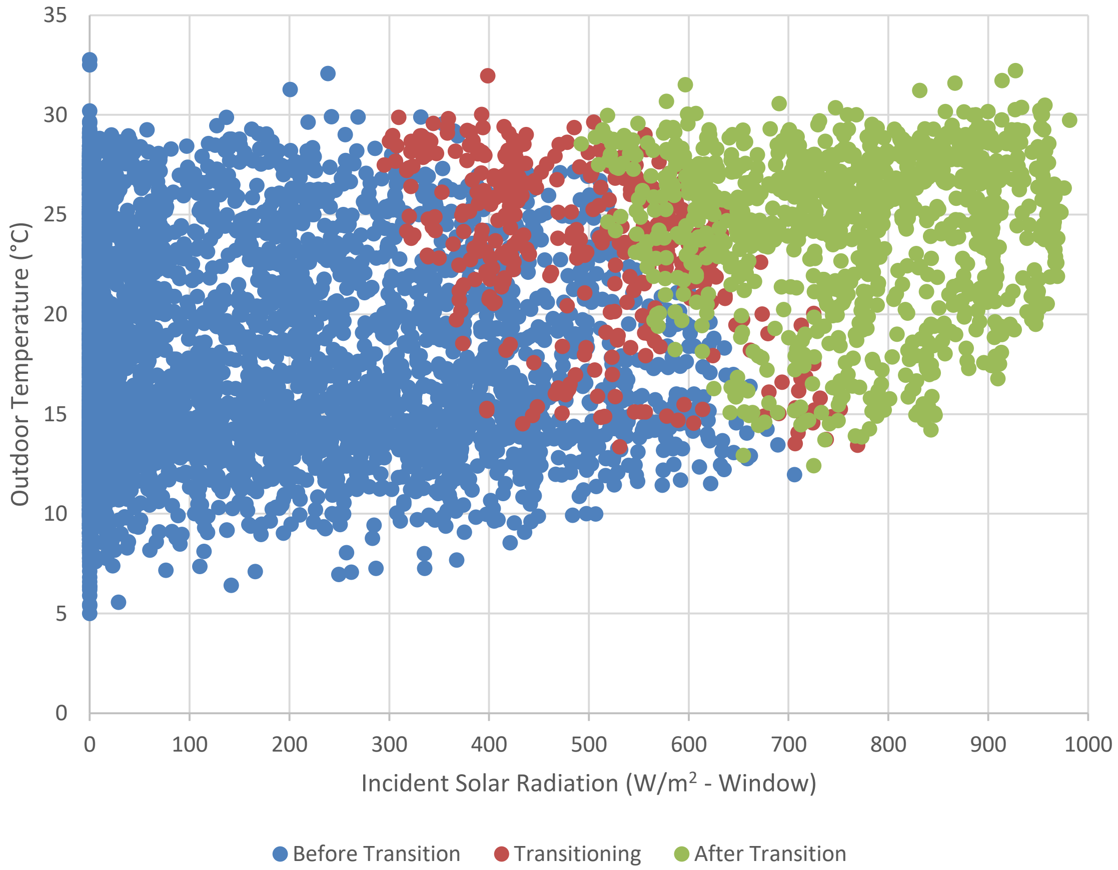


Figure 7 - The state of the HPC layer under combination effects of irradiation and outdoor ambient temperature

To explore the impact of incident solar radiation on the 6wt.% HPC layer temperature, the data were further analysed, the results presented in Figure 8. As can be seen, the HPC layer temperature increases in direct proportion to incident solar radiation. The HPC layer reaches a maximum temperature of 70°C with an incident solar radiation intensity of approximately 1000W/m^2, confirming the assumption that although the outdoor temperature may be much lower than the transition temperature range, the added heat provided by the incident solar radiation pushes the HPC layer temperature into the transition range. As the HPC layer is sandwiched between two glazing panels, this design helps to decouple the HPC layer from the indoor thermal environment and any unwanted effects this would have.

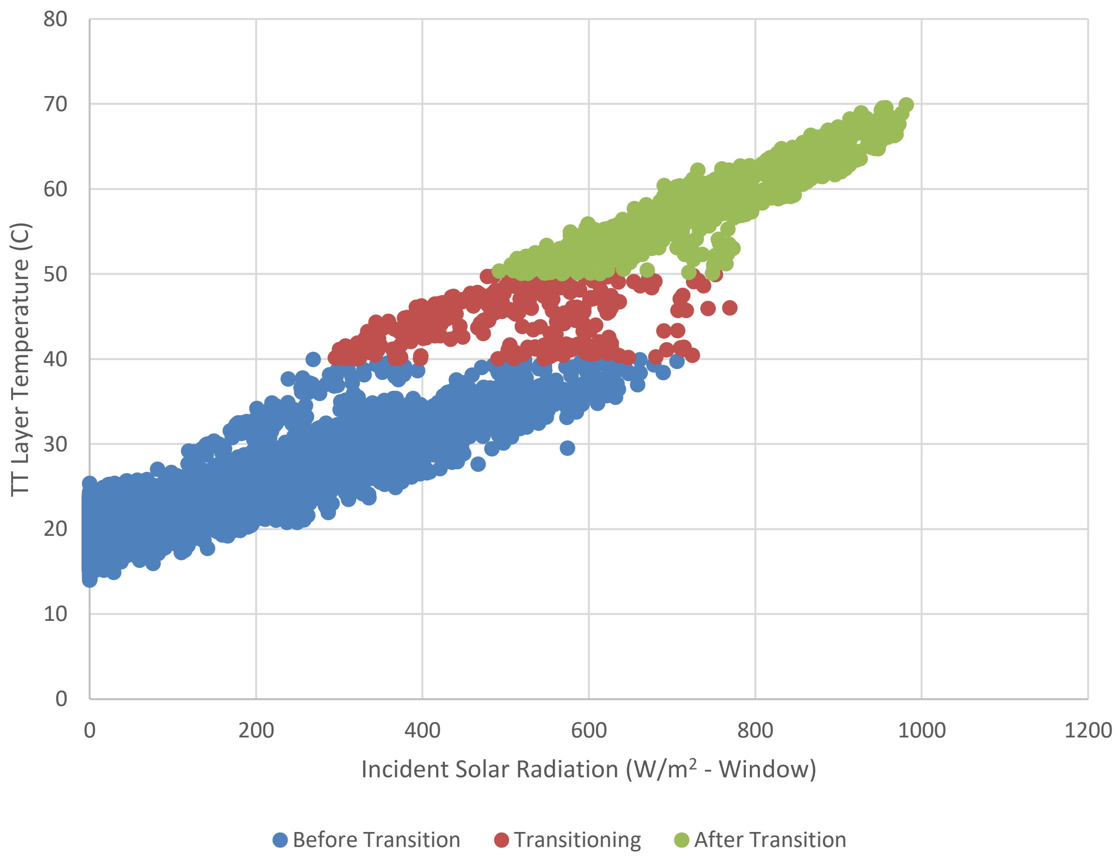


Figure 8 - The effect of irradiation on the HPC layer temperature

4.4.3 Window Heat Gain and Incident Solar Radiation

Building upon the analysis from section 4.3, Figure 9 shows the window total heat as a function of incident solar radiation. The inherent changeability of the 6wt.% HPC TT window results in a range of SHGCs that depend on the state of the window with two transition states (before and after) clearly evident from the graph. Before transitioning, the SHGC is 0.56 and post transition it is 0.44. The transitioning points appear split in this way as the first group is made up of points attempting to transition predominantly due to high levels of incident radiation while the second group is made up of points attempting to transition predominantly due to high ambient temperatures; when both factors are present the transition occurs fully. It is therefore easy to see the interrelationship between incident solar radiation and window total heat gains. However what is slightly more ambiguous is the SHGC during transition which very much depends on the combinations of incident solar and ambient temperature.

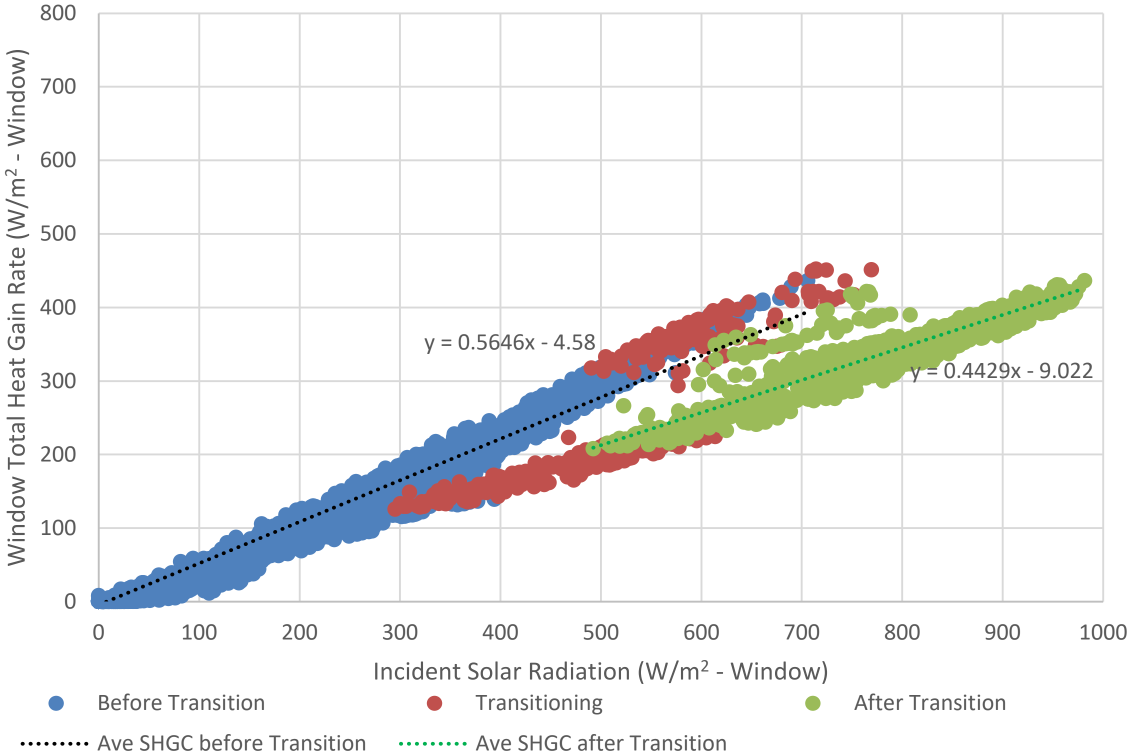


Figure 9 – Sets of hourly external incident radiation and window total heat gain through a year

4.4.4 Heat Gain/Loss through windows

Monthly Simulations

Figure 10 shows the monthly heat gains/losses for the Double Glazing (ODG), solar control Low-E (LE) and 6wt.% HPC TT window combinations. Unlike the heat gains, the heat losses are primarily caused by the conductive, convective and radiative heat transfer processes between the indoor and outdoor environment, these dominated by the thermal transmittance (U-value) of the glazing unit. The thin HPC layer does not significantly affect this u-value and this is evident when comparing the losses for both the ODG and TT units which have identical U-values ($2.7 W/m^2K$). Improvements in heat loss performance can however be seen with the LE unit that has a considerably lower U-value of $1.7 W/m^2K$.

With respect to heat gains, the figure clearly shows that there is a defined transition point where the performance of the LE and HPC-based TT units cross in both March and October. That is, at some point during these two months, the HPC-based TT unit begins to match the overall thermal performance of the LE unit, irrespective of the differences in U-values. As can be seen from the figure, during the heating period (i.e. from October until March), the ODG unit's high solar transmittance results in higher (beneficial) solar gains. With the lowest solar transmittance, the LE unit results in the lowest beneficial solar gains.

However from March until October, the TT unit shows a marked reduction in overall gains over its LE counterpart, showing the importance of the switching / transition point in helping to control unwanted solar gains.

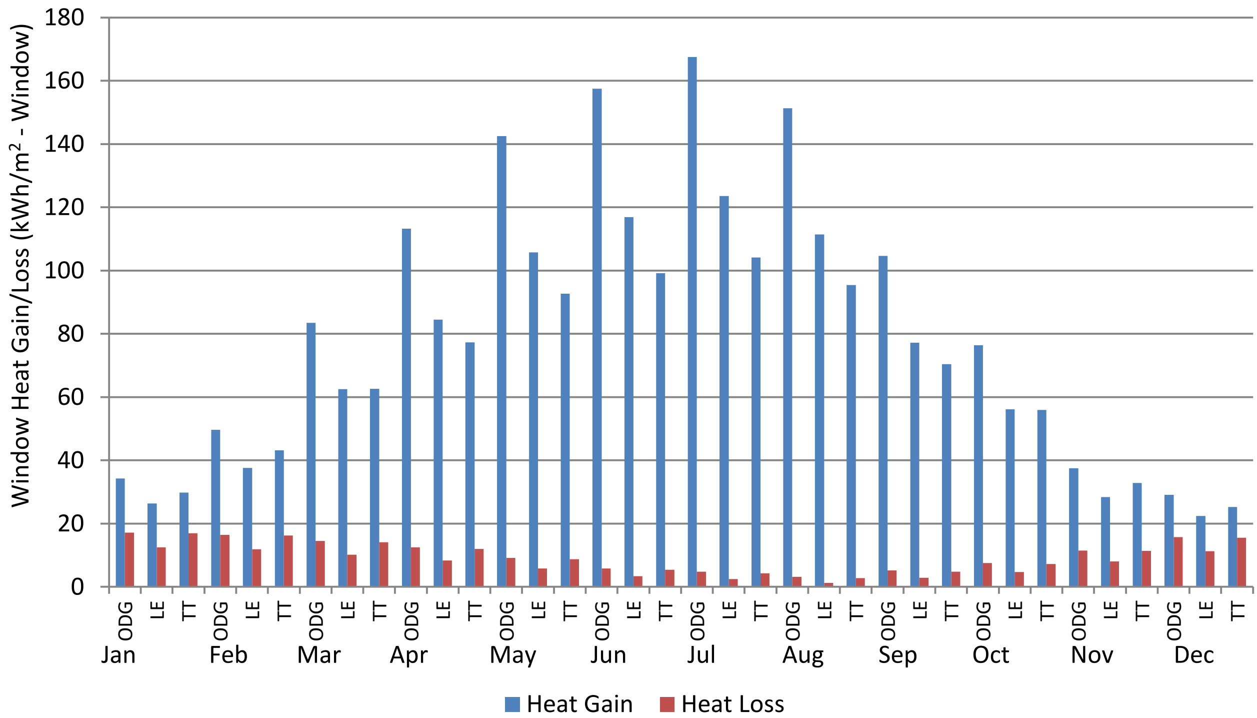


Figure 10 – Monthly window heat gains/losses comparison between ODG, LE and 6% HPC TT

Annual Simulations

Figure 11 shows the annual heat gains/losses through windows for the different window types. Overall, the TT window had the largest reduction in annual solar heat gain of the three glazing systems. In comparison with ODG, the LE unit reduces heat gains by approximately 26% or 294kWh/m^2 (through window). Additionally, it reduces heat losses by approximately 33% or 41kWh/m^2 when compared to ODG. The TT reduced heat gains by 31% or 358kWh/m^2 (when compared to ODG. From Figures 10 and 11, it can be seen that the TT window provides larger benefits than the LE window during the cooling period. As heat gains are predominantly due to incident solar radiation during this period this shows that the TT window's translucent and reflective state has taken effect. The solar control LE window appears more beneficial during the heating period, however, as heat losses are predominantly affected by the thermal transmittance (U-value) of the glazing unit and reduced emissivity.

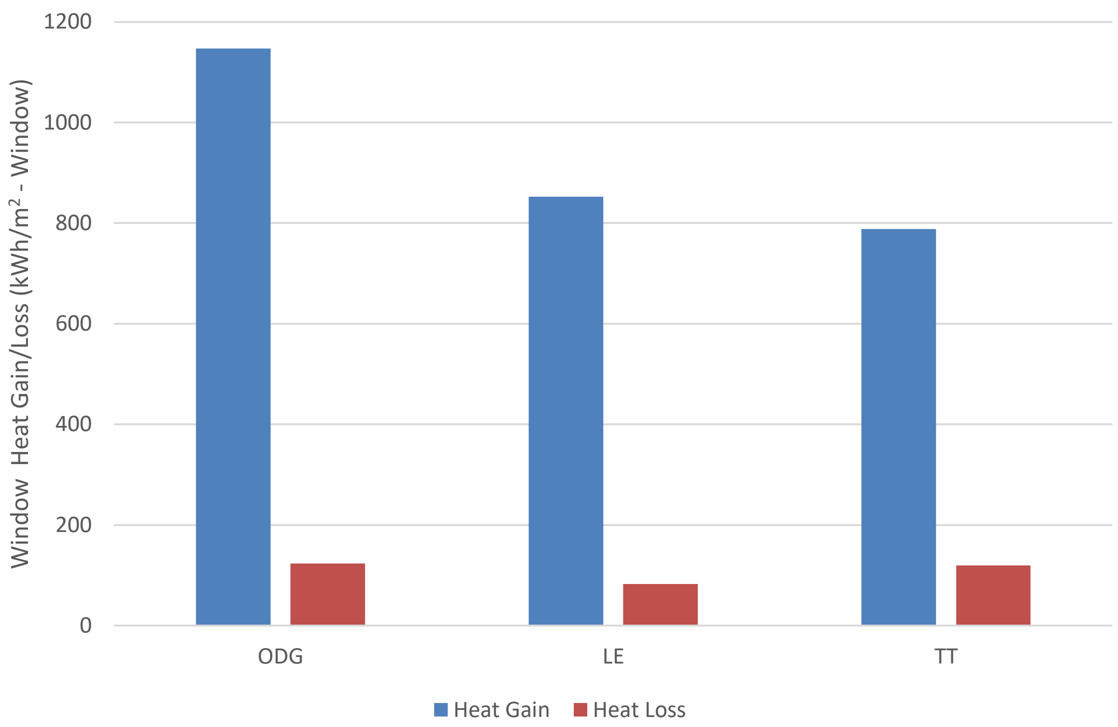


Figure 11 - Annual window heat gains/losses comparison between ODG, LE and 6% HPC TT

4.4.5 Room Heating/Cooling and Lighting Loads

Monthly Simulations

Figure 12 shows the monthly room heating/cooling loads as well as the attributed lighting loads. Although a decreased HVAC load is important, a whole system view must be taken to fully understand the energy implications of the alternate window choices. As can be seen, for this particular building type, cooling dominates from March to November and the benefits of the HPC-based TT unit can be seen from April until September. For example, in the month of July, the LE window reduces the cooling load by approximately 19% compared with the ODG, while the TT window reduces the cooling load by 28%. A close inspection of the data however shows that for the entire year, artificial lighting is required for the HPC-based TT unit in order to reach the minimum of 500 lux within the office. For example, in the same July period, both the ODG and LE unit require no artificial lighting whereas the TT unit requires 0.25 kWh/m^2 as the glazing unit will have switched from its transparent to translucent state for a significant period of the working day lowering the visible transmittance to 0.16. However in the case of the ODG and LE units, artificial lighting is only required between the months of October and February, with the higher visible transmittance of the ODG unit requiring less lighting energy. It can clearly be seen therefore that the benefits of the TT unit are somewhat mitigated by the increased energy consumption that arises due to lighting loads and any additional cooling demand that will be placed due to these loads. It is however evident in the round that the TT unit does give rise to lower energy demands overall during the cooling period.

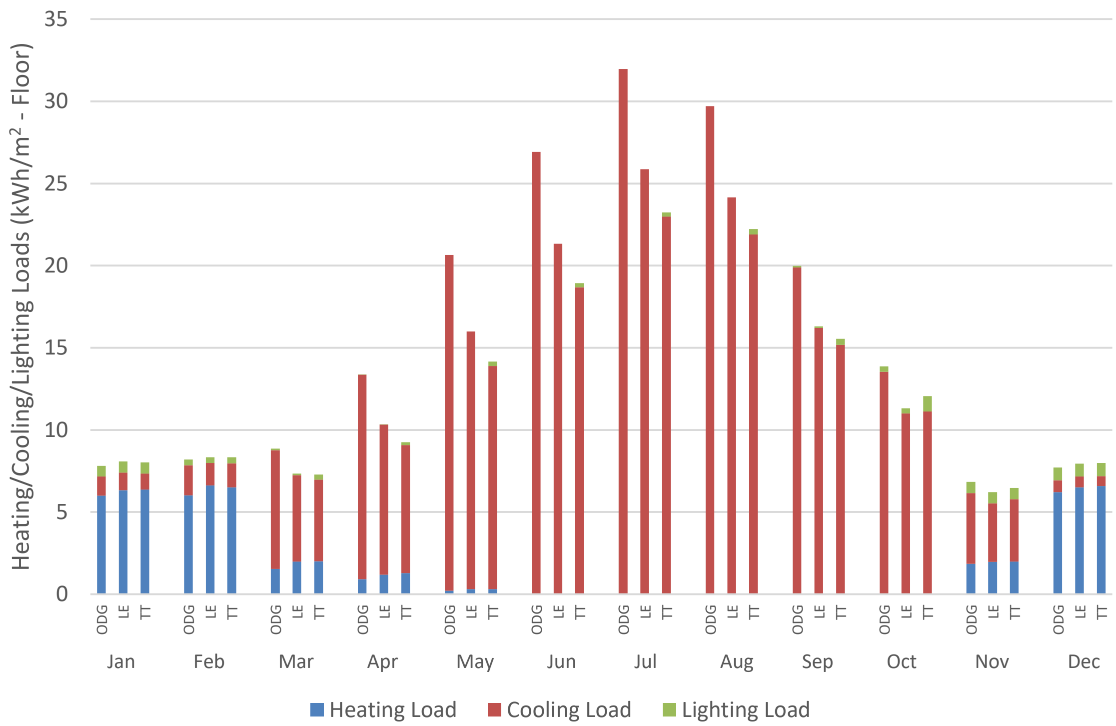


Figure 12 - Monthly Heating/Cooling and Lighting Load comparison between ODG, LE and 6wt.% HPC TT

Annual Simulations

Table 6 and Figure 13 show the annual heating/cooling and lighting loads for the office with different window types installed. From Figure 13, it can be seen that there are no substantive differences in annual lighting loads between ODG and LE units. This is not true for the TT unit however which requires in the order of 80% more lighting energy to reach the required illuminance levels. Proportionally however there is little substantive difference in heating loads between the three glazing types. The main difference can be seen in cooling loads where a 6wt.% HPC-based TT unit will reduce overall annual cooling requirements by 27.7% over an ODG unit and by 9.9% over a LE unit for this particular example. Overall this translates to total energy savings of approximately 22% over ODG and 6% over LE coated units. This must be seen with respect to potential issues surrounding daylight availability and the associated health and wellbeing consequences that arise due to this which are a product of the reduced visible transmittance of the unit in its transitioned state.

Table 6 – Annual loads for the three window types

	Energy Consumption kWh/m^2 PA		
Load	**ODG**	**LE**	**6wt.% TT**
Lighting	2.96	3.05	5.43
Cooling	170.16	135.25	123.04
Heating	22.78	24.95	25.06
Total	195.9	163.25	153.53

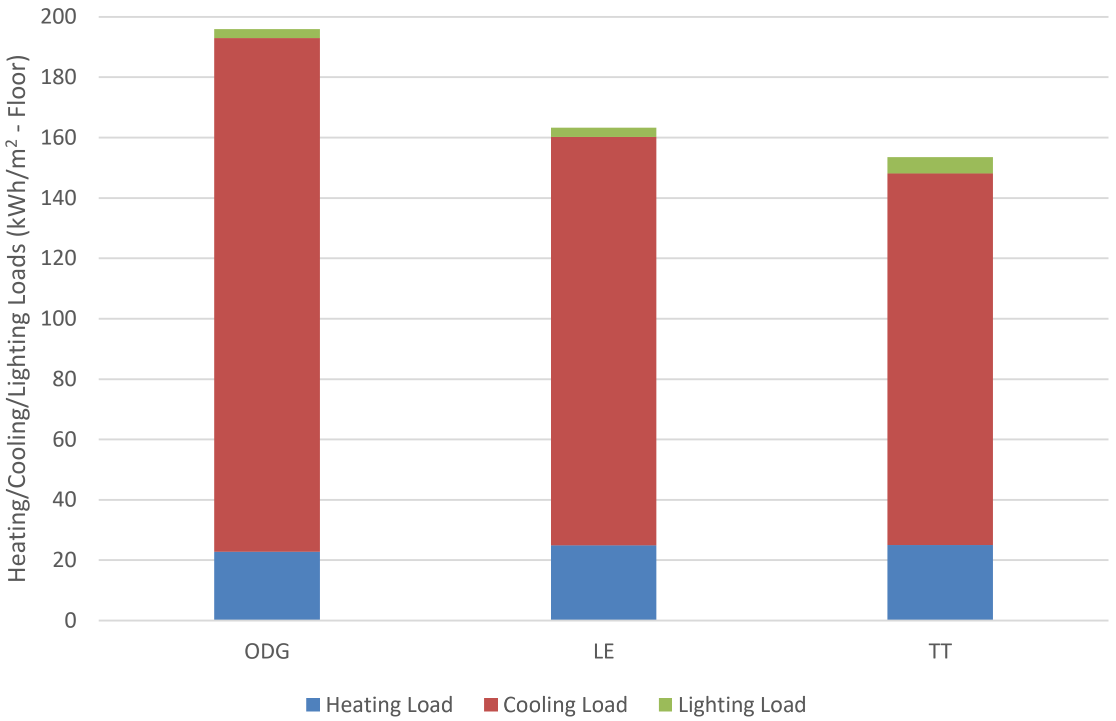


Figure 13 - Annual Heating/Cooling and Lighting loads comparison between ODG, LE and 6wt.% HPC TT

4.5 Effect of Transition Temperature for a Horizontal Roof with 6 wt.% HPC TT Window Installed

The final suite of simulations sought to explore the impact of transition temperature (T_s) on overall performance, particularly with respect to window total heat gains, solar heat gain coefficients and annual energy consumption. Studies to date have shown that the addition of sodium chloride to the HPC mixture can work to reduce this range [17]. As such, using the original spectral data but applying it to lowered transition temperatures, predictions were carried out for transition temperatures of 35 - 45°C, 30 - 40°C, 25 - 35°C, and 20-30°C.

4.5.1 Heat Gain through window

Figure 14 shows the total heat gains through a 6wt.% HPC-based TT window subject to varying transition temperatures. These are compared to the total heat gains of ODG and solar control LE windows. It can be seen that reducing the transition temperature from 40-50^{o}C to 20-30^{o}C reduces the overall annual window heat gain by 147kWh/m^2. When compared to ODG and LE units, gains are reduced by 505.6 and 211.3 kWh/m^2 respectively representing annual reductions of 44% and 24.7% respectively.

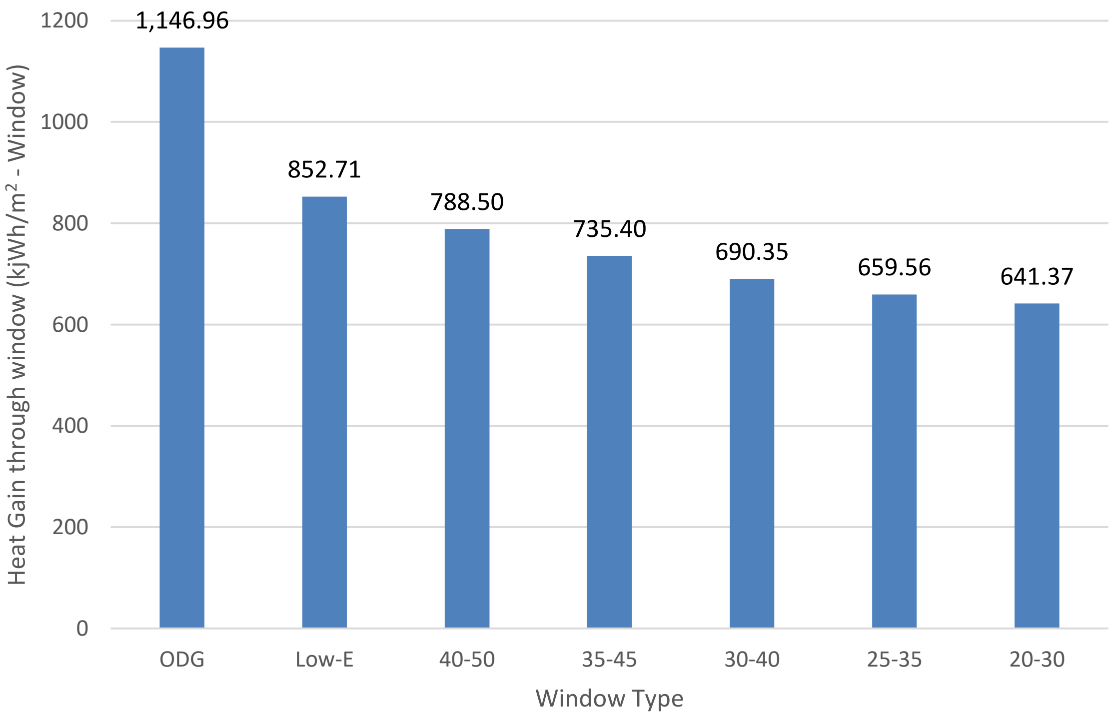


Figure 14 – Annual Window Total heat Gain comparison between the different windows and transition temperature ranges

As the transition temperature range decreases, the TT window is able to enter its translucent / reflective state for longer periods of time therefore decreasing both solar and visible light transmittance for extended periods. Whilst this might be beneficial from the perspective of cooling loads, this has to be offset against both the additional heating demands of the building during the heating period and the associated lighting demands during all periods that may be affected significantly by the window entering its switched state.

4.5.2 Window Heat Gain and Incident Solar Radiation

The SHGC of the 6wt.% HPC TT has been explored in depth in section 4.4. This section will look at the SHGCs of the five transition temperature ranges of the 6wt.% HPC TT. In so doing, it compares these transition temperatures against each other and also with the ODG and LE test windows. Figure 15 shows the window total heat gain plotted against incident solar radiation for the five transition temperature ranges of the 6wt.% HPC TT. The hourly points are separated into the three states: before transition, transitioning and after transition.

As discussed previously, the average range of the SHGC for a 6wt.% HPC TT with the original 40-50°C transition temperature range, is approximately 0.44 – 0.56, this a product of the TT's ability to change its spectral properties. The average range of the SHGC for transition ranges of 35 - 45°C HPC TT and for 30 – 40°C TT are also 0.44 - 0.56. Although the transition temperature has changed, the optical characteristics remain constant, however, with lower transition temperatures the number of translucent hours increases.

When the transition temperature range falls to 25-35°C and 20-30°C, in the Palermo climate, the number of translucent hours greatly increases resulting in the SHGC becoming a single average value; the SHGC for 25 – 35°C and 20 – 30°C HPC TT are both 0.44 on average. In other words, the window has transitioned to its translucent state for a significant period across the year. This coefficient falls below that of even the solar controlled LE window (0.54), meaning that during the cooling period, the solar heat gain through the window is reduced further by the use of the TT window. However during the heating period this configuration reduces passive solar heating significantly which may be undesirable.

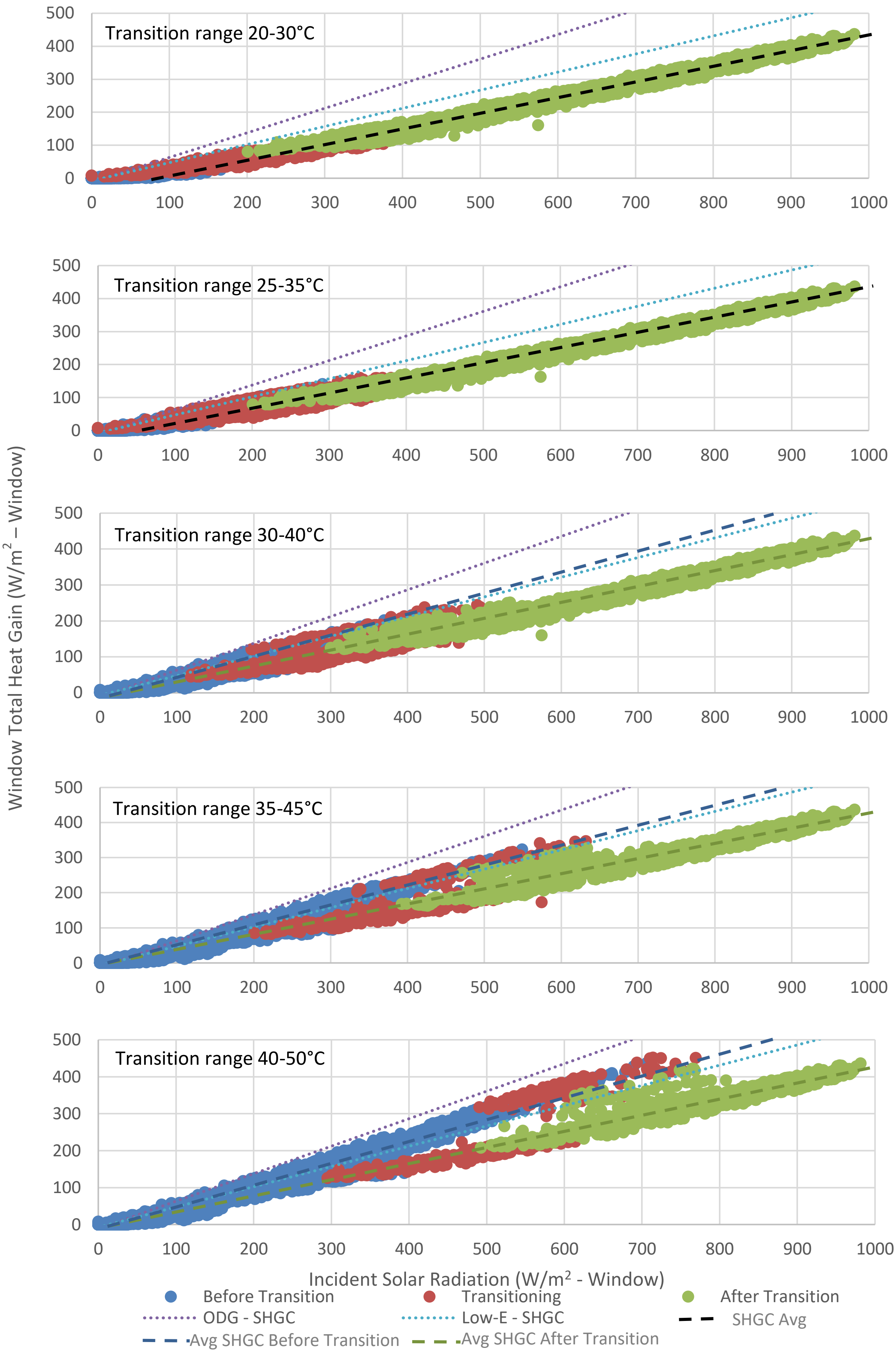


Figure 15 – Window Solar Heat Gain Coefficients for the different transition temperature ranges

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4.5.3 Room Heating/Cooling and Lighting Loads

By exploring the energy implications of the lowered transition temperature ranges, the ideal transition temperature range for this particular office example located in Palermo can be identified. Table 7 and Figure 16 shows the energy consumption for the office with different window types/ranges separated into the three types of energy consumption. Whilst lowering the transition temperature range further slightly reduces the cooling load, it also increases the lighting and heating loads. This is a direct consequence of the TT windows, particularly at lower transition temperatures being in their translucent state for a larger numbers of hours, even during the winter months where this is undesirable. Therefore, when using thermotropic windows in a practical design, the true impact of transition needs to be considered. As such, the windows need to be tuned based on numerous factors, one of which is the transition temperature and its relationship with the prevailing climate, plane orientation and plane inclination. This is evident in the table and figure below where, based solely on overall energy consumption for this particular example of a horizontal roof located in Palermo, a 6wt.% HPC TT window, with a transition temperature range of 35-45°C, saves the most energy. It reduces the overall energy consumption by approximately 45.4 kWh/m^2 and 12.78kWh/m^2 when compared with ODG and LE coated units. This however must be seen in light of the reductions to daylight and potential impacts on occupant health and wellbeing that will arise due to the glazing having switched to its translucent state.

Table 7 – Annual loads for the three window types with 5 HPC concentrations

	Energy Consumption kWh/m^2 PA						
Load	**ODG**	**LE**	**6wt.% TT 40-50**	**6wt.% TT 35-45**	**6wt.% TT 30-40**	**6wt.% TT 25-35**	**6wt.% TT 20-30**
Lighting	2.96	3.05	5.43	6.88	10.00	13.17	18.02
Cooling	170.16	135.25	123.04	117.68	115.20	114.59	116.17
Heating	22.78	24.95	25.06	25.91	26.94	27.74	27.47
Total	195.9	163.25	153.53	150.47	152.14	155.5	161.66

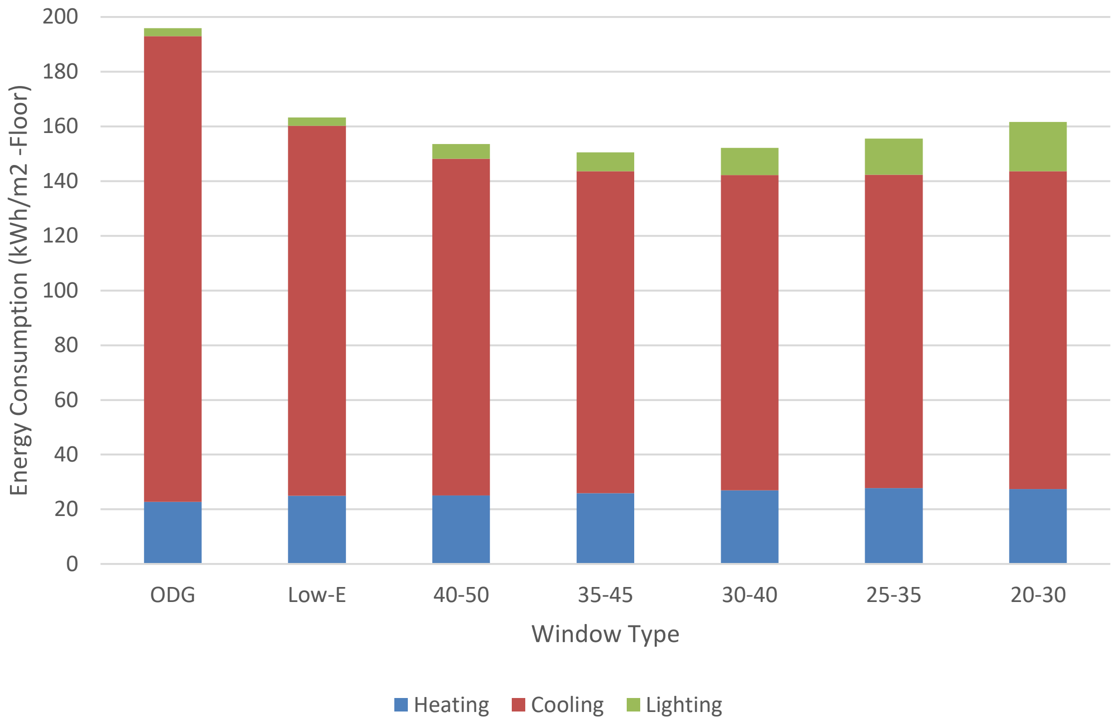

Figure 16 – Annual Energy consumption comparison between the different types/transition temperature ranges

5. Conclusion

Thermotropic layers made of varying HPC concentrations (2wt.%, 4wt.% and 6wt.%) were synthesised and tested in this study. The developed thermotropic layer has a transmission temperature range of 40-50˚C. A 6wt.% HPC based thermotropic window, below the transition temperature (below 40˚C), has a visible transmittance of 0.9, and solar transmittance of 0.74. Above the transition range (over 50˚C), it has a visible transmittance of 0.16, and solar transmittance of 0.11. In addition, simulations of a small office in Palermo Italy with the developed HPC based thermotropic (TT) window installed, at 4 different plane inclinations to the horizontal (90˚, 60˚, 30˚ and 0˚) were carried out using the simulation software, Energy Plus. The following conclusions can be drawn:

- For a window at a 0˚ tilt angle, the 6wt.% HPC based thermotropic window had a dynamic SHGC that ranged between 0.44-0.56, while the SHGC of the ODG was 0.74 and the SHGC of the solar control Low-E was 0.54. As the majority energy demand comes from cooling, the ability of the thermotropic window to reduce the transmitted radiation at peak temperatures greatly reduces this load; while the switch-ability still allows for passive solar heating to take place in the winter months. Overall, the thermotropic window provided an annual energy saving of over 22% when compared with that of a double glazing.
- When exploring the effect of the HPC concentration it was found that the higher the percentage of HPC presents, the greater the reduction in window solar heat gain, reducing the window heat gains by up to 31.3% compared with double glazing. The SHGC range rises with increased HPC concentration with the 6wt.% HPC TT window providing an overall energy saving of 22%.
- Looking at the effectiveness of the TT windows at varying orientations found that although the window heat gains are not at their highest when at 0°, the window is more capable of retaining heat in this position due to its longer midday exposure to the sun. This heat retention allows for the window to remain in the reflective state longer than at steeper tilt angles, meaning the TT windows at this transition temperature range, although showing an energy saving compared to the double glazing at shallower tilt angles, only show an energy saving improvement compared to the LE at 0°.
- Lowering the transition temperature range reduces the window heat gains with the lowest range providing the least amount of heat gains; when the transition temperature range is reduced to 20-30°C, heat gains are reduced by 44%, in comparison to the ODG. The SHGCs of the TT windows at lower transition temperature ranges become single values instead of providing a range, showing the switch-ability of the TT window has been removed, with the window spending the majority of the time in the tinted state. This accounts for the large reductions in heat gains as the average SHGC is 0.44; even lower than that of the solar control Low-E. Although this is beneficial in the cooling season, in the heating season, passive solar heating is restricted increasing the HVAC heating load. This effect can clearly be seen when looking at the energy consumption; the 6wt.% HPC TT with transition temperature range of 35-45°C provides the largest energy saving of 23%.

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