Simulation of Energy Performance of Buildings with Innovative Aerogel Glazing Systems

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Abstract

Silica aerogel window systems were investigated as a strategy to improve thermal comfort and energy performance in a multifunctional building. Experimental data were used for compiling a new meteorological file for Perugia and Perez model was applied in order to process the beam and diffuse solar radiation. The new weather file was implemented in a simply model simulated by means of TRNSYS and EnergyPlus software and results were compared. The validated simulation model was applied in a three floor multifunctional building in different Italian and Chinese cities comparing conventional and innovative (aerogel) glazing systems. Results show that aerogel solution decreases the heating energy demand in all the simulated climatic conditions, especially in the cool climate (energy saving in the 17 - 45% range), while it is slightly significant in cooling period.

Introduction

Building envelope has an important role in energy performance and thermal comfort. Especially transparent surfaces represent the weakest part of the building, due to their low thermal insulation. Large windows are a problem especially in south façades and in hot climates, due to the high heat gains. In order to reduce energy consumptions and related environment issues, a lot of advanced materials for building envelope were investigated in the specific Literature and many of them are available on the market.

International Energy Agency (2015) found that building construction combined energy consumption is responsible for 36% of the total energy consumption and is growing by 1% per year. Data are confirmed also by Pérez-Lombard et al. (2008), who found that buildings are responsible for approximately 40% of energy consumption and 36% of CO₂ emissions. In 2018, almost 60% of final energy consumption for heating and cooling (80% of which is used for buildings) was estimated by European Environment Agency (2018).

The improvement of efficiency through new materials was studied by many Authors, such as materials with high thermal resistance and good moisture management, advantageous for building envelope.

New materials like PCMs (Phase Change Materials) and TIMs (Transparent Insulating Materials) were widely applied in building sector. They were investigated not

only by means of laboratory experiments, but also by dynamic simulation models, in order to evaluate their effectiveness.

PCMs can effectively absorb and release massive latent heat during phase transition, in a narrow temperature range, and then reduce building cooling loads in tropical climates (Feustel and Stetiu, 2011). Delaney (2012) simulated a commercial building with PCM ceiling in 10 climatic zones. Results showed a peak cooling reduction of about 25% and, in general, monthly and annual heating and cooling requirements reduced in all climatic zones. Sun et al. (2018) investigated the annual energy performance and indoor comfort level of a typical office served by window integrated Semi-Transparent Photovoltaic (STPV), through EnergyPlus simulation; the study was carried out considering different window systems in five China typical climate conditions. STPV absorb part of the solar radiation incident on the window surface, to generate electrical power. The optimal design scenario of applying window integrated PV can result in a reduction in energy consumption up to 73%. Comparing the base case, an annual energy saving in the 17% - 56% range was obtained from the simulated application of intelligent or adaptive glazing technologies (AGTs) in a typical hospital waiting area located in Cairo (Egypt) (Sadek and Mahrous, 2018). Thermal transmittance (U-value), solar reflectance, and solar heat gain coefficient (SHGC) of glazing have significant effect on building energy consumption (Ihara et al., 2015; Ghoshal and Neogi, 2014). Vacuum glazing windows performance was studied by Cho (2017) through simulation and experimental studies in office buildings in Korea. The simulation revealed a U-value of 0.682-1.466 W/m²·K and 0.607-1.154 W/m²·K both for vacuum glazing and double vacuum glazing. Based on the results of the energy simulation, when using U-value of vacuum glazing, the heating and cooling energy consumption in buildings decreased by about 3%, with respect to low-e glass and argon gas filled windows. Furthermore, in double vacuum glazings, the heating and cooling energy consumption in buildings decreased by about 4%. Mujeeb et al. (2016) focused on the energy performance and economic feasibility of nano-aerogel glazing and nano-vacuum insulation panels (VIPs), when applied to a multi-story office building located in the Dhahran region of Saudi Arabia: an energy saving of 14% in the annual energy consumption was obtained replacing the double glazing windows with nanogel

glazing achieves, while polystyrene foam and nano VIP in walls and roof yield savings of 0.5% and 0.8% respectively.

Recently, a lot of attention was devoted to silica aerogels, a nanomaterial characterized by a low density and a thermal conductivity lower than the air. Aerogel was widely used for many applications in commercial and high-tech fields, such as waste management (gas absorption, radioactive waste confinement), thermal insulation (cryogenic to high temperatures), laser experiments, sensors (ultrasonic and gas), nuclear particle detection (Cherenkov), optics and light-guides, electronic devices, capacitors, high explosive research and catalysts (Riffat and Qiu, 2012). Meanwhile, thanks to its ultra-low thermal conductivity and high visible transmittance, aerogel is interesting for glazing buildings applications. Aerogel has a solar transmittance of 84–92% and a U-value below 0.5 W/(m²K) (thickness in the 7–12 mm range) and aerogel superinsulation glazings have a tendency to scatter the transmitted light and an excellent thermal performance (Ye et al., 2013; Jelle et al., 2012; Koebel et al., 2012; Baetens et al. 2011; Riffat et al., 2012; Buratti et al. 2012a, 2012b and 2017; Moretti et al., 2014, 2017 and 2018).

The influence of innovative aerogel solutions on the energy demand of different buildings was also investigated by means of simulation models. Moretti et al. (2018) studied the application of aerogel in buildings' envelope: three types of advanced multiwall PC panels (thickness 16, 25, and 40 mm) with translucent granular aerogel were compared basing on numerical characterization. The simulations show that the reduction in energy demand is in the 7–12% range, depending on the building site, and on the aerogel thickness, when compared to the conventional double glazing, Gao et al. (2016) investigated the application of aerogel glazings in energy efficient buildings: the aerogel solution, compared to the double glazing, can contribute to about 21% reduction in energy consumptions related to heating, cooling, and lighting. By employing the validated model, the applicability of aerogel glazing system in various climates was also evaluated by Chen et al. (2018). Aerogel glazing system is suitable to apply in cold regions and in the south and north orientations of the regions characterized by hot-summer and cold-winter.

The present study aims at developing a numerical analysis of innovative gazing systems with aerogel in interspace, taking into account annual energy demand and indoor thermal comfort issues. A numerical simple model was implemented and validated by means of data collected in an experimental field, composed of two boxes with a large window in south façade and a weather station for the outdoor measurements. A new weather file for Perugia was created by means of experimental data; this file was optimized with Perez model, in order to process the beam solar radiation and diffuse solar radiation. The new weather file was implemented in both EnergyPlus and TRNSYS software and the results were compared.

New weather file was used in the case study, an ideal multifunction building with large windows; it was modelled in order to compare heating and cooling loads with different climatic conditions and two different transparent systems: a conventional double glazing window with 90% argon between two float glass and an innovative glazing system with granular aerogel in interspace.

Methodology

Climate conditions influence with TRNSYS and E+

The experimental field at pilot scale is composed of two boxes of about 1.60 m x 2 m x 2 m height and of an external weather station installed on the roof of the Department of Engineering of the University of Perugia (Figure 1). For the aim of the present paper, data from only one of the boxes were used. It has south-oriented traditional window.

Figure 1: Experimental field: boxes and weather station.

The external climatic conditions data are monitored by a weather station, equipped with specific probes (E-logger): outdoor temperature, relative humidity, global solar radiation, wind velocity and direction (Figure 2). The station, installed externally, on the roof and close to the test rooms, is able to monitor and store the data collected by the probes: their characteristics are shown in detail in Table 1.

Figure 2: Weather station with the installed sensors.

Table 1: Weather station: features of the probes.

Air Temperature	
Measuring range	-50÷70°C
Accuracy	0.1°C
Resolution	0.01°C
Relative Humidity	
Principle of operation	Capacitive
Measuring range	0÷100%
Accuracy	±1.5% RH
Wind velocity	
Principle of operation	32-sector optoelectronic disc
Accuracy	0÷3 m/s=1.5%; >3 m/s= 1%
Resolution	0.07 m/s
Wind direction	
Principle of operation	Hall effect or 2 kΩ potentiometer
Measuring range	0÷360°
Accuracy	1%
Resolution	0.3°
Solar radiation	
Daily uncertainty	10 %
Spectral range	285÷3000 nm
Irradiance measuring range	0÷4000 W/m ²

The measurements from the weather station were used to create a weather file in .epw format, by using the weather converter program within the EnergyPlus software package. For optimizing the experimental meteorological data, a specific applicative function was developed in TRNSYS, in order to process the beam solar radiation and diffuse solar radiation. The global horizontal radiation, the air temperatures, and the relative humidity were needed for implementing the Perez model (Perez et al., 1986). This application showed the peak of global radiation and beam radiation reduced, while tendency of diffuse radiation varied with the time.

In order to validate the new weather file, the simulation results of a simply model implemented in TRNSYS and EnergyPlus software, were compared with measured data.

The main input data are the geometry, material features of the building, the meteorological data, and the air change rates. The first part of the model implementation was the creation of the geometry: for TRNSYS, detailed information was described in TRNbuild while for EnergyPlus a model with Euclid extension for SketchUp was created. The geometry was simple and a considerable part of the south front façade was occupied by the window. The location was Perugia. No shadows around the experimental site were present.

In the room a lot of probes were installed but indoor air temperature and surface temperature of the glass are now analysed. The start time has an impact on simulation results (Buratti et al., 2013); it was chosen from 1st of January to 31st of December, for having reliable results. Time step used for simulation was equal to 1 hour. For these preliminary simulations, it was not considered the heating and cooling system, internal loads of people, lighting, and equipment because they were not present in

the experimental field. Data obtained by the weather station in the experimental field were compared with TMY climatic file (Typical Meteorological Year), in order to make them more reliable. The experimental values, both the air temperature and the solar radiation, were very different from data based on TMY (average difference of the air temperature is about 9%).

The differences between simulated and measured values were significantly reduced after the solar radiation balance with solar processor: the difference in indoor temperature is reduced by 17.6% (from 5.1 °C to 4.2 °C) and the average difference is minimized to 1.7 °C for EnergyPlus. For TRNSYS, the maximum difference is reduced by 42.6% (from 12.7 °C to 7.29 °C) and the average difference is minimized to 2.2 °C.

The new weather file used in the simulations given by EnergyPlus and TRNSYS showed a good reliable trend with measured indoor air and glazing surface temperatures. The setting data were modified several times and the best calibration was obtained, as shown in the following. The results in the period 12th - 18th June 2018 are reported as for example. The measured indoor temperature (Figure 3) was in agreement with the ones simulated by EnergyPlus. However, it generally overestimated the peak value of daytime, due to the difficulty in evaluating the direct and diffuse solar radiation. In these days the maximum difference between simulated and real values was about 4 °C, but in some days the peak were coinciding. The values simulated with TRNSYS always evaluated a lower temperature in the afternoon with respect to the measured one. However, both EnergyPlus and TRNSYS simulation results can better evaluate the temperatures in the night, with maximum differences of 2.3 °C and 1.8 °C respectively.

Figure 3: Indoor air temperatures: comparison between simulation and measured data.

The trends of the surface temperature of the double glazing system are shown in figure 4. Both EnergyPlus and TRNSYS models underestimated the peak values of daytime. During the first days, the temperatures of the glazing surface simulated by EnergyPlus were in accordance with the measured ones; in the next days they were always better than the ones simulated by TRNSYS. The maximum difference between EnergyPlus and real values was about 7 °C during the

hottest hours of the days and it was about 1.5 °C during the night.

Figure 4: Surface glass temperatures: comparison between simulation and measured data.

Despite both the software are able to simulate the thermal behaviour of the box with a sufficient reliability, for modelling the case study EnergyPlus software was chosen because easier to be implemented, especially for data of innovative glazing system with aerogel in interspace.

The case study

To further evaluate annual energy demand savings, a three floor ideal multifunctional building was investigated and a comparison of heating and cooling demand was performed.

The 3D model is shown in Figure 5. It consists of three floors, for a total height of about 9 m. Each floor zone has a total area of 1600 m². The east and west façades are bigger than the others and they receive more solar radiation, with wider glass windows. The height of the strip windows is 1.5 m.

A thermal transmittance of the building opaque envelope of about 0.57 W/m²K is established and 0.05 m of insulation board are provided in perimeter walls. The first and the ground floors are clay/cement mix, with plasterboard and polystyrene; their thermal transmittances are 0.52 W/m²K and 0.48 W/m²K respectively. The distance between floors is 3 m. The partition between zones and external wall is a gypsum plasterboard wall, with a 0.06 m thickness layer of air gap; its thermal transmittance is 3.41 W/m²K. The roof has a thermal transmittance of 0.32 W/m²K. Annual simulations were carried out for the building. The time step used in the simulations is 1 hour. The convection coefficients of the surface for the external side and internal one are automatically calculated by Simple Combined Algorithm. All the external walls are considered as heat exchanged surfaces, exposed to outside temperature conditions.

The occupancy of people is assumed 0.05 persons per m² for all the three zones. The presence of occupants is considered from 8.00 am to 6.00 pm for the offices every workday. Internal gains from lighting and equipment are imposed equal to 7 W/m². The schedule assumed for the use of the lights and equipment is from 8.00 am to 6.00

pm, for a typical workday. The considered infiltration rate is 0.6 ACH (air changes per hour) for the three floor zones. Moreover, in order to evaluate the annual energy demand, the ventilation rate is not considered when the HVAC system is turned on.

Room air set-point temperature was also based on occupancy schedules (8.00 am - 6.00 pm), with a daytime set-point of 26°C in cooling period and 20°C during the heating period.

Figure 5: 3D Model of the multifunctional building.

Simulations were carried out considering the building and the other hypotheses, as described above, but varying the glazing system and the city.

Two kinds of windows were considered:

- a conventional double glazing system: total thickness 0.020 m, composed of a float glazing pane 4 mm thick, 90% argon (12 mm thickness), and a second float glazing pane (4 mm); the total transmittance is 2.7 W/m²K, g-value is 0.8 and visible transmittance is 0.82;
- silica aerogel glazing system: total thickness 0.028 m; composed of a float glazing pane 4 mm thick, granular aerogel (20 mm thickness), and a second float glazing pane (4 mm); the total transmittance is 0.8 W/m²K, g-value is 0.7 and visible transmittance is 0.67.

Three typical cities with different climate conditions were chosen both in Italy and China. Palermo, Rome and Perugia were chosen for the Italian climate zones and Harbin, Beijing and Hong Kong for the China areas. Palermo and Rome are characterized by hot climate; Perugia is an inland city in the centre of Italy, with intermediate tempered climate. Hong Kong, in Southern China is characterized by hot summer and warm winter; Beijing has cold winters and Harbin has severe cold winter (North of China). Harbin has about the same latitude of Perugia and the latitude of Beijing is similar to Palermo, despite the very different climate conditions. The yearly temperature variations in the Italian cities are always lower than those of Chinese ones. As shown in Figure 6, the external temperatures of Chinese cities are very different, especially during the winter (in January, for example, the temperature in Hong Kong is 16.4 °C while in Harbin is about -16.7 °C).

The global solar radiations of the selected cities are shown in Figure 7: during the winter period, the global radiation of the Chinese cities is higher than the Italian ones but during the summer it is lower. The peak value of Hong Kong (July) is a little bit lower.

Figure 6: Monthly temperatures of the selected cities.

Figure 7: Monthly global radiation of the selected cities.

The yearly minimum value of global solar radiation is the one of Perugia (1256.41 kWh/m² per year), while Beijing has the maximum one (1513.26 kWh/m² per year).

The simulation hypothesis for heating and cooling system operating periods vary with the climatic zone. For Italian cities they were chosen according to the Norms (Decree Law of 26/06/2015), for Chinese cities the winter period could be the same (December – February), while the summer period is June to September for Beijing and Hong Kong, and May to August for Harbin.

The main hypotheses of the simulation model are reported in Table 2.

Table 2: Envelope features and model simulation hypotheses.

Envelope	
Opaque wall	$U = 0.57 \text{ W/m}^2\text{K}$
Roof	$U = 0.32 \text{ W/m}^2\text{K}$
Ceiling	$U = 0.52 \text{ W/m}^2\text{K}$
Floor	$U = 0.48 \text{ W/m}^2\text{K}$
Double Glazing	float clear glass (4 mm) - argon 90% (12 mm) - float clear glass (4 mm)
Aerogel Glazing	float clear glass (4 mm) – granular aerogel (20 mm) - float clear glass (4 mm)
Internal Loads (Working days from 8:00 a.m. to 6:00 p.m.)	
Lighting	7 W/m ²
People	0.05/ m ²
Infiltration rate	
All cities	0.6 vol/h

Heating and cooling system: operating periods (working days from 8:00 a.m. to 6:00 p.m.)		
Temperature set-point	Heating (20 °C)	Cooling (26 °C)
Palermo	12/01 – 03/31	04/15 – 10/14
Rome	11/01 – 04/15	04/15 – 10/14
Perugia	10/15 – 04/15	04/15 – 10/14
Bolzano	10/01 – 04/30	04/15 – 10/14
Hong Kong	12/01 – 03/01	06/01 – 09/30
Wuhan	12/01 – 03/01	06/01 – 09/30
Beijing	12/01 – 03/01	06/01 – 09/30
Harbin	12/01 – 03/01	05/01 – 08/30

Results and discussion

The impact of the innovative solution on building energy performance is evaluated in terms of heating and cooling energy demand: ideal energy loads are calculated as the heating and cooling heat transfer rates needed to be removed or added to the zone to maintain the indoor temperature conditions, without considering any equipment for heating, cooling, and ventilation. The results of Italian and Chinese cities are shown in Table 3 and Table 4.

With respect to heating demand with the standard glazing system (Table 3 and 4), the lowest value is related to the hottest cities, Palermo and Hong Kong, with 0.49 MWh/year and 0.001 MWh/year respectively. The highest value is reached by Harbin for the Chinese cities (91 MWh/year) while the peak value for the Italian climate is about 15.38 MWh/year for Perugia. Cooling demand with the standard glazing system is highest for Palermo among the Italian cities and Hong Kong among the Chinese ones. During cooling period, cities have different energy demand varying with months. In May and September, Hong Kong needs the biggest cooling energy. From June to August, the maximum value is related to Palermo because of the highest solar radiation (monthly value ranges from 6000 to 6500 Wh/m²). Rome also has cooling energy demand from June to August higher than Hong Kong, the warmest Chinese city.

Table 3: Comparison of energy demand per year and difference between double glazing window and aerogel window (Italian cities).

	Double Glazing [MWh per year]	Aerogel Glazing [MWh per year]	Difference [MWh per year]	Difference [%]
Palermo				
Heating	0.49	0.05	0.43	-*
Cooling	108.33	106.84	1.49	1.4
Rome				
Heating	7.08	2.99	4.10	-*
Cooling	90.03	89.42	0.61	0.7
Perugia				
Heating	15.38	8.47	6.91	45.0
Cooling	72.26	73.24	-0.98	-1.4

* the percentage value is not significant because the heating/cooling energy demand are very low.

Table 4: Comparison of energy demand per year and difference between double glazing window and aerogel window (Chinese cities).

	Double Glazing [MWh per year]	Aerogel Glazing [MWh per year]	Difference [MWh per year]	Difference [%]
Hong Kong				
Heating	0.001	0	-	-*
Cooling	81.33	76.73	4.60	5.6
Beijing				
Heating	36.45	26.82	9.63	-*
Cooling	60.64	59.40	1.24	2.0
Harbin				
Heating	91.00	75.65	15.35	17.0
Cooling	55.92	57.52	-1.60	-3.0
* the percentage values are not significant because the heating/cooling energy demand are very low.				

When considering aerogel glazing system, it has a significant influence in heating period, as expected, while its impact is slightly significant in summer. In Harbin, for example, the annual energy demand for heating is decreased of about 15% with innovative glazing solution as a consequence of a U-value reduction of 70% with respect to the standard double glazing system. The effect of innovative glazing system is showed in Figures 8-11 respectively for Perugia, Harbin, Palermo, and Hong Kong. In Figure 8, a comparison between monthly energy demand with the two glazing solutions is evaluated for Perugia: the monthly energy saving is in the 41-45% range in heating period (December-February). However, aerogel window increases the cooling loads in middle seasons, while during the cooling period an energy saving is observed, but it is low (values of about 3%). In fact, silica aerogel in the glazing system involves a significant reduction of the thermal transmittance, while g-value is almost equal (0.8 and 0.7 for conventional and innovative glazing systems, respectively). This trend also appears in other cities like Rome and Beijing, not reported for the save of brevity.

Figure 8: Perugia-Effect of glazing system on monthly energy demand.

The trend of the energy demand in Harbin is shown in Figure 9: during the heating period a significant energy

saving is found with the innovative glazing system (about 30 % in March). On the other hand, during the hottest months of the year, the effect of the aerogel glazing is negligible.

In Palermo the effect of the innovative glazing solution is not very remarkable (Figure 10). From June to August, the monthly energy saving varies from 1 % to 4%. In April, May and October the effect is disadvantageous.

In Hong Kong the trend is similar to Palermo (Figure 11): the effect of the innovative glazing solution is not very remarkable from May to October and during April the two glazing systems are equivalent.

Figure 9: Harbin-Effect of glazing system on monthly energy demand.

Figure 10: Palermo-Effect of glazing system on monthly energy demand.

Figure 11: Hong Kong-Effect of glazing system on monthly energy demand.

Conclusion

Aerogel in the interspace of the glazing systems could be a good strategy to reduce heating consumptions in multifunctional buildings with large windows; their performance is often evaluated by numerical analysis, without any comparison with experimental data. In the present work a new weather file was created and optimized for Perugia by data of an experimental field with a weather station. This file was validated by means of a simply simulation model of a box at the pilot scale and implemented in EnergyPlus and TRNSYS. The EnergyPlus validated model was used then to simulate the effect of an innovative glazing system with aerogel in interspace in terms of energy demand in a three floor multifunctional building in different climate conditions of Italy and China.

Preliminary simulations show that the yearly energy demand decreases thanks to the use of the aerogel in the cities with the lowest temperatures: in particular the reduction ranges from 17% in Harbin to 45% in Perugia. Nevertheless, the impact of aerogel window is different depending on the climatic zone in cooling period: a negligible difference on energy demand occurs in Perugia and Harbin (1.5% - 3%), and a slightly significant cooling decrease in cities with mild temperatures (Rome and Palermo). The application of the aerogel glazing is recommended, especially for cities with cold winter. In fact, the increasing of the costs is not so significant; it was estimated that in Italy the price of 1 m² window with 20 mm of aerogel in interspace is about 60 Euros higher than the standard system with air.

Future studies will focus on the evaluation of the lighting performance of the innovative solutions. The use of glazing surfaces with innovative transparent materials is advantageous because they ensure good light entry, without problems of glare or heat discomfort conditions. Nevertheless, it is equally important to employ the latest generation lighting technology solutions; it can provide visual comfort for users and low energy consumptions, also when solar radiation is no longer effective.

References

- Baetens, R., Jelle, B.P. and A. Gustavsen (2011). Aerogel insulation for building applications: a state-of-the-art review. *Energy Build.* 43, 761–769.
- Buratti, C. and E. Moretti (2012a). Glazing systems with silica aerogel for energy savings in buildings. *Applied Energy*. 98, :396-403.
- Buratti, C. and E. Moretti (2012b). Experimental performance evaluation of aerogel glazing systems. *Applied Energy*. 97, :430-437.
- Buratti, C., Belloni, E. and D. Palladino (2014). Evolutive housing system: refurbishment with new technologies and unsteady simulation of energy performance. *Energy Build.* 74, 173–181.
- Buratti, C., Merli, F. and E. Moretti (2017). Aerogel-based materials for building applications: Influence of granule size on thermal and acoustic performance. *Energy and Buildings*. 152, :472-482.
- Buratti, C., Moretti, E. and M. Zinzi (2017). High energy-efficient windows with silica aero- gel for building refurbishment: experimental characterization and preliminary simulations in different climate conditions. *Buildings* 7, 8.
- Buratti, C., Moretti, E., Belloni, E. and F. Cotana (2013). Unsteady simulation of energy performance and thermal comfort in non-residential buildings. *Building & Environment* vol. 59, pp. 482-491, 2013.
- Chen, Y., Xiao, Y., Zheng, S., Liu, Y., and Y. Li (2018). Dynamic heat transfer model and applicability evaluation of aerogel glazing system in various climates of China. *Energy*. 163, :1115-1124.
- Cho, S. and Kim, S.-H. (2017). Analysis of the Performance of Vacuum Glazing in Office Buildings in Korea: Simulation and Experimental Studies. *Sustainability*. 9, 936.
- Decree of 26/06/2015 - National guidelines for the energy certification of buildings.
- Delaney, S. E. B. J. P. (2012). Phase Change Materials: Are They Part of Our Energy Efficient Future?. *Proceedings of the 2012 ACEEE summer study on energy efficiency in buildings*. California, USA, 2012, pp. 160–72.
- European Environment Agency (2018). *Final energy consumption by sector*.
- Feustel, H. E. and C. Stetiu (2011). Thermal performance of phase change wallboard for residential cooling application. *Lawrence Berkeley National Laboratory*.
- Gao, T., Ihara, T., Grynning, S., Jelle, B. P. and A. G. Lien (2015/2016). Perspective of aerogel glazings in energy efficient buildings. *Building and Environment*. 95, : 405-413.
- Ghoshal, S. and S. Neogi (2014). Advance Glazing System - Energy Efficiency Approach for Buildings a Review ☆. *Energy Procedia* vol. 54, pp. 352-358, 2014.
- Ihara, T., Gustavsen, A. and B. P. Jelle (2015). Effect of facade components on energy efficiency in office buildings. *Applied Energy* vol. 158, pp. 422-432, 2015.
- International Energy Agency (2015). *Energy Technology Perspectives 2015 : mobilising innovation to accelerate climate action: International Energy Agency, 2015*.
- Jelle , B.P., Hynd, A., Gustavsen, A., Arasteh, D., Goudey, H. and R. Hart (2012). Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Solar Energy Mater. Solar Cells* 96,1–28.

- Koebel, M., Rigacci, A. and P. Achard (2012). Aerogel-based thermal superinsulation: an overview, *J. Sol. Gel Sci. Technol.* 63, 315–339.
- Moretti, E., Francesca Merli, F., Erdem Cuce, E. and C.inzia Buratti (2017).,.
- Moretti, E., Zinzi, M. and E. Belloni (2014). Polycarbonate panels for buildings: experimental investigation of thermal and optical performance. *Energy Build.* 70, 23–35.
- Moretti, E., Zinzi, M., Merli, F. and C. Buratti (2018). Optical, thermal, and energy performance of advanced polycarbonate systems with granular aerogel. *Energy & Buildings.* vol. 166, pp. 407-417, 2018.
- Mujeebu, M. A., Ashraf, N. and A. Alsuwayigh (2016). Energy performance and economic viability of nano aerogel glazing and nano vacuum insulation panel in multi-story office building. *Energy.* 113, : 949-956.
- Perez, R., Stewart, R., Arbogast, C., Seals, R. and J. Scott (1986). An anisotropic hourly diffuse radiation model for sloping surfaces: Description, performance validation, site dependency evaluation. *Solar Energy* vol. 36, pp. 481-497, 1986.
- Pérez-Lombard, L., Ortiz, J. and C. Pout (2008). A review on buildings energy consumption information. *Energy & Buildings* vol. 40, pp. 394-398.
- Riffat, S. B. and G. Qiu (2012). A review of state-of-the-art aerogel applications in buildings. *International Journal of Low-Carbon Technologies* vol. 8, pp. 1-6.
- Sadek, A. H. and R. Mahrous (2018). Adaptive glazing technologies: Balancing the benefits of outdoor views in healthcare environments. *Solar Energy.* 174:, 719-727.
- Sun, Y., Shanks, K., Baig, H., Zhang, W., Hao, X., Li, Y., He, B., Wilson, R., Liu, H., Sundaram, S., Zhang, J., Xie, L., Mallick, T. and Y. Wu (2018). Integrated semi-transparent cadmium telluride photovoltaic glazing into windows: Energy and daylight performance for different architecture designs. *Applied Energy.* 231:, 972-984.
- Thermal and Acoustic Properties of Aerogels: Preliminary Investigation of the Influence of Granule Size. ,
- Ye, H. , Meng, X., Long, L. and B. Xu (2013). The route to a perfect window. *Renew. Energy* 55, (2013) 448–455.