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High Energy-Efficient Windows with Silica Aerogel for Building Refurbishment: Experimental Characterization and Preliminary Simulations in Different Climate Conditions

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Abstract: The paper deals with the potential of high energy-efficient windows with granular silica aerogel for energy saving in building refurbishment. Different glazing systems were investigated considering two kinds of granular silica aerogel and different glass layers. Thermal transmittance and optical properties of the samples were measured and used in building simulations. The aerogel impact on heat transfer is remarkable, allowing a thermal transmittance of 1.0–1.1 W/(m^2·K) with granular aerogel in interspace only 15 mm in thickness. A 63% reduction in U-value was achieved when compared to the corresponding conventional windows, together with a significant reduction (30%) in light transmittance. When assembled with a low-e glass, the U-value reduction was lower (31%), but a moderate reduction in light transmittance (about 10%) was observed for larger granules. Energy simulations for a case study in different climate conditions (hot, moderate, and cold) showed a reduction in energy demand both for heating and cooling for silica aerogel glazing systems, when compared to the conventional ones. The new glazings are a suitable solution for building refurbishment, thanks to low U-values and total solar transmittance, also in warm climate conditions.

Keywords: high energy-efficient windows; nanogel windows; silica aerogel; building refurbishment; Nearly Zero Energy Buildings (NZEBs); energy saving in buildings

1. Introduction

Glass façades have an important role in buildings in terms of energy demand, thermal comfort, and daylighting: the main total energy losses (up to 60%) can depend on the windows, especially in highly glazed buildings. In order to speed up refurbishment of existing buildings towards Nearly Zero Energy Buildings (NZEBs), innovative glazing systems have been spread in the market and might be suitable in places of conventional glazing windows, especially in cold climates [1–3]. Aerogel windows seem to have the largest potential for improving the thermal performance and daylighting in glazing systems, because of very low thermal conductivity (about 0.020 W/m·K for translucent granular aerogel at room temperature) and density (about 80 kg/m^3), together with good optical transparency and acoustic insulation [4–9].

Opaque silica aerogel-based materials, such as flexible blankets and aerogel-based plasters and concrete, have recently appeared on the market [10,11]. Silica aerogels, both in monolithic and granular translucent form, can be used in high-insulated nanogel windows: transparent monolithic panes were developed 20–30 years ago, but their application in glazing systems has still not penetrated the market, and few prototypes have been manufactured for research purposes [12,13]; for these reasons, building applications have focused on glazing systems with granular aerogels [14–17]. Different translucent daylighting systems with granular aerogel have been emerging in the market. The most popular systems are multiwall polycarbonate panels for skylights, roofs, walls, structural panels for continuous façades, and finally insulated glass units. Many of these innovative solutions can be found in schools, commercial and industrial buildings, airports, etc., especially in the US and in Northern Europe [4,6,7,18]. The main application has been focusing on roof solutions [7,8], where an outside view is usually not essential or where they can also be integrated at façade spandrels [14].

Thermal and optical properties of granular aerogel glazing systems are significantly affected by aerogel layer thickness and particle size: a significant reduction in U-value is observed by incorporating the aerogel granules into the cavity of double glazings (58% and 63%) [19–21]. When the aerogel layer thickness increases to 60 mm, a U-value of 0.3 $W/(m^2{\cdot}K)$ can be achieved [16,22]. When compared to conventional glazings, the ones with granular aerogel also have significant benefits when used for roof solutions, because U-values are not dependent on the tilted angle to the vertical plane, for example, in gas-filled glazings [8,22].

The paper deals with the potential of highly energy-efficient windows with silica aerogel for energy saving in order to create Nearly Zero Energy Buildings (NZEBs) or as a strategy in building refurbishment; in order to evaluate the potential spread of these solutions in the fenestration market, their performance was compared to conventional glazing solutions. The experimental characterization of double glazing units (DGUs) with aerogel in interspace is carried out by considering different kinds of silica granular aerogel and glass layers. Solar and light transmittance of aerogel windows are investigated by means of advanced instrumentation, able to measure the optical properties of diffusing and scattering materials. In this work, a large integrating sphere apparatus, designed for complex transparent and translucent systems, was used. Thermal transmittance (U-value) of DGUs is measured using a Heat Flux Meter in steady-state conditions. Then, the energy performance of aerogel windows is discussed thanks to a case study: energy demand of a non-residential building is calculated by means of Energy Plus software by using experimental data as input data and considering different climate conditions (cold, moderate, and hot climates). The results are finally compared in order to evaluate the benefits of using innovative systems with aerogel instead of conventional solutions.

2. Materials and Methods

2.1. The Investigated Samples

Two prototypes of aerogel glazing units were assembled by incorporating aerogel granules into the air space of the corresponding double glazing units, in order to investigate their optical and thermal properties and to carry out numerical simulations on energy performance based on experimental data.

The double-glazing units with aerogel in interspace (Figure 1b) were used to realize two prototypes of windows (an aluminum frame window, Type 1 [20], and a wood frame window, Type 2) with two mobile shutters. The two windows were compared to conventional solutions with the same frame and glass, but with an air gap (Figure 1a).

Aerogel in granular form was put in a gap 15 mm thick, while external and internal layers are float glass 4 mm in thickness. Window Type 1 was assembled with two conventional clear float glass layers, whereas Window Type 2 has a low-e and solar control coating on the inner side of the external glass. During the assembly process, the glazing system was subject to mechanical vibration in order to ensure a compact packing of aerogel granules between the glass layers. Two kinds of silica aerogel granules were considered: type "A" for the window frame Type 1 and type "B" for the other window. Type "B" is the most recent aerogel, characterized by larger granules, allowing enhanced daylighting properties, as shown in Figure 2. Table 1 shows the main characteristics of the DGU samples.

(**a**) (**b**)

Figure 1. Wood frame window prototype Type 2 (**a**) with conventional double glazing units (DGUs) and (**b**) with aerogel in the interspace between glass layers.

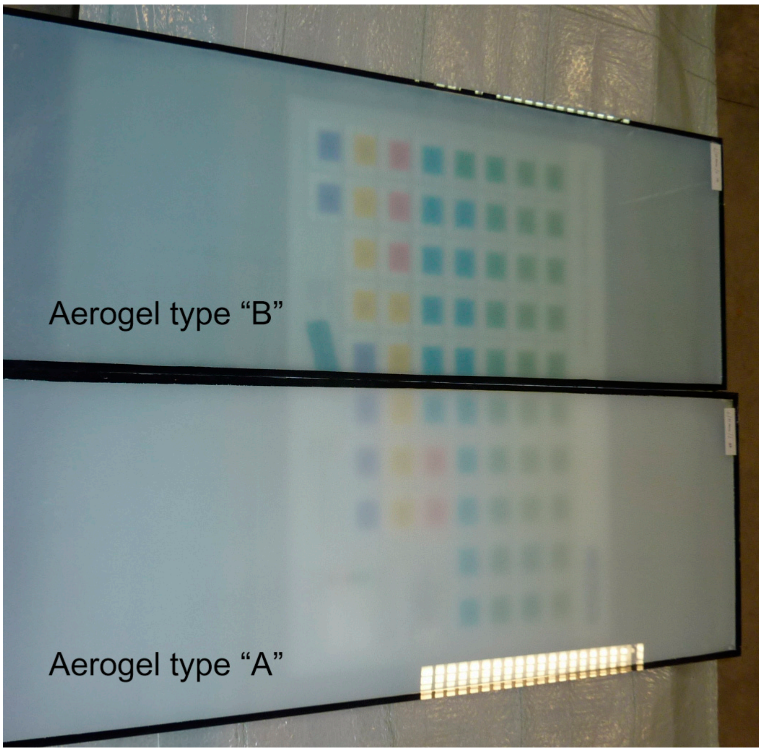

Figure 2. Glazing units with aerogel: LOW-E DGU AEROGEL with aerogel type "B" (at the **top**) and DGU-AEROGEL with aerogel type "A" (at the **bottom**).

Table 1. The investigated glazing systems: conventional DGU and DGU with aerogel.

Name	External Layer	Interspace	Internal Layer	Window Frame
DGU	Float clear glass (4 mm)	Air (15 mm)	Float clear glass (4 mm)	Type 1 aluminum
DGU-AEROGEL	Float clear glass (4 mm)	Granular aerogel type "A" (15 mm)	Float clear glass (4 mm)	
LOW-E DGU	Solar control and low-e glass (4 mm)	Air (15 mm)	Float clear glass (4 mm)	Type 2 wood
LOW-E DGU-AEROGEL	Solar control and low-e glass (4 mm)	Granular aerogel type "B" (15 mm)	Float clear glass (4 mm)	

2.2. Experimental Campaign

The optical characterization of all the samples was carried out by means of a built-in spectrophotometer with a large-diameter integrating sphere (75 cm diameter, with an internal surface made of Spectralon, SphereOptics GmbH, Herrsching, Germany), needed to accurately characterize geometrically complex and scattering transparent materials; a full description can be found in the literature [23,24]. The layout of the facility can be adjusted to perform transmittance, reflectance, and absorptance measurements, using a single beam measurement procedure (Figure 3). The near-normal incidence transmittance and reflectance were measured in the 350–2000 nm range, covering about 97% of the solar spectrum.

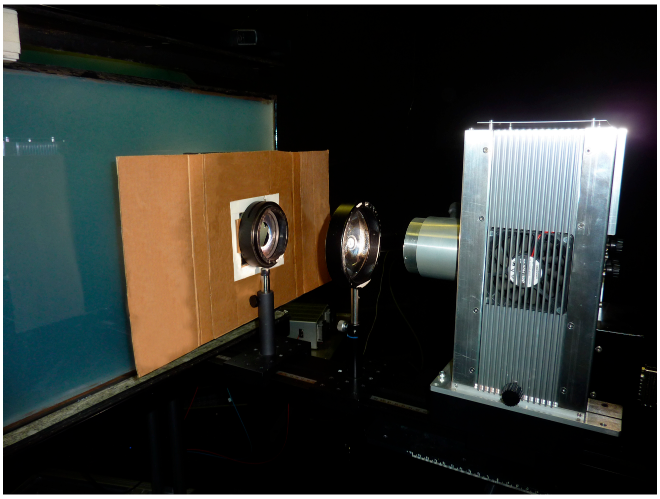

Figure 3. Optical measurements for a glazing unit with aerogel.

The thermal transmittance of the window prototypes was measured according to UNI EN ISO 12567-1 [25]: during the measurements, three thermofluximeters were fixed on the glazing system, in order to evaluate the U-value of the glazing only in steady-state conditions [20].

2.3. Simulations

The energy performance of the innovative glazing systems proposed in the present paper was investigated by EnergyPlus^{TM} software (Version 8.4, U.S. Department of Energy's (DOE), Washington DC, USA) [26–28]. Many simulations with different configurations and settings were performed considering a typical office building built in the 1990s as a reference (Figure 4). The external dimensions are 80 m × 20 m × 10 m, and large strip windows (window-to-wall ratio about 50%) are in the East and West walls. The mid-floor of the building was chosen for the study so that just the façades are exposed to the external environment conditions (weather, sun, wind, etc.), whereas the roof and the floor exchange heat with zones at the same temperature. Moreover, the ground temperature has no effect on the performance of the chosen zone. The internal loads (people, lighting, and equipment) were defined as reported in Table 2. The lights are fully dimmable in order to ensure energy savings: artificial light is automatically reduced and switched off when the illuminance level is equal to 500 lux. The heating and cooling system operating periods are set according to the climatic zone, considering an indoor air temperature of 20 °C and 26 °C, respectively. The office occupancy was set from 8:00 to 18:00, five days a week.

The influence of aerogel glazings on building energy performance was evaluated in terms of heating, cooling, and lighting energy demands, taking into account different climatic conditions. The simulations were run for three different cities: Rome (Italy), characterized by hot climate, Paris (France), with a moderate climate, and Ottawa (Canada) with a cold climate (Figure 5).

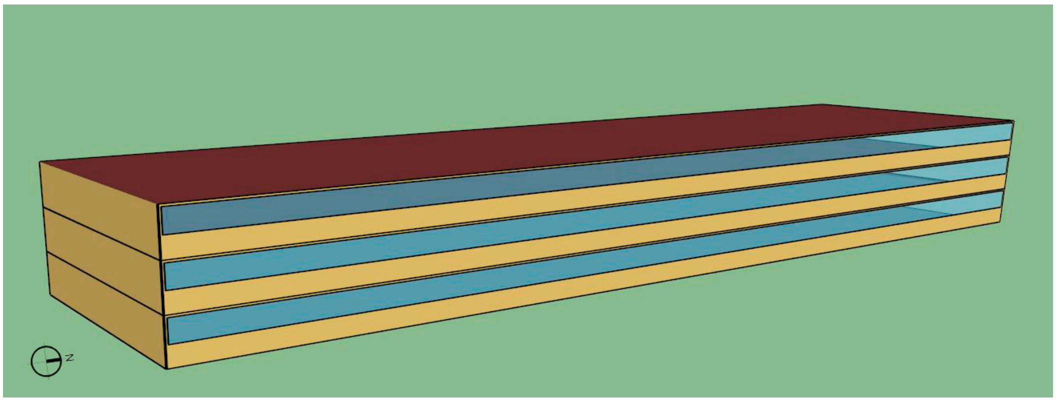

Figure 4. The reference office building for energy simulations.

Table 2. Simulation hypotheses.

<table>
<tr><th>Internal Loads</th><th colspan="2">Values</th><th>Schedule</th></tr>
<tr><td>Lighting</td><td colspan="2">$7\ \mathrm{W/m^2}$ (500 lux, fully dimmable)</td><td rowspan="3">8:00–18:00
five days a week</td></tr>
<tr><td>People</td><td colspan="2">$0.05\ \mathrm{persons/m^2}$</td></tr>
<tr><td>Equipment</td><td colspan="2">$7\ \mathrm{W/m^2}$</td></tr>
<tr><th colspan="4">Operating Periods of Heating and Cooling System and schedule</th></tr>
<tr><th>City</th><th>Heating (20 °C)</th><th>Cooling (26 °C)</th><th>Schedule</th></tr>
<tr><td>Rome</td><td>1 November–15 April</td><td>16 April–14 October</td><td rowspan="3">7:00–19:00
five days a week</td></tr>
<tr><td>Paris</td><td>15 October–30 April</td><td>1 May–14 October</td></tr>
<tr><td>Ottawa</td><td>15 October–30 April</td><td>1 May–14 October</td></tr>
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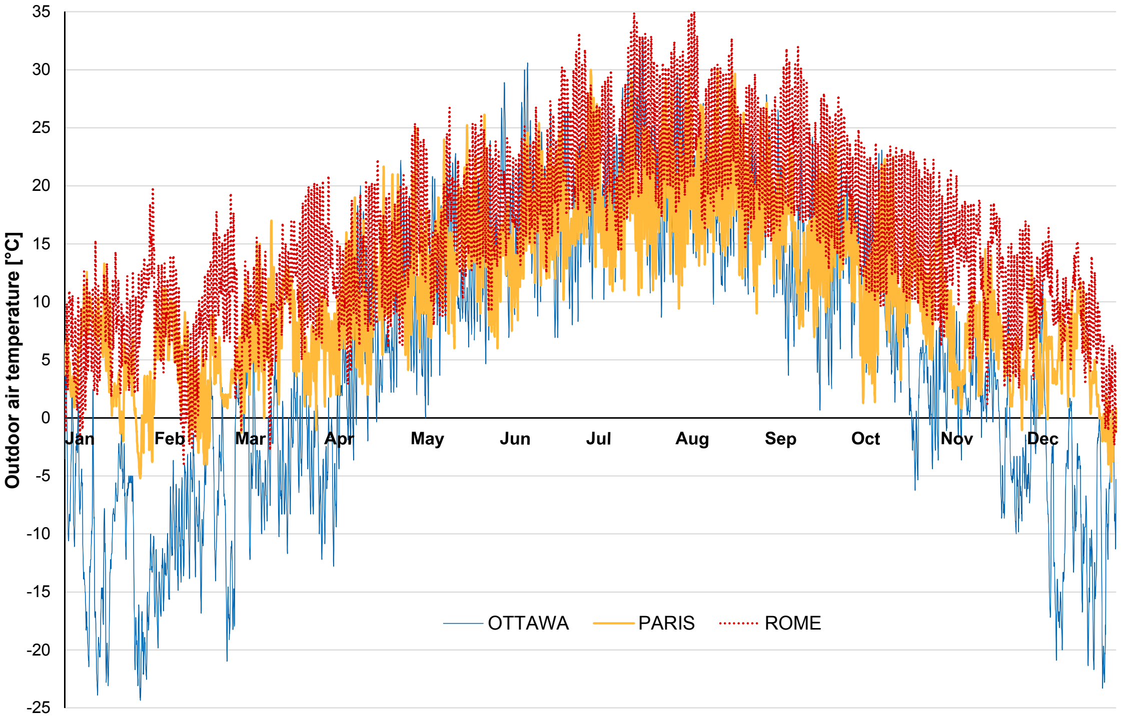


Figure 5. Outdoor air temperature for the investigated cities.

3. Results and Discussion

3.1. Optical and Thermal Performance

The spectral transmittance and reflectance of all the samples are reported in Figures 6 and 7, respectively. By comparing empty and aerogel filled glazings, it is interesting to note a modification of the spectral response shape, especially in the visible range, and typical selective absorption peaks are shown in the spectral transmittance values (at about 1400 nm, 1700 nm, and 1900 nm) [20]. As known, part of the radiation is diffused and scattered when transmitted through the material [19–22,29]. Data about the assembled sample with float glasses and aerogel show a significant impact on the granules: the reduction is more evident in the visible range, whereas the transmittance diminishes by about 0.1 in the IR range. The transmission of the samples LOW-E DGU and LOW-E DGU-AEROGEL in the near infrared range is very low due to solar control and low-e coating, and the influence of aerogel granules is negligible. Moreover, the reduction in the visible range due to the granular aerogel is very low and equal to about 0.1.

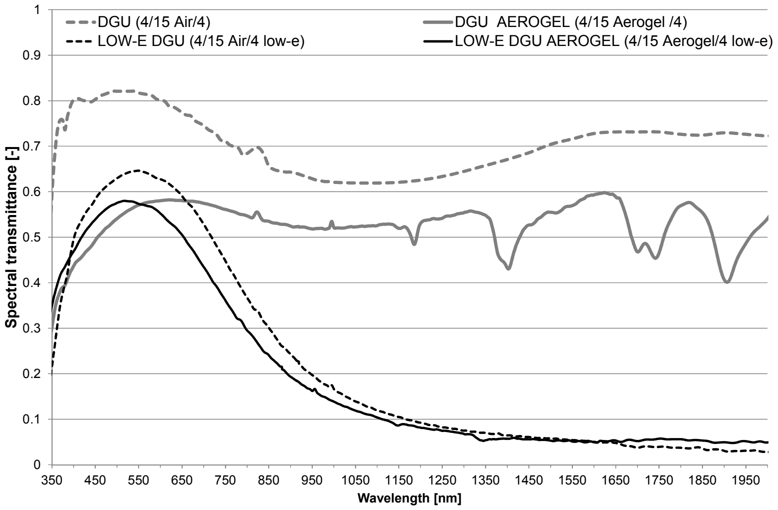


Figure 6. Spectral transmittance at normal incidence.

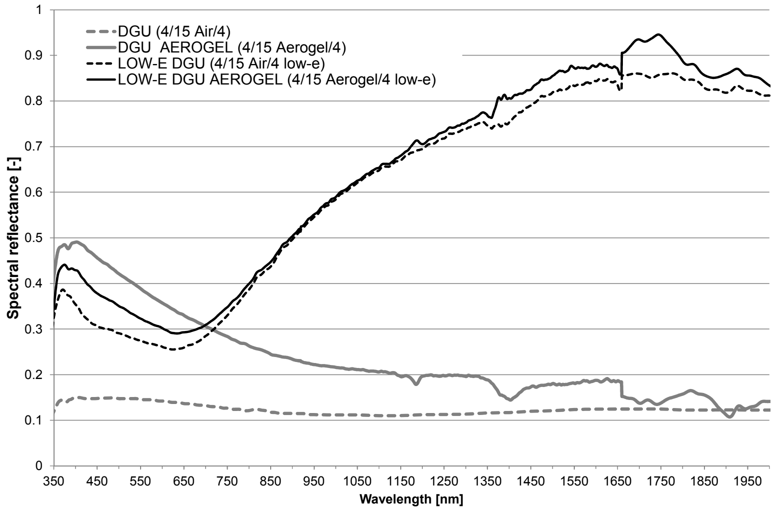


Figure 7. Spectral reflectance at normal incidence.

The aerogel significantly also influences the reflectance spectrum (Figure 7), especially in the visible range, where the values increased up to 0.45–0.5. As expected, the reflectance trend is strictly linked to the glass layer type: for the samples with solar control and low-e coating, the reflectance is very high in the NIR range, up to about 0.9 at 1750 nm.

In Table 3, the broadband values calculated for transmittance and reflectance in the visible and solar spectrum are reported, according to the standard reference EN 410 [30] and the U-value of the only glazing calculated by data measured with the thermofluximeters [20].

Table 3. Lighting, solar, and thermal performance of the samples.

Acronym	Light Transmittance τ_v	Light Reflectance ρ_v	Direct Solar Transmittance τ_e	Solar Reflectance ρ_e	Total Solar Transmittance g	U–value (W/m^2·K)
DGU	0.82	0.15	0.76	0.14	0.80	2.7
DGU-AEROGEL	0.57	0.38	0.53	0.31	0.57	1.0
LOW-E DGU	0.63	0.27	0.39	0.43	0.41	1.6
LOW-E DGU-AEROGEL	0.57	0.32	0.35	0.46	0.36	1.1

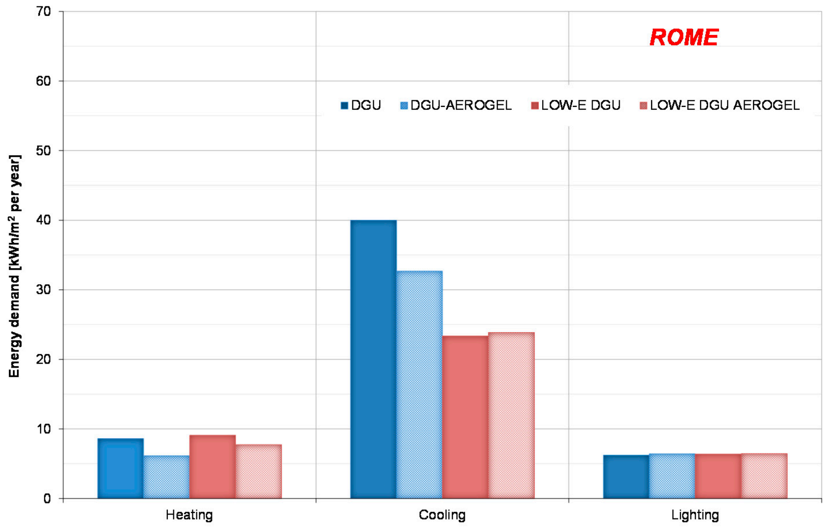
The contribution of the innovative glazing system on thermal properties is remarkable: the thermal transmittance is 1.0–1.1 W/(m^2·K) for the aerogel glazing systems, in good agreement with literature data [7–9,14,19,31]. The U-value of the glazing depends on the thermal resistivity of each glass layer and on the gas (convective heat transfer) and radiation conductance in the interspace, where the radiation heat transfer is strictly related to the emissivity of the inner side of the glasses: with a low-e coating (the emissivity is about 0.1) and air (or argon) in the interspace, a significant reduction in the radiation conductance can be observed; the U-value of LOW-E DGU is in fact 1.6 W/(m^2·K) instead of 2.7 W/(m^2·K). The aerogel in the interspace between the glass layers has a dual impact on thermal conductance: the convective heat transfer within the cavity becomes negligible, as reported in the literature [18,22], and the radiative heat transfer is limited due to the transmittance of the aerogel in the infrared spectral range, which is very low [8], except in the 3500–5000 nm range. For this reason, the low-e coating does not influence the overall heat transfer in the window when aerogel is placed in the interspace between the glass layers (Table 3). Therefore, the thermal conductivity of silica aerogel granules is the main responsible for the glazing U-value, and the particle size has an impact on thermal performance of the glazing, as shown in the literature [14,16,31]. In particular, small granules allow a better performance than the larger ones: for instance, the thermal conductivity varies in the 19–21 mW/mK range at 10 °C, when the average particle size increases [31]. For these reasons, the measured U-value of DGU-AEROGEL is lower than the value of the glazing with the low-e coating and larger granules of aerogel in the interspace.

The reduction of the U-value due to the aerogel in the interspace with respect to DGU and LOW-E DGU samples is about 63% and 31%, respectively. The corresponding reduction in light transmittance (τ_v) is about 30% and 10%, respectively, due to the improved daylighting performance of granules type "B".

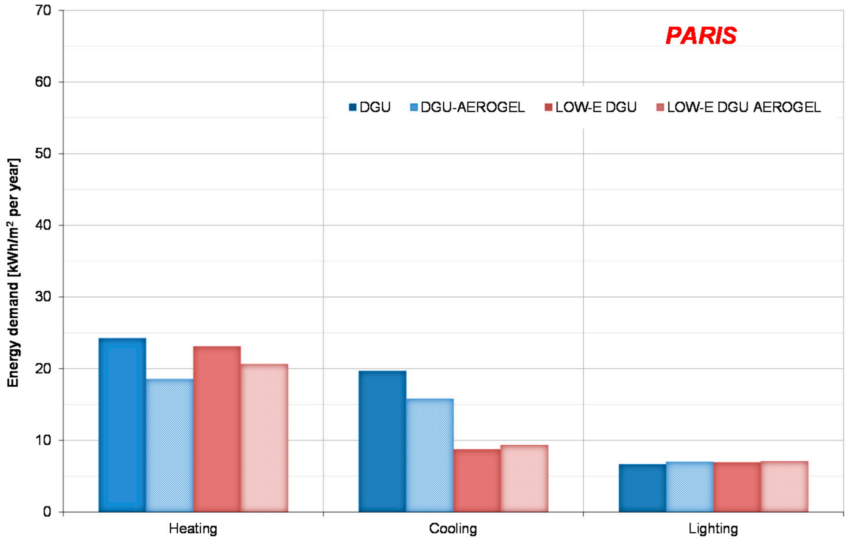
Finally, the total solar transmittance or solar factor (g) was estimated using the methodology suggested by the EN 410, based on the thermal properties of the samples and on the spectral reflectance and transmittance of the glazing and of the glass layers [32] (Table 3). For both windows, the presence of granules reduces the solar factor (12–39% reduction) due to the lower transmittance in the NIR range, reaching a value of 0.36 for the glazing with the solar control low-e glass (LOW-E DGU AEROGEL).

3.2. Energy Performance

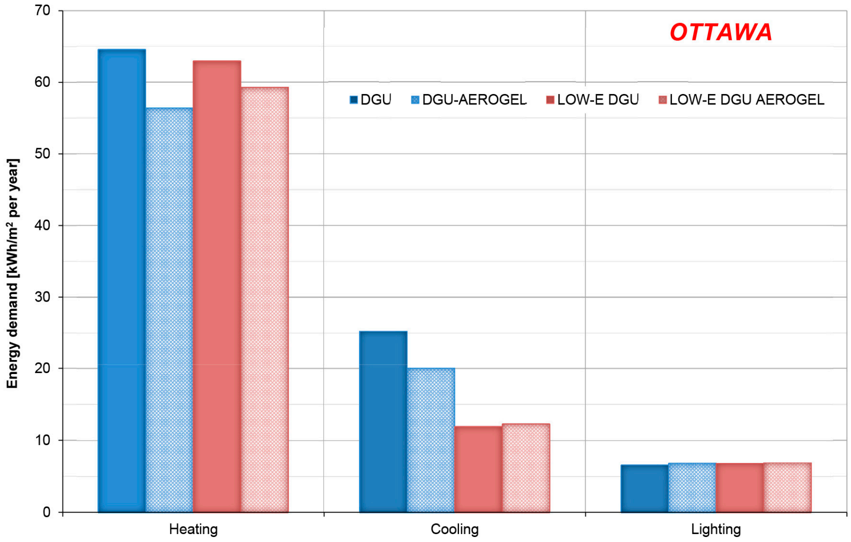
The influence of aerogel glazings on building energy performance was evaluated in terms of heating, cooling, and lighting energy demands, expressed in kWh/m^2: ideal energy loads were calculated by the software to meet the zone loads, without considering any equipment for heating, ventilation, and air conditioning in the simulations (Figure 8).



(**a**)



(**b**)



(**c**)

Figure 8. Heating, cooling, and lighting energy demand for the investigated glazings in Rome (**a**); Paris (**b**); and Ottawa (**c**).

Glazings with granular aerogel in interspace (DGU-AEROGEL) result in the most efficient systems for heating in all climate conditions: the reduction in energy demand is 13% for Ottawa, 24% for Paris, and 29% for Rome, when compared to the conventional glazing. The reduction is consistent with U- and g-values of the windows: in Ottawa (Figure 8c), with higher solar radiation, especially in the wintertime, the solar factor reduction diminishes the heat gain from the aerogel window, penalizing the overall result. For the same reasons, glazings with low-e coating have the worst behavior than the other solutions due to the lower g-value.

The annual cooling energy demand for DGU-AEROGEL decreases by a percentage from about 18% (Rome) to 21% (Ottawa) with respect to DGU. As expected, the energy demand for cooling is minimum for the glazing systems with low-e coating (LOW-E DGU and LOW-E DGU AEROGEL), due to the significant reduction in solar factor (i.e., 0.36–0.41): when compared to DGU, the reduction is in a range from 40% (Rome) to 56% (Ottawa). However, when the aerogel window is assembled with low-e glass, the benefits of the translucent material in the interspace are negligible, and the energy demands for cooling are quite similar.

In general, for building refurbishment, granular aerogel glazing systems could be considered a good solution in terms of annual energy demand reduction with respect to conventional double glazings, especially in warm climates. The results are in agreement with literature data [33,34]: Huang and Niu evaluated the influence of translucent aerogel glazing systems on the energy performance in humid subtropical cooling-dominant climates (Hong Kong). With respect to the reference case (conventional double glazing), aerogel glazing systems reduce the total annual space cooling load by around 4%, and the annual cooling load reduction was almost the same as the one achieved by low-e glazing, showing that silica aerogel glazings might be a suitable solution, also in cooling-dominated climates.

Finally, the energy demands for artificial lights are quite similar for all windows: the daylight illuminance on the working plane is higher than the recommended value (500 lux) for a large amount of time during the year, also for glazing systems with aerogel, due to the high window-to-wall ratio for the investigated building, and the increase in energy demand for the aerogel solution is negligible.

4. Conclusions

Different design options for windows have a large impact on the energy efficiency in highly glazed buildings: low thermal transmittance values can be crucial to ensure acceptable heating demand and low energy use; at the same time, the solar transmittance should be thoroughly evaluated, especially in warm climates. Among innovative glazing solutions, windows with granular aerogel in interspace seem to be the most promising, because of very low thermal transmittance, good daylight transmittance, and a remarkable light weight, and some translucent glazing systems are spreading in the market [7,8,18,34].

Two innovative glazing systems with silica granular aerogel in interspace were manufactured and investigated for building refurbishment by means of a thermal and lighting experimental campaign and energy simulations. Two types of granular silica aerogel (15 mm thickness with different particle sizes) and different glass layers (conventional float glass and solar control low-e glass) were considered, and the results were compared in order to evaluate the benefits of using innovative systems with aerogel in place of conventional solutions.

The aerogel impact on thermal properties is remarkable: the thermal transmittance is 1.0–1.1 $W/(m^2 \cdot K)$, lower than a glazing with low-e coating and a similar total thickness. With respect to the corresponding conventional windows, a 63% reduction in U-value was achieved for windows with clear float glasses, whereas, when assembled with a low-e glass, the reduction was lower (31%). Optical measurements with a large sphere apparatus allowed for an accurate optical characterization of the samples, which diffuse and scatter the light. When compared to conventional windows with the same external and internal glass layers, a very modest reduction in light transmittance (about 10%) was observed for large granules, whereas the reduction is significant (30%) for the small granules;

however, the τ_v value is suitable for daylighting (it is equal to 0.55). For both windows, the presence of granules reduces the solar factor (12–39% reduction), due to the lower transmittance in the NIR range.

The results of the preliminary energy simulations for this case study showed that the new aerogel glazing systems are a suitable solution for building refurbishment, thanks to low U-values and solar transmittance, also in warm climate conditions. Moreover, they allow for significant daylighting illuminance in buildings, improving visual comfort due to light diffusing, and could have energy demands for lights very similar to those of conventional solutions, especially in buildings with a high window-to-wall surface ratio. In general, translucent systems such as granular aerogel filled systems allow light to propagate uniformly within rooms, thus minimizing daylight problems, such as high contrast zones, and preventing glare, as shown in the literature [14,15,29]. Future studies should focus on the impact of aerogel systems on indoor visual comfort and on energy consumption for artificial lights in buildings.

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