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Energy consumption of hybrid Smart Water-filled glass (SWFG) building envelope

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Abstract

Thermal properties have significant impact on ecological footprint and life-cycle assessment of buildings. This is even more crucial aspect for glass buildings, which have been criticised as major factors in climate change around the world. Recent debates on glass facades, which culminated in plans for a "glass building ban" in New York City highlighted the importance of innovation in glass construction.
The current solutions for mitigating energy consumption for glass facades are improving insulation (U-value) and solar heat gain coefficient (SHGC) with advanced glazing or using shading devices. A fourth approach is the recent technology of water-filled glass (WFG), which utilizes water layer to improve thermal comfort and energy performance of the façade.
This paper introduces Smart Water-filled Glass (SWFG) control method, which enables the change of the opacity of the façade element by colouring the fluid over a year regarding seasonal changes. The impact of changing transparency of water layer on cooling and heating energy demand is evaluated by simulating and analysing the energy performance of a reference office room with large glazing facade in different climates.
The significance of this energy evaluation is that a water-filled glass with switchable transparency is simulated and assessed here for the first time. The paper analyses the performance in seven cities from all relevant major climatic regions using LBNL WINDOW and TRNSYS (v.18) As a novel approach, the simulation study makes it possible to evaluate the overall performance of two proposed operational methods (insolation-based & storage-based) for adjusting water layer settings depending on climate conditions and reusability of the captured heat in water layer. Moreover, seven different base cases are presented in this study to compare the performance of proposed system, including conventional solutions (e.g. double or triple glazing with/without shading) and a state-of-the-art switchable technology (e.g. electrochromic glazing or EC).
The results verify the hypothesis that the impact of SWFG compared to WFG varies depending on the climate with 0%-5.28% for hot climates and 0.25-3.39% for climates with heating demand. The discussion includes comparison with standard glass facades, where SWFG shows 47.41%-78.01% energy savings depending on climate. The climate-based approach of SWFG and WFG offers a significant shift in façade design that sees glass buildings as an opportunity for sustainability rather than liability for climate change.

Keywords:

Building sustainability, water-filled glass, glazing systems, solar control, energy-efficiency, glass buildings

1. Introduction

Environmental impact throughout the life-cycle of buildings is a significant contributing factor to climate change. Buildings contribute to 40% of total CO_2 emissions. [1] This is particularly true for glass buildings, which have higher operational energy demand due less effective insulation (U-value) and higher embodied energy because the utilisation of steel and glass on facades. This impact is driven by high-rise buildings further, which have higher glass-to-wall area ratio and higher energy demand [2]. Additionally, this is also represented in the increased demand of cooling in buildings, which is driven further by climate change and because the use of glass: energy consumption for cooling is estimated to contribute to 14% of all energy use and has been doubled since 2000. [1] In light of these developments, there is an emerging debate and criticism globally around glass facades and especially glass buildings with experts calling for stringent regulations for glass construction [3], which culminated in the "glass buildings ban" of the mayor of New York City as a response to global warming. [4] Additionally, from an embodied energy perspective, there is a tendency in building regulations that shift from an operational energy focus approach towards a life-cycle assessment (LCA) of buildings, for which the recent 'Energy Plus Construction Minus' (E+C-) approach in France is a clear example. [5] These developments show that there is a significant need for innovation in glass construction that can improve operational performance without negative impact on embodied energy.

Energy efficient strategies for glass facades can be divided into four groups, which either i) focus on insulation (U-value) typically by adding additional glass layers [6], ii) utilising some kind of shading or iii) improving the reflectance (Solar Heat Gain Coefficient or SHGC) by using coating that can be either permanent (e.g. Low-E [7]) or dynamic (e.g. electrochromic glazing or EC [8], suspended particle device window or SPD [9], or polymer dispersed liquid Chrystal or PDLC [10]). The fourth approach is to use a fluid medium in the glass, e.g. air, which may be ventilated towards inside [11] or outside [12] of the building. The other option for fluid is to use water, which has the advantage of absorbing large proportion of heat in the fluid layer that can be utilized by the mechanical system of the building [13]. An additional advantage of this technology is that water can be heated or cooled, which minimizes chances for discomfort.

Water-filled glass (WFG, shown in Figure 1) has been introduced first in 2007 [14], in 2009 [15] and was patented [16] by the author. The technology has been researched by other research groups in different aspects. P. Sierra and J. A. Hernandez introduced a mathematical model for dynamic U-value and SHGC of WFG windows [17]. T. Gil-Lopez and C. Gimenez-Molina presented annual energy consumption of the system for continental climate through prototype test and simulation [18]. T.T. Chow presented mathematical model for tropical climate [19] and L.Y. Liu et.al. evaluated the system for major climate regions in China [20]. Additionally, the author of this article built two experimental buildings with this technology: Water House 1.0 [21] in Hungary and Water House 2.0 [22] in Taiwan. These buildings were a further step in the development of the technology as they were constructed with an interconnected building envelope where water flow was enabled between panels and parts of the building as opposed to individual windows. This improved the thermal responses of the structure, which was introduced as trans-structural system [23]. Finally, the authors of this article published a global assessment of energy consumption of clear WFG envelopes [24]. The article goes beyond energy evaluation as it also presents the economic viability of the structure in terms of energy savings and costs in 13 cities. Although there is currently no market price for this technology available, the energy savings and their market value present a competitive return-on-investment (ROI) if we factor it against the additional material costs resulted by only the thickness of glass and necessary pipework. The experimental buildings were kept for a longer period which also presented that the system does not pose short term durability issues as the water is kept in a closed system, which offered sufficient protection with minimal maintenance.

The previous research projects explore the thermal and energy performance of WFG window and offer assessment on its impact on energy consumption. However, these projects did not explore the possibilities of changing transparency of WFG, which is significant because of four reasons. Firstly, an SWFG (WFG with changing transparency of water layer) has better absorption in water layer (with higher opacity levels), which may have direct impact on the energy performance of the system. Secondly, such switchable (dynamic) technology needs to be analysed from an operational standpoint, which would identify options for ideal opacity settings based on environmental conditions. Thirdly, such technology needs an evaluation from a climatic standpoint and should be assessed in all major climatic regions to evaluate the viability of the technology on a global scale. Finally, an analysis of SWFG gives the opportunity to compare water-filled glass envelope with other technologies like electrochromic windows or integrated semi-transparent photovoltaic panels (PV). This paper introduces the design and energy aspects of SWFG technology and analyses its impact with case studies in each major climate with a comparison to standard double glass, transparent water-filled glass (WFG) and electrochromic window (EC).

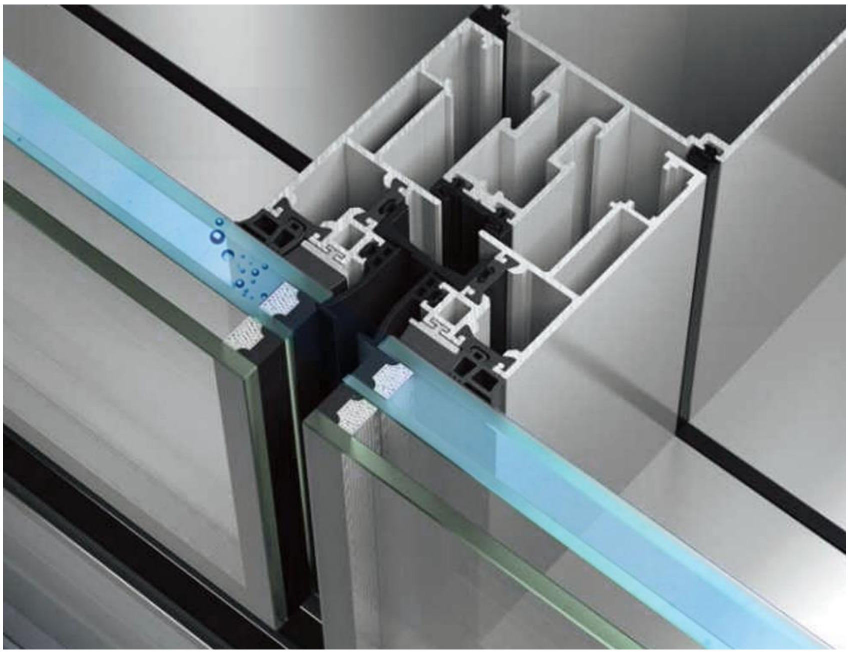

Figure 1: Water-filled glass (WFG) construction system, isometric diagram

2. Methodology

The methodology section of the article is divided into two major parts. The first part presents the design, climatic and operational aspects of the proposed water-filled glass technology that directly influenced the simulation model and the final results. The second part presents the dynamic simulation method, which is based on the physical properties of assigned construction and material to the reference office room, and defined simulation setups for heating, cooling, ventilation in TRNSYS. Besides, operational considerations are defined in simulation as they are presented in the previous chapter.

2.1. Design, Climate and Operational aspects of Smart Water-filled Glass (SWFG) envelope

2.1.1. Design aspects of Smart Water-filled Glass (SWFG)

In terms of construction and mechanical system, the design aspects of SWFG follow the same logic and decisions that were introduced for the simulation of WFG system in previous publication [24]. These can be summarised as following:

- Considering options for using double or triple glazing, the latter was chosen because of additional insulation capacity. This solution is more ideal also because of the heating-cooling function of WFG/SFWG and it protects the glazing from freezing and external condensation.
- The WFG/SWFG facade was designed without additional shading as the system was meant to use the colouring of the water for this effect (additional indoor curtains were added for shading but were ignored for the simulation). The standard glazing systems were used for comparison with or without shading (base cases).
- The heating-cooling source for the façade was ground coupling. The simulation used the ground temperature of the site as a reference for the tempering effect).
- The glass panes used for making WFG/SWFG system were assumed to be clear glass, which increased the opacity range of the system (between 0-40%). The standard glazing systems used for comparison (base cases: Base_2G and Base_SHGC0.2) has Low-E coating. This means that energy performance of the SWFG presented here can be further improved with coating or different glazing (e.g. absorption glazing).
- The thermal storage of the system was only assumed for heating of the building and the simulation counted captured absorption only for heating periods because the system has been considered with short-term thermal storage. (Other potential heat uses, such as domestic hot water (DHW) was not included in the model).

2.1.2. Climate considerations of SWFG

The simulation analyses the performance of SWFG in seven cities from four major Köppen-Geiger climatic regions between types A-D. Polar climate (type E) was not assessed because of two reasons: Previous research on WFG suggested that the system would not work effectively in such conditions [24]. Additionally, using darker glazing in an area with lower insolation seemed not to be viable.

The climate classification used Kottek revisions [25]. We used Ladybug EPW Map tool for the simulation. Location of the cities are shown in Figure 2 with additional information in Table 1.

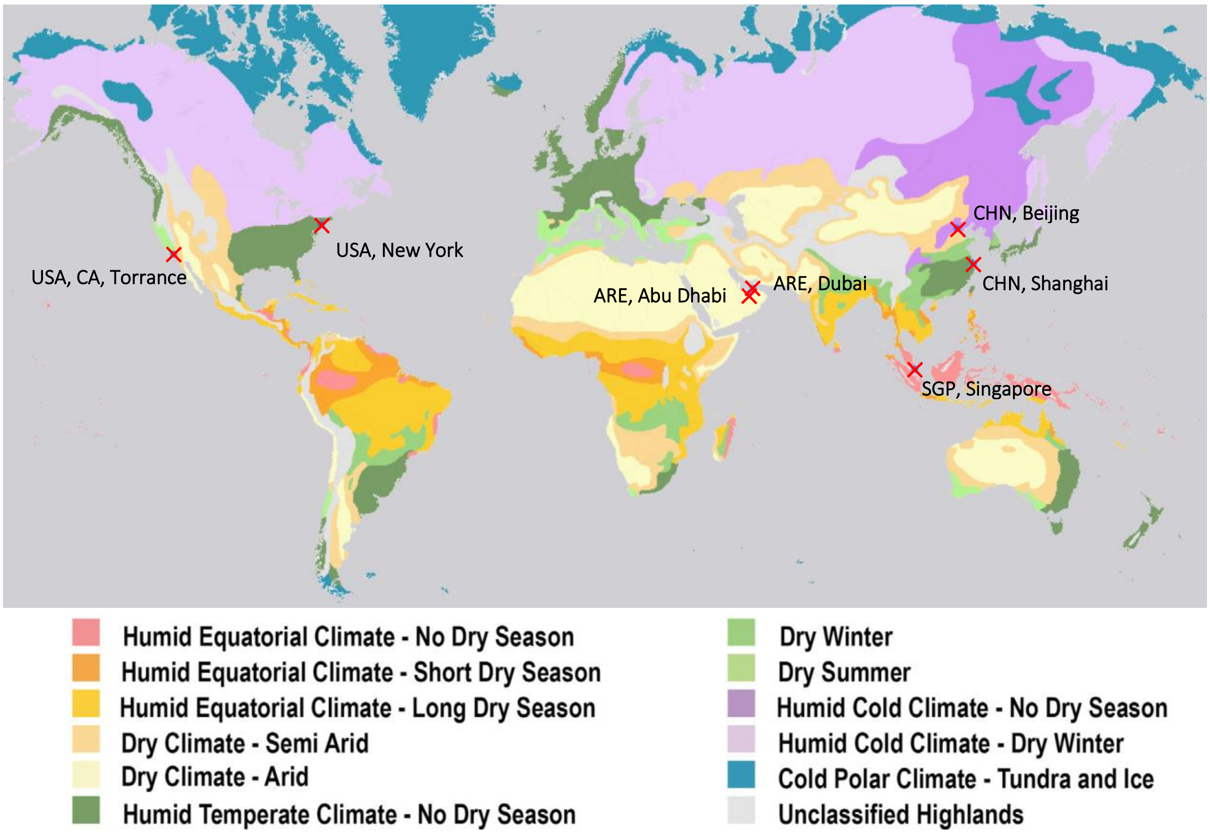

Figure 2. The selected seven cities shown on map with Köppen-Geiger climatic regions

Table 1: Climate classification of selected cities

City	Country	Latitude	Longitude	Altitude (m)	Avg. ground temperature (°C)	Climate
Singapore	Singapore	1.37	103.98	16	27.5	Af
Dubai	UAE	25.20	55.27	16	28.9	BWh
Abu Dhabi	UAE	35.41	51.19	1190	27.7	BWh
Torrance, California	United States	33.78	-118.32	27	16.3	Bsk
Shanghai	China	31.17	121.43	7	16.0	Cfa
New York	United States	40.78	-73.97	40	12.2	Cfa
Beijing	China	39.80	116.47	32	12.5	Dwa

2.1.3. Operational Considerations

The significant difference between WFG and SWFG is the change of transparency of the water layer, which raises the question of optimal operational opacity settings. The simulation counts with three possible settings: 0% (clear, pure water), 20% and 40% of dyeing, which looks similar to switchable electrochromic glazing systems. (Theoretically there is the possibility to set numerous opacity options between zero to above 90% opacity, but small changes would be neither visible nor would have a significant impact on energy performance.)

Based on the energy and importance of absorption (potential reuse of captured heat), the system may operate in two different ways:

- The captured energy is only beneficial for lowering cooling load because there is no significant demand for heating and the energy cannot be reused in the building. In this case the SWFG has more significant impact on visual comfort (shading) than energy performance. In such cases, the opacity settings follow the average solar intensity, which can be called *insolation-based approach*.

- The captured energy can contribute to heating and therefore generate further energy savings. In such cases the increased absorption with higher opacity settings becomes more relevant in the performance of the system, while an ideal balance had to be reached between optimum heat and natural illumination. Such settings can be called *storage-based operation.*

2.2. Annual Dynamic Simulation Setup

Precedent studies showed the potential of water layer as part of the glazing system as a solar collector to harvest solar heat gain [26, 27]. In this study, in order to evaluate the potential of WFG for different type of climates under smart control of water transmissivity, advanced dynamic simulation study was conducted in TRNSYS (v.18). Therefore, annual performance of a reference room (see Figure 3) with different WFG systems (static, no control of water transmissivity over a year) and SWFG system (dynamic with smart control of water transmissivity) were compared to different base cases. Different glazing systems were applied in the reference room and the annual simulated results were shown and discussed in section 3 (Results and Discussion).

Simulating the optical and thermal behaviour of water in glazing system is the main challenging part. For the annual simulation, window properties for every WFG configuration should be defined separately to be used in TRNSYS model. Using the state of the art modelling techniques for complex glazing systems (using BSDF data), it is possible to calculate the absorbed solar radiation and temperature for each layer and gap specifically [30].

The optical and thermal properties of water layer in WFG system (15 mm thickness) was defined as it was described by the authors in previous publication [24]. Based on the published optical properties of water layer, and its dynamic thermal behaviour (in the temperature range from zero to 50 °C) [28, 29] the inner water-filled cavity plus all other layers (glass panes and gaps) were modelled in LBNL WINDOW software (v.7.6). In this study, different base cases representing conventional systems (insulating double or triple glazing) and available switchable glazing technology (electrochromic glazing (EC)) were also modelled in LBNL WINDOW. Table 2 shows all the base cases including an insulating double glazing window (SHGC≥0.4) with and without shading control, a solar protection double glazing window (SHGC≤0.2), a triple glazing, and a switchable EC glazing with two or 4 settings.

For evaluating the overall performance of different façade systems, a reference room was defined as an office room with 17.50 m² floor area and a large glazing facing toward the equator (south orientated for north hemisphere). The dimensions were assumed 5.0 m length, 3.5 m width and 3.0 m height, of a standard office room for one occupant (Figure 3). The size of the window was assumed 3.3 m by 2.8 m (9.24 m² area). In this model, the U-value of 0.19 W/m²K was assumed for the only external wall (see Figure 3, green surface) on the south façade. And other walls, ceiling, and floor were assumed to be internal (adiabatic) with U-value of 0.3, 0.6, and 0.6 W/m²K respectively (see Figure 3, red surfaces). The properties of the façade systems (including U-vale) were considered in TRNSYS regarding the selected system for each simulation (see Table 2).

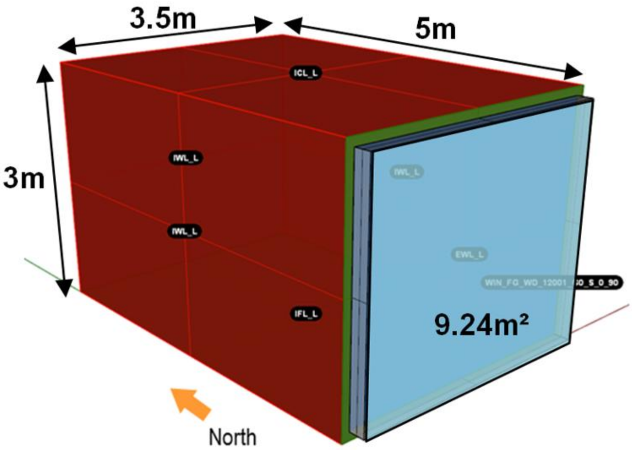

Figure 3: Reference room simulation model in TRNSYS

During the working hours (Mon-Fri: 8:00-18:00), 130 W/m^2 for a person, and 140 W/m^2 for a computer were applied in addition to artificial lighting gain of 5 W/m² (controlled by available daylight setpoint of 300-500 lx) in simulation as internal gains. The infiltration of the building was assumed n=0.25 ACH which increases during the working hours into n=1.45 ACH. In addition, a night ventilation (n=5 ACH) was assumed during summer (when room temperature is greater than outdoor temperature).
An ideal heating and cooling system were used with a cooling setpoint temperature of 25°C and a heating setpoint temperature of 21°C during the occupied hours. For the rest of the time building was controlled by applying some setbacks (29°C for cooling and 15°C for heating).

For the first three base cases, an insulating double glazing system with Low-E coating with U-value of 1.4 W/m²K and 0.62 SHGC value were assumed. This window without any shading (always clear) is called "Base_2G". For "Base_2G+AS" the same window was assumed by using an external automatic shading system. The shading system with 75% shading fraction (Fc = 0.25) was controlled during the simulation based on the total solar irradiation (IT) falling on the window surface (following DIN:4108-2 standard when IT ≥ 200 W/m²). The "Base_2G+PS" was also the same window but permanently (always) shaded. The "Base_2G+PS" case is not a feasible solution; however, it is useful since it represents a bench mark with minimum cooling demand.
According to some regulations for code compliant glazing system in cooling dominated climates, lower SHGC value is required. The " Base_SHGC0.2" is a double glazing with solar protection (SHGC = 0.2) and can be used as a good base case. The "Base_3G" represents a triple glazing with U-value of 1.2 W/m²K and 0.50 SHGC value. This case is actually with the same construction make up for WFG but without water (when the water is fully evacuated; see Figure 4).
As an additional base case, the "Base_EC" and "Base_EC_4st" are for an electrochromic glazing (EC) with two-step and four-step automatic control which represents the state-of-the-art switchable window technology in the market. The two-step radiation based control was applied to switch the EC from clear (T_{sol} 29%) into middle state (T_{sol} 2%) when the global radiation (IT) on the façade goes above the threshold (here 200 W/m²). The four-step illuminance based control was also used to switch the EC based on the available daylight in four different steps when the horizontal illuminance (E_h) on the workplace goes above the thresholds (here 600 lx, 800 lx, and 1000 lx).
In terms of appearance, SWFG is somewhat similar to electrochromic windows and building-integrated semi-transparent PVs, but there are some crucial differences. In case of electrochromic window, SWFG is capable to absorb heat, which can be reused later to increase energy savings further. Electrochromic windows only reflect heat and cannot profit from the heat surplus. This may bring significant advantage for SWFG in climates with significant heating demand, while in cooling dominated climates the performance of the two may be similar, which is why we choose this technology as a base case comparison. In case of integrated semi-transparent PV, SWFG shows some similarity with this technology because both profit from external solar load. However, SWFG can become transparent and integrated PV cannot, which would not make a fair comparison between the two.
Table 2 shows the performance of different base cases and Water-filled Glass (WFG) systems (with different water transmissivity).

Table 2: Thermal and optical properties of different base cases and Water-filled Glass systems (with different water transmissivity)

Case name	**Window Type**	**Glazing System Settings**	**Shading / switchable window Control**		**U_g [W/m^2K]**	**SHGC [%]**	**T_{sol} [%]**	**T_{vis} [%]**
Base_2G	Insulating double glazing (SHGC ≥ 0.4)	16 mm Gap filled with argon, Low-E	No extra shading, always clear		1.4	62%	43%	62%
Base_2G+PS		16 mm Gap filled with argon, Low-E	Always shaded (Fc = 0.25)		1.4	46%	32%	46%
Base_2G+AS		16 mm Gap filled with argon, Low-E	automatic 2-step Radiation based control when	IT<200 W/m² Clear	1.4	62%	43%	62%
				IT≥200 W/m² Shaded (Fc = 0.25)	1.4	46%	32%	46%
Base_SHGC0.2	Solar protection double glazing (SHGC ≤ 0.2)	16 mm Gap filled with argon, Low-E	No extra shading		2.16	20%	15%	20%
Base_3G	Triple glazing (WFG_air)	15mm Gap filled with air	No extra shading		1.2	50%	33%	51%
Base_EC	Electrochromic window (EC)	double glazing system 16 mm Gap filled with argon, Low-E	Automatic 2-step Radiation based control when	IT<200 W/m² Clear	1.3	43%	29%	44%
				IT≥200 W/m² Mid-tinted		16%	2%	4%
Base_EC4st			Automatic 4-step Illuminance based control when	E<600lx Clear	1.3	43%	29%	44%
				600lx≤E<800lx Low-tinted		21%	7%	12%
				800lx≤E<1000lx Mid-tinted		16%	2%	4%
				E≥1000 lx Full-tinted		14%	0.4%	0.7%
WFG_0%		15mm Gap filled with clear water,	Always clear water 0% dyed		2.9	55%	27%	44%

WFG_20%	Water Filled Glazing	15mm Gap filled with dyed water	Always 20% dyed water		54%	22%	35%
WFG_40%		15mm Gap filled with dyed water	Always 40% dyed water		52%	16%	26%

As Figure 4 shows, main construction make up for WFG system similar to a conventional triple glazing system with three glass panes and two cavities. The outer gap is 8mm thick and filled with Argon. The inner gap is 15mm thick and can be filled (or evacuated) with water. In order to evaluate the full potential of the WFG system, water filled glass system with three different shading effects were defined (pure vs. dyed water layer).
The 1st configuration (WFG_0%) is filled with clear water in the inner gap. This option is identical to transparent WFG panel and was also used later for comparing WFG with SWFG. The 2nd configuration (WFG_20%) and 3rd configuration (WFG_40%) have the same construction but the water is dyed for 20% and 40% opacity. The dying can increase the potential of the system for solar protection. Consequently, this leads to more absorption in the water layer which can provide more useful heat gain (during heating period) and more heat rejection (during cooling period).

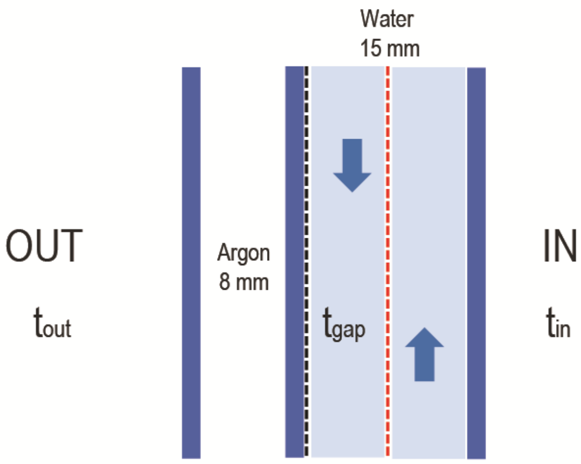

Figure 4: Layout of WFG. The simulation utilizes a virtual (dummy) layer (shown with red dashed line) that provides the absorption properties identical to the water layer with the given thickness.

In this study, the Q_{useful} kWh/m²a is an annual energy saving index for solar gain potential of the WFG system, which was used in previous publications [24]. The captured energy here refers to the absorbed heat during heating periods as this energy can be potentially reused for heating and lead to further energy savings. Captured heat outside heating period was ignored by the model because the simulation assumed no additional heat demand in the building (e.g. swimming pool). The unused heat is therefore absorbed by the ground during cooling periods.

Additionally, we verified these assumptions with measurements on absorption, which we used for simulation on energy consumption of transparent WFG [24]. We used a small prototype that can be filled with water (shown as Figure 5) to confirm the absorption overall and in visible spectrum in transparent state. We used LP Standard Pro Spectrometer. The thickness of the prototype was the same as the panel used for the simulation, including the thickness of the water layer (15mm). The absorption showed no difference in the visible spectrum.

Figure 5: The water-filled Glass prototype used for the measurements

3. Results and Discussion

The discussion of results is divided into three sections. The first section presents the annual consumption of the reference room with different types of façade systems (including base cases and WFG systems) for every city and assigns each climate into the two operation modes: 1) insolation-based or 2) storage-based operation. The final energy consumption will be determined based on the selected operation mode for smart controlling of the water transmissivity over a year (what is called SWFG). The second section presents detailed energy performance of the cities with insolation-based operation mode. Finally, the third section presents the annual energy performance of the cities with storage-based operation.

3.1. Overall annual energy consumption; base-cases versus WFG system

Figures 5-11 show the annual energy consumption of the reference room with different types of façade systems for each selected climate. Based on the performance of façade system and applied control strategy for using optional shading device, the final annual energy consumption for all cases were simulated. As described before, based on the climate conditions, insolation-based operation or storage-based operation might be found more effective.

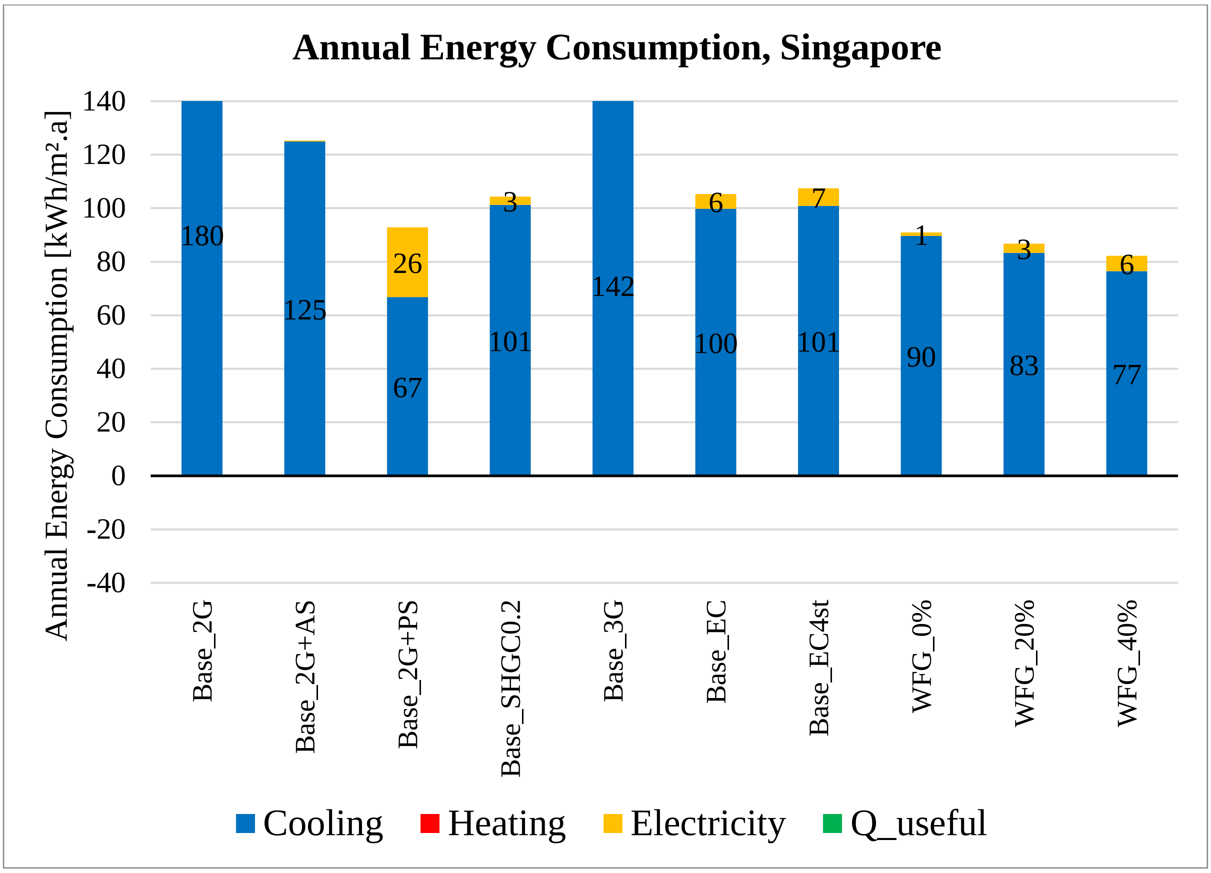

Figure 5: Energy consumption of the reference room in Singapore climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

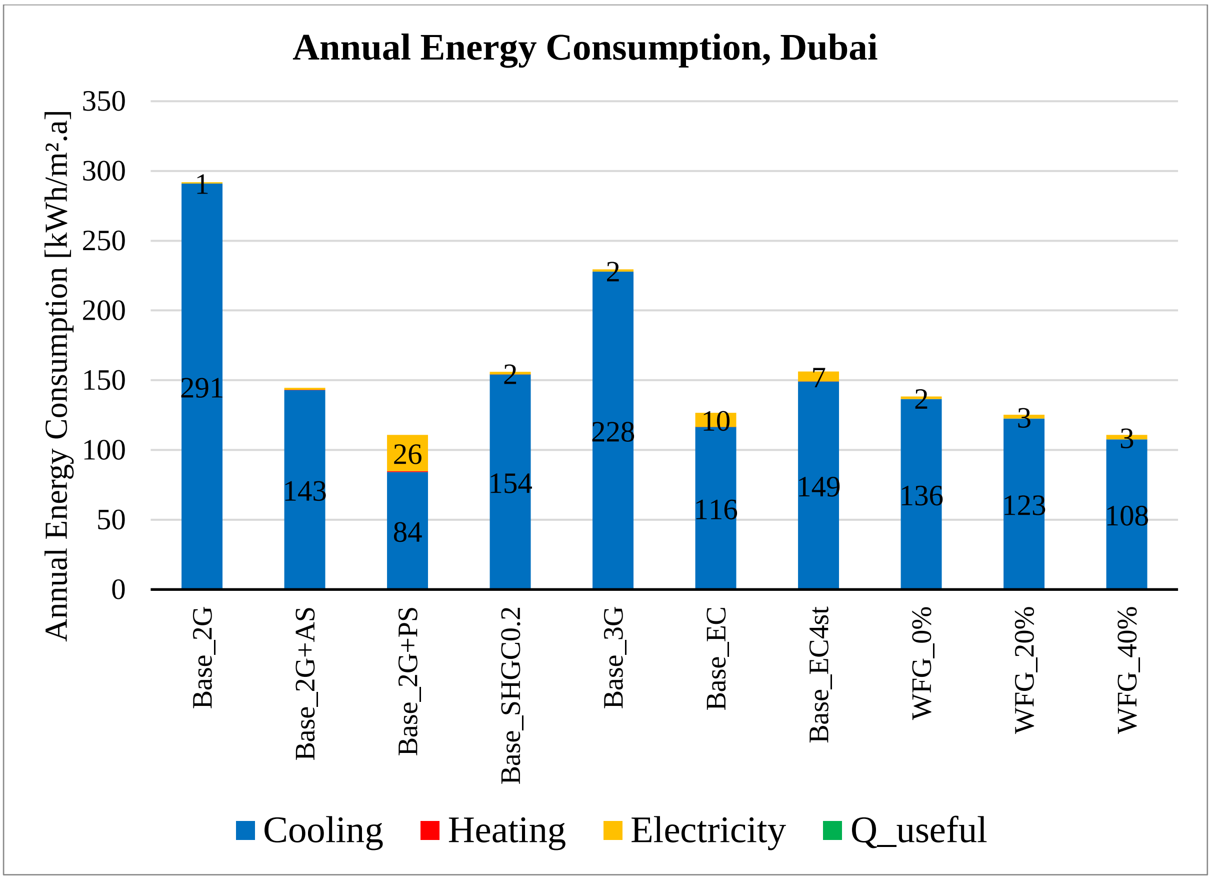

Figure 6: Energy consumption of the reference room in Dubai climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

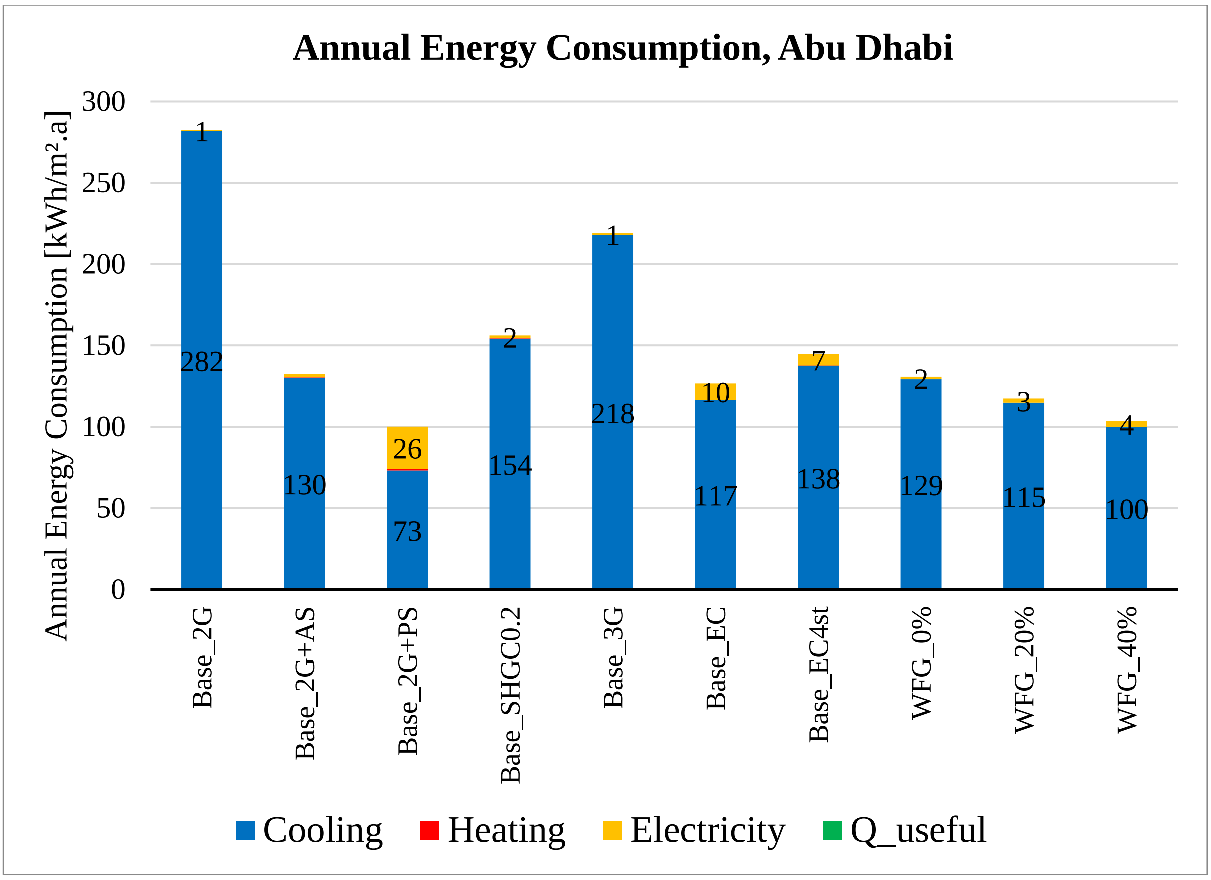

Figure 7: Energy consumption of the reference room in Abu Dhabi climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

The results in Figures 5 to 7 show the annual results of the simulations for three different cities with cooling dominant climates. One can see that the absorbed solar radiation in water layer in WFG systems cannot be used (Q-useful = 0) for Singapore, Dubai and Abu Dhabi since these climates do not have noticeable heating demand. Thus these cities were assigned to insolation-based operation.

The results also show that the cases without any shading (Base_2G and Base_3G) require the highest cooling energy. This fact indicates the impact of shading systems for such a reference room with large glazed area facade. Using a window with solar protection layer (Base_SHGC0.2 when SHGC≤0.2) helps to reduce cooling demand significantly. One of the efficient base cases was the double glazing window together with the automatic radiation-based shading device (Base_2G+AS). And finally, as expected the switchable EC provided the best performance (among base cases) and saved cooling energy considerably.

One can also see that the WFG systems performed very well compared to the acceptable base cases such as “Base_SHGC0.2” and “Base_2G+AS”. It is also clear that the performance of WFG systems with different water layer opacities (clear to dark, 0% to 40%) stayed somewhere close to the EC system with the ability to switch from fully-tinted to clear.

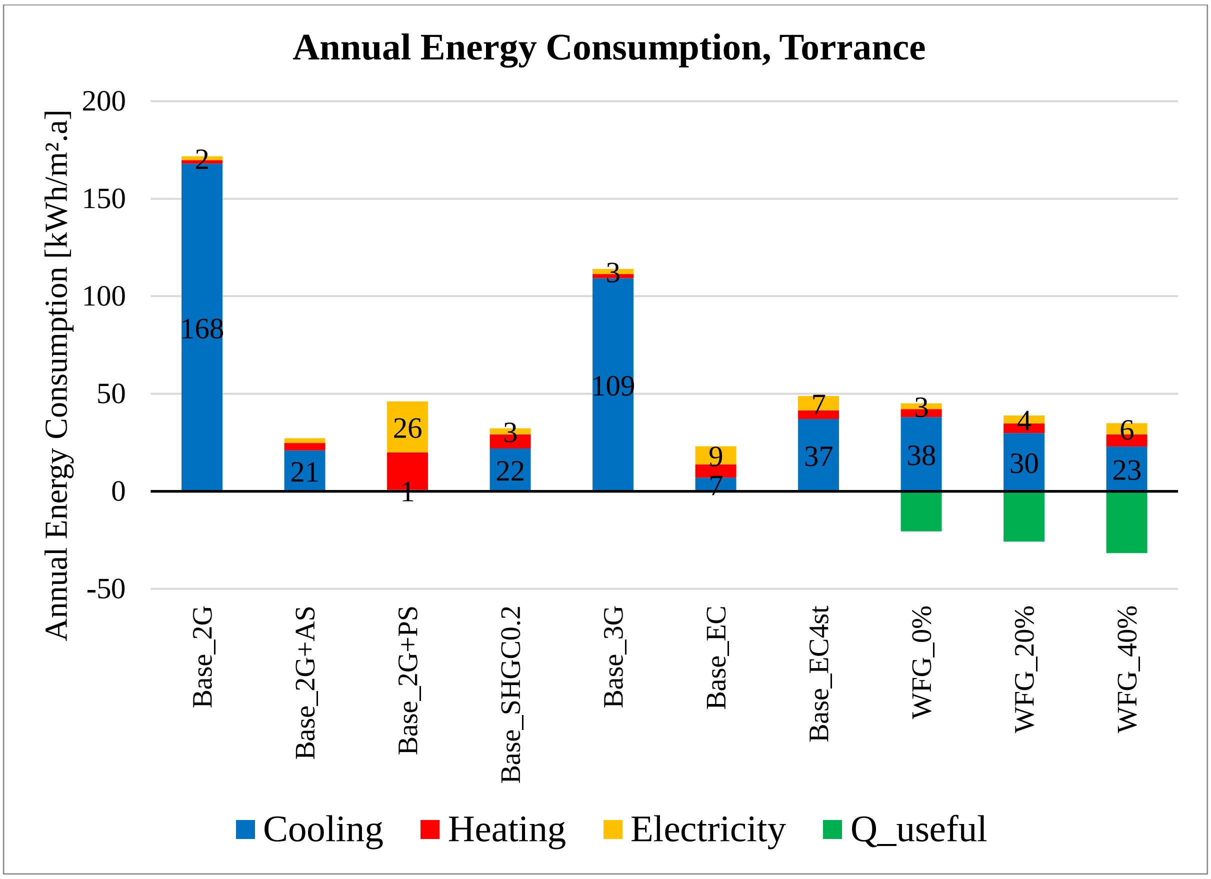

Figure 8: Energy consumption of the reference room in Torrance climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

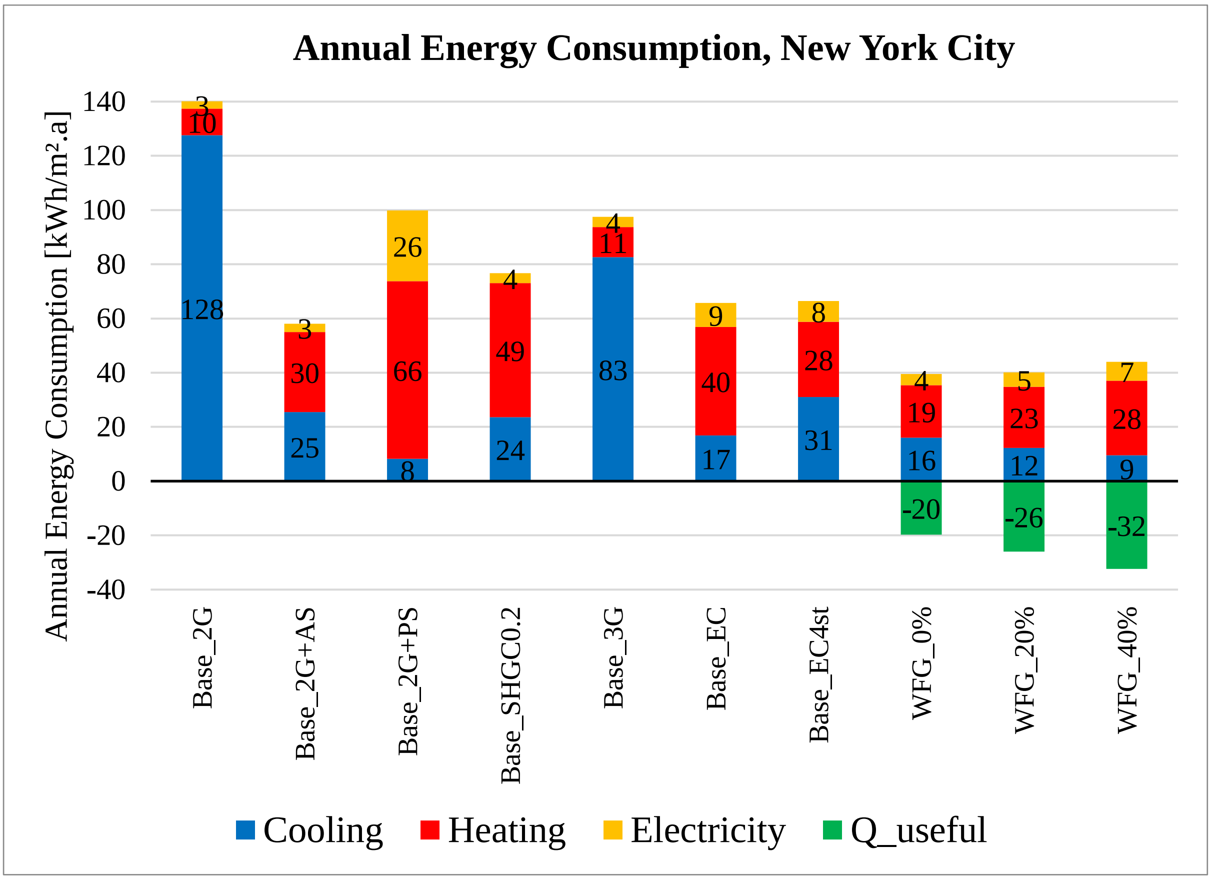

Figure 9: Energy consumption of the reference room in New York climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

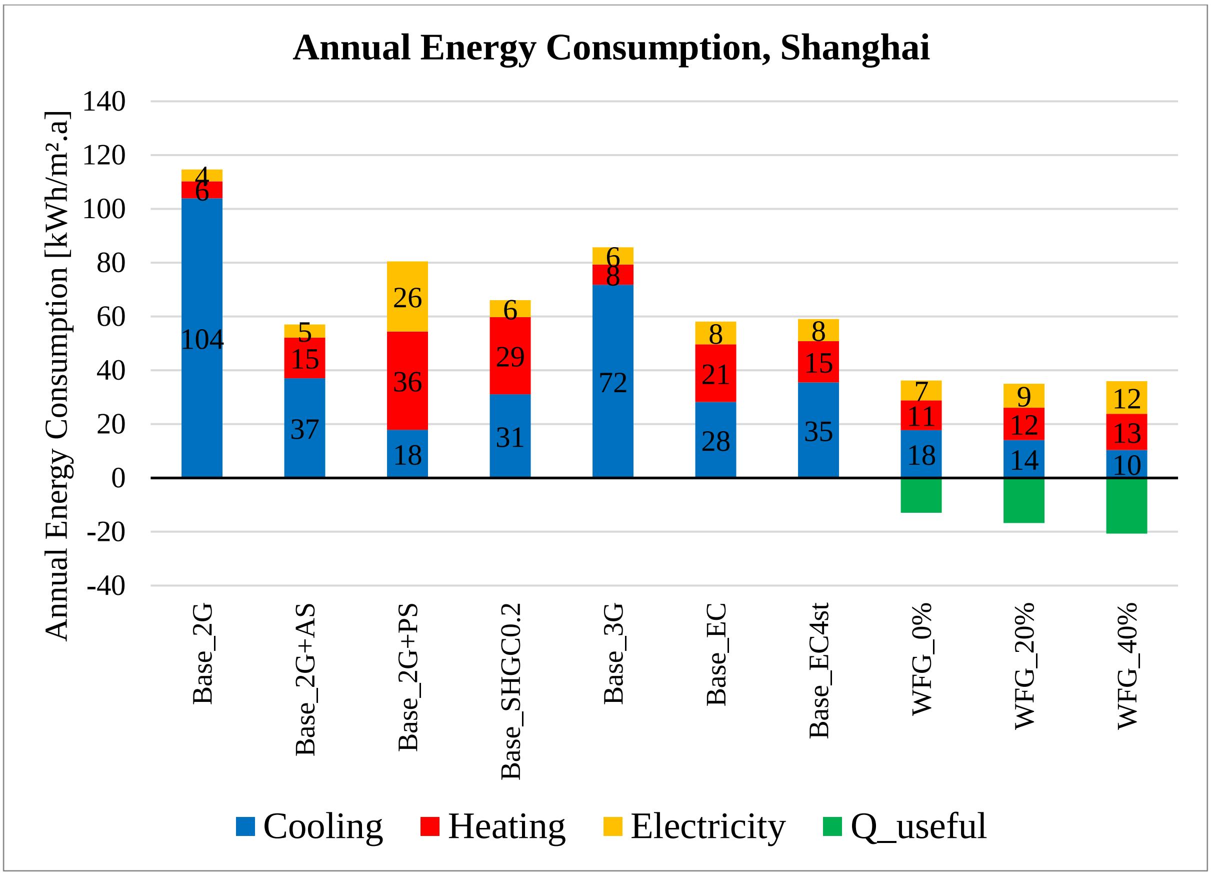

Figure 10: Energy consumption of the reference room in Shanghai climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

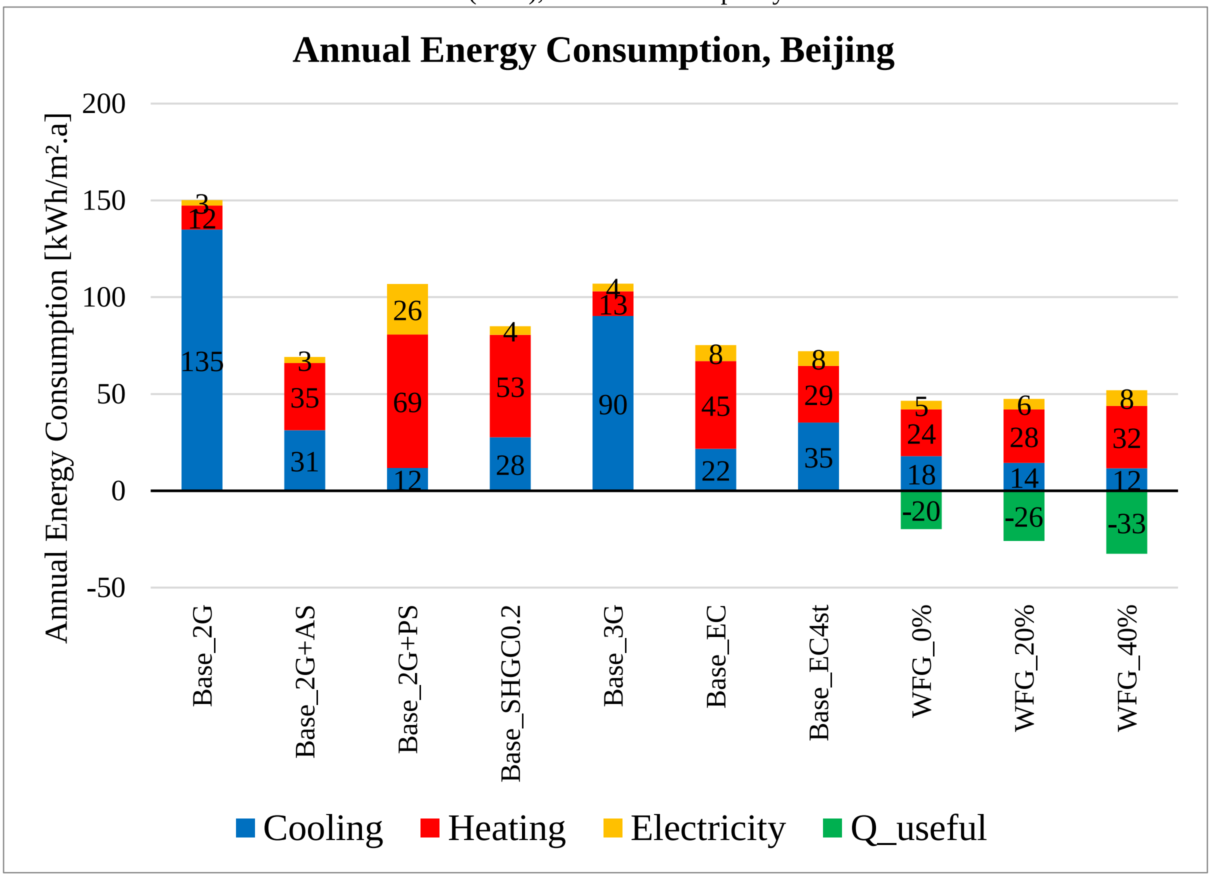

Figure 11: Energy consumption of the reference room in Beijing climate, showing base cases and WFG with 0% (clear), 20% and 40% opacity

Figures 8 to 11 show the annual results of the simulations for four different cities with both cooling and heating demands over a year. In these climate conditions the WFG systems were able to absorb useful amount of solar radiation in water layer (Q-useful) which can be used for preheating in order to reduce the overall heating demand of the building. In case of Torrance, the heating load was not considerable and this need can be covered even by using WFG system with clear water (WFG_0%). Meaning that changing transparency had no major benefits for heating energy saving. because of this, Torrance case was considered as insolation-based operation as well. The remaining three cities were assigned to the storage-based operation.

The results show that the cases without any shading (Base_2G and Base_3G) may lead to the highest cooling energy demand (and thus total energy demand). This fact showed the importance of shading systems in reducing energy even for a temperate climate conditions when the room has a large glazed area facade.

Using a window with solar protection layer (Base_SHGC0.2) helps to reduce cooling demand but also yields to an increasing heating demand. In these climate conditions, double glazing window together with the automatic radiation-based shading device (Base_2G+AS) and the switchable EC (Base_EC) performed the best.

One can see that the WFG systems performed very well compare to all base cases including “Base_EC” in New York, Shanghai, and Beijing. However, in Torrance both “Base_2G+AS” and “Base_EC” worked better than WFG systems. These results can be explained by considering the impact of applied Low_E coating in those cases, while the WFG configuration used in this study does not have a Low_E coating on the inner glass pane to avoid longwave radiative heat exchange from water layer toward the room. Additionally, EC with 4 states did not perform better than WFG or SWFG.

3.2. Energy consumption of WFG with insolation-based operation

Figures 12 to15 show the energy consumption of the WFG systems as stacked bar charts for the selected four cities (Singapore, Dubai, Abu Dhabi, and Torrance). The results indicate the energy consumption break-down for cooling (in blue), heating (in red), electricity for lighting (in yellow), and potential providing of useful heat gain in water layer (as Q_useful, in green) for every month over a year. As the figures show, the energy consumption correlated with the opacity and the darkest setting for WFG had the possibility to absorb more solar radiation and provide greater amount of Q_useful.

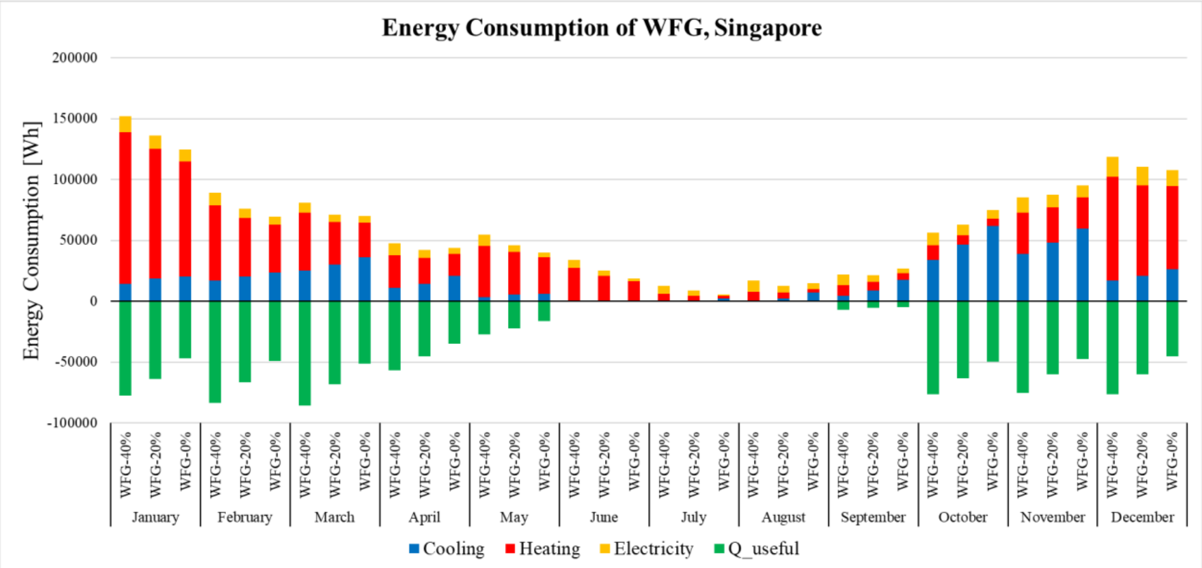

Figure 12: Heating, cooling and electricity energy consumption of WFG in Singapore climate, showing WFG with 0%/clear, 20% and 40% operation.
Detailed results are available on our Repository upload [31]

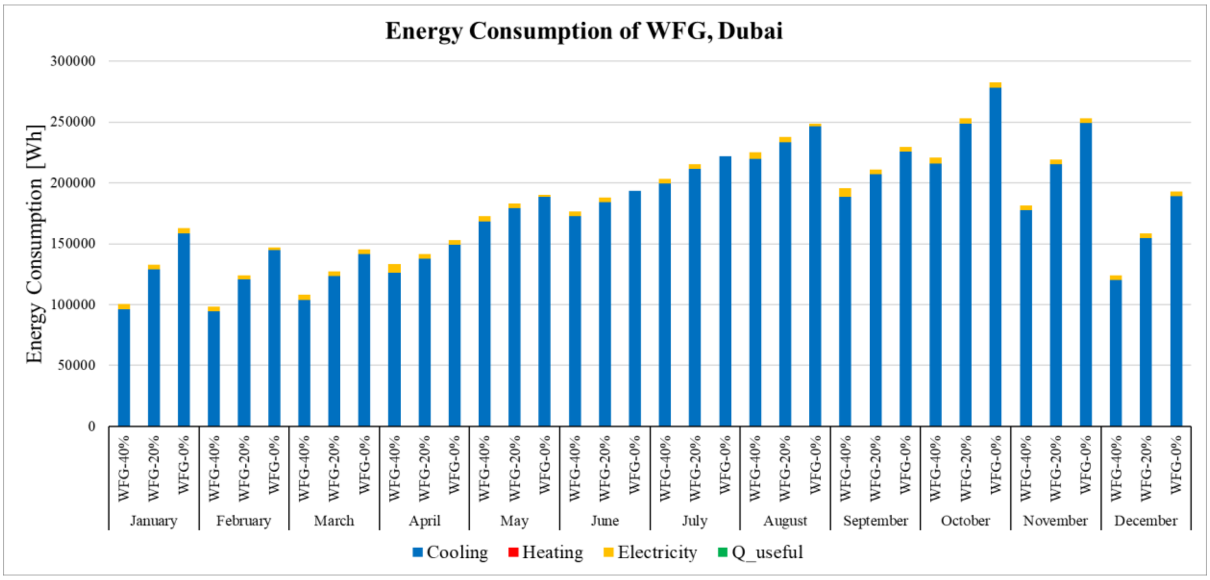

Figure 13: Heating, cooling and electricity energy consumption of WFG in Dubai climate, showing WFG with 0%/clear, 20% and 40% operation.
Detailed results are available on our Repository upload [32]

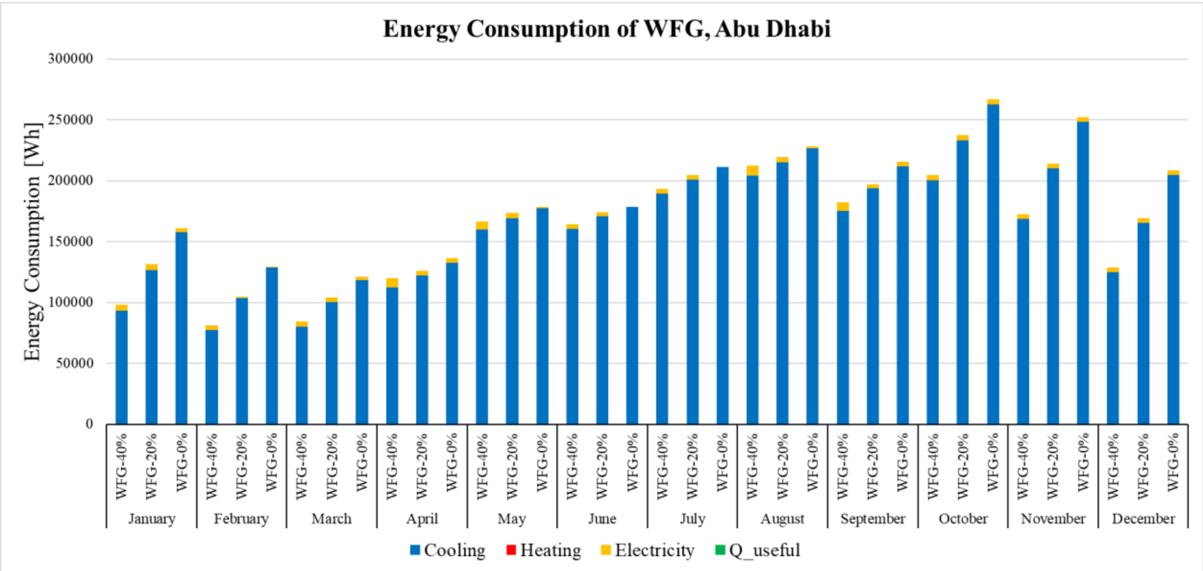

Figure 14: Heating, cooling and electricity energy consumption of WFG in Abu Dhabi climate, showing WFG with 0%/clear, 20% and 40% operation.
Detailed results are available on our Repository upload [33]

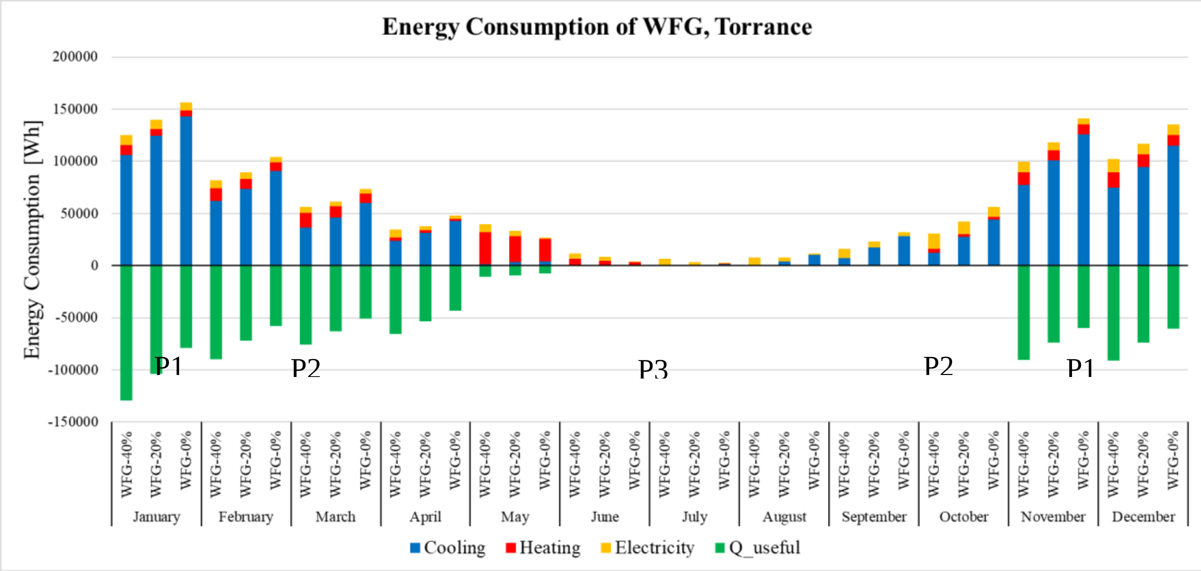

Figure 15: Heating, cooling and electricity energy consumption of WFG in Torrance climate, showing WFG with 0%/clear, 20% and 40% operation.
Detailed results are available on our Repository upload [34]

The results show that the ideal setting for these cities (Singapore, Dubai, Abu Dhabi, and Torrance) would be using WFG with 40% dyed water throughout the year. However, such setting would not be viable as it would undermine other functions of the glass façade (e.g. natural daylighting). Therefore, instead of keeping the opacity settings constantly dark (40%), the setting follows the change of insolation for the year to keep indoor available daylighting at a relatively sufficient level. This solution aligns with the fact that SWFG is less adaptive than EC in terms of changing transparency and therefore frequent changes in opacity are not desirable for the system.

To determine ideal insolation periods for the model of operation, as shown on Figure 16 we used daily average of global radiation over a year for Singapore, Torrance, Abu Dhabi, and Dubai as reference.

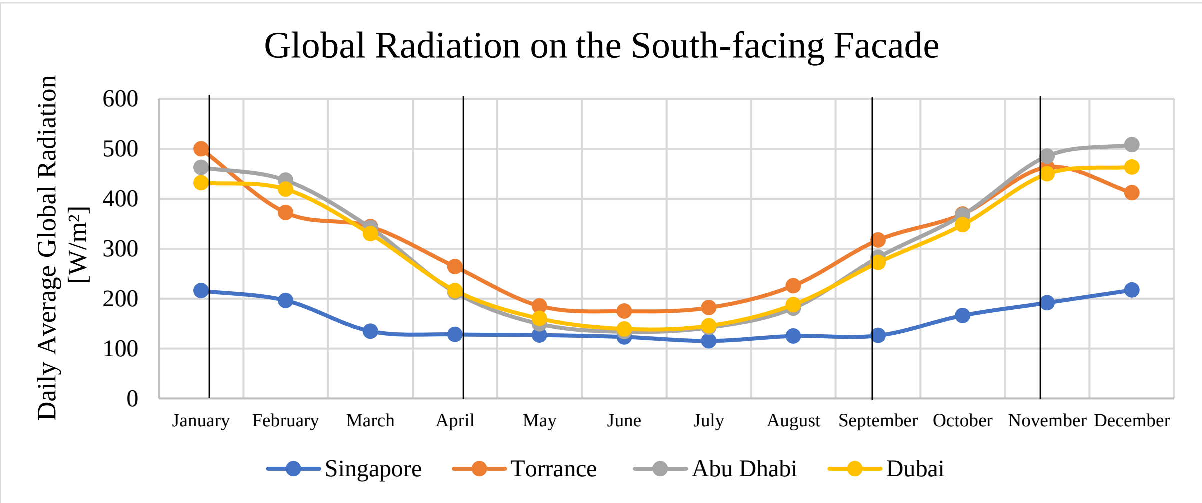

Figure 16: Monthly average solar radiation in Singapore, Torrance, Abu Dhabi and Dubai

The figure divides the year into four periods as following:

- November 15th – January 15th (P1): The solar intensity on the south-facing facade is the highest during this period and WFG was operated with 40% opacity in this case.
- January 15th – April 15th and September 15th – November 15th (P2): This period has average solar load and WFG was set for 20% opacity during this period.
- April 15th – September 15th (P3): This period has the lowest insolation on the south-facing facade. During this period the WFG system was operated for the clear state with 0% opacity. The energy savings of WFG and its absorption capacity even with clear water makes it

possible to operate the system with 0% opacity during this period, which is one of the most important advantages of the proposed system.

The calculation of total energy consumption was based on the determined periods above. Table 3 showed the annual energy consumption of SWFG with insolation-based scenario for each city. The results for Singapore, Dubai and Abu Dhabi were quite similar as expected. In case of Torrance, the results were different mainly because the energy consumption was significantly lower during summer time. This can be explained because much of the cooling demand due to solar gain was effectively mitigated by the absorption of the water layer in WFG system. Consequently, the overall energy consumption ended up being much lower. Figures 5 to 8 and 12 to 15 showed the absorbed energy in water layer (Q_useful), as it offers the possibility for further energy savings e.g. for domestic hot water supply or swimming pool. However, these options were not considered in our TRNSYS model specifically, but the Q_useful was used as a source for pre-heating to lower the heating demand.

Table 3: Annual energy consumption of SWFG (WFG with changing transparency) for Singapore, Dubai, Abu Dhabi and Torrance climate with insolation-based operation.
Detailed results are available on our Repository upload for Singapore [31], Dubai [32], Abu Dhabi [33] and Torrance [34]

Period		**Operational Opacity**	**Total annual energy consumption (Wh)**			
			Singapore	**Dubai**	**Abu Dhabi**	**Torrance, CA**
January	1st - 15th	clear (0%)	62674	42931	53512	61754
	16th - 31st	20%	64362	75542	61809	63658
February	1st - 28th	20%	112282	124109	104575	79964
March	1st - 31st	20%	116729	127300	104138	50501
April	1st - 15th	20%	56924	67161	54978	20543
	16th - 30st	40%	70847	79498	76257	19657
May	1st - 31st	40%	142046	190268	178686	19093
June	1st - 30th	40%	132589	193535	178588	3506
July	1st - 31st	40%	139887	222113	211209	2166
August	1st - 31st	40%	139039	248614	228132	11789
September	1st - 15th	40%	56481	112921	102896	17558
	16th - 30th	20%	53967	106501	102177	10423
October	1st - 31st	20%	133368	252850	237404	42127
November	1st - 15th	20%	62367	114336	114030	43985
	16th - 30th	clear (0%)	63495	85770	78744	53281
December	1st - 31st	clear (0%)	111858	124124	128641	87984
Annual energy consumption (kWh):			**1518.92**	**2167.57**	**2015.78**	**587.99**
Annual energy consumption ($kWh/m^2.a$):			**86.80**	**123.86**	**115.19**	**33.60**

3.3. Energy consumption of SWFG with storage-based operation

Figures 17 to 19 show the annual energy consumption for the other three cities (New York, Shanghai, and Beijing). The overall energy consumption was depended highly on solar absorption in water layer and its ability to reduce both cooling and heating demand. As the figures presented, the energy demand for heating became zero for most of the period because the captured heat in water layer was sufficient to cover it. This means that the opacity setting for heating during winter can be regulated because even a lower absorption can be already sufficient (it is not necessary to operate always with 40% opacity). Changing to lower opacity (0% or 20%) is also ideal for daylight provision since the insolation is the lowest for this period. Based on these facts, the year was divided into four periods (as shown on Figure 17) for the storage-based operation method:

- November 15th – January 15th (P1): The heating demand was the major energy need in this period. The energy consumption for each opacity scenario was relatively close (the captured energy increases with higher opacity, but the heating and electricity demand increases as well because of lower indoor solar gain and available daylight). The ideal opacity level for SWFG during this period can be considered 40%, which may lead to a better thermal comfort and energy performance, especially considering that the highest amount of solar gain and daylighting is during this period.
- January 15th – April 15th and September 15th – November 15th (P2): This period was characterised with high absorption levels and minor heating demand. The ideal operational opacity for this period depended on energy consumption (not just heating but also cooling and electricity). In respect of these, the 20% option was an ideal operation for this period.
- April 15th – September 15th (P3): This period has lower heating and cooling energy consumption for WFG than the rest of the year. The actual energy consumption was very close for different opacity settings; therefore the regulation of opacity should not be determined clearly from energy perspective. The ideal opacity was set to 0% because the solar intensity was lower than the rest of the year.

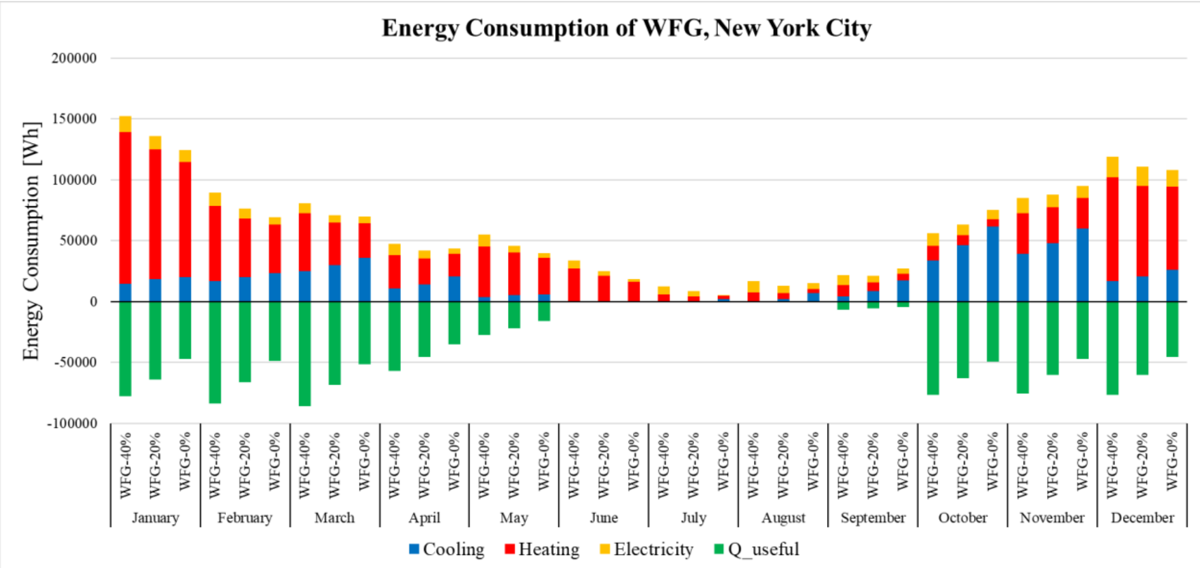

Figure 17: Heating, cooling and electricity energy consumption and captured (useful) heat of WFG in New York climate, showing SFWG with 0%/clear 20% and 40% operation.
Detailed results are available on our Repository upload [35]

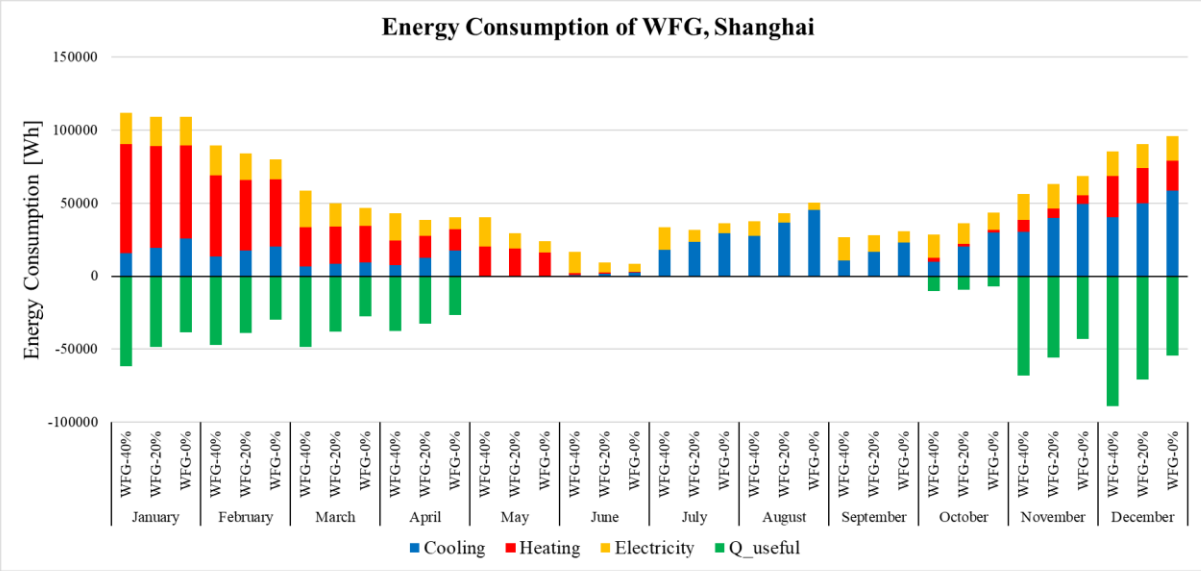

Figure 18: Heating, cooling and electricity energy consumption and captured (useful) heat of WFG in Shanghai climate, showing WFG with 0%/clear, 20% and 40% operation.
Detailed results are available on our Repository upload [36]

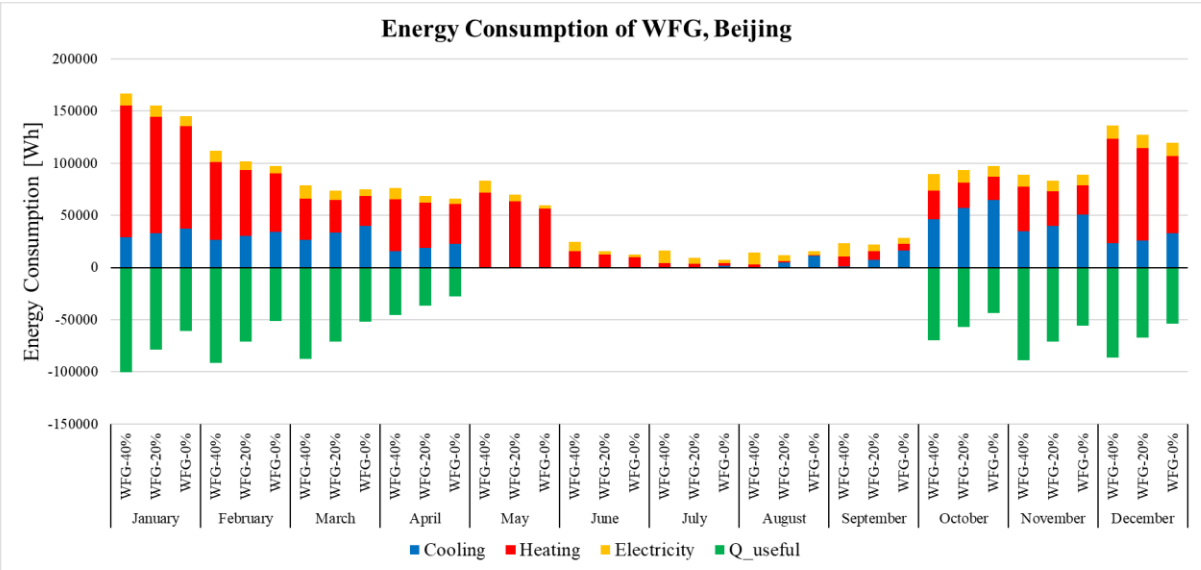

Figure 19: Heating, cooling and electricity energy consumption and captured (useful) heat of WFG in Beijing climate, showing WFG with 0% /clear, 20% and 40% operation.
Detailed results are available on our Repository upload [37]

Figure 17 to 19 show that the energy consumption was low from April 15th till September 15th (P3 period). This was the period when the absorbed energy in water layer may not be used to lower overall energy consumption because there was no significant heating demand. The energy performance during this period can be assumed very similar to the cities with insolation-based operation method; because Q_{useful} (absorbed solar gain in water layer) is zero during summer. During this period, the absorbed heat in water layer also helped the cooling demand to be decreased significantly. The overall energy load was lowest for 0%/clear scenario and highest with 40% opacity. This is mainly due to the higher electricity consumption when darker setting was applied (more supplemental artificial lighting), which made relatively small difference between the three options.
In the remaining part of the year, the total energy consumption increases for each scenario, which is caused by the increasing demand for cooling and heating. Both demands increase with higher opacity. The absorbed energy can be used for heating, which reverses the order between the three scenarios:

40% has the lowest energy consumption (with highest absorption) and clear/0% has the highest. The Figures show that the absorbed heat (Q_{useful}) covers the heating demand ($Q_{heating}$) between February-April and September-November for each scenario. These 'free heating' periods are the longest with 40% setting and shortest with 0%/clear scenario, which creates a difference between the three options.

Table 4 shows the annual energy consumption of SWFG with storage-based operation methods for each city. As expected, Beijing is the highest, which is caused by higher heating demand compared to Shanghai and New York. Just like in case of Torrance earlier, the model calculated absorbed energy (Quseful) during heating demand only (Qheating) Any additional captured energy was ignored in the energy balance shown in the Table below.

Table 4: Annual energy consumption of SWFG for New York City, Shanghai and Beijing climate with storage-based operation.
Detailed results are available on our Repository upload for New York [35], Shanghai [36], and Beijing [37]

Period		**Operational Opacity**	**Total annual energy consumption (Wh)**		
			New York	**Shanghai**	**Beijing**
January	1st - 15th	clear (0%)	50413	20373	23174
	16th - 31st	20%	25752	48911	52450
February	1st - 28th	20%	28019	45224	38317
March	1st - 31st	20%	36459	24557	42342
April	1st - 15th	20%	8558	13748	20378
	16th - 30st	40%	14822	10754	35049
May	1st - 31st	40%	23962	23955	60005
June	1st - 30th	40%	18573	8440	12457
July	1st - 31st	40%	5464	36385	7474
August	1st - 31st	40%	15023	50529	15755
September	1st - 15th	40%	8991	21626	10737
	16th - 30th	20%	10247	8884	11898
October	1st - 31st	20%	55251	34299	68974
November	1st - 15th	20%	42312	19029	23862
	16th - 30th	clear (0%)	15630	31253	25347
December	1st - 31st	clear (0%)	58715	66684	49700
Annual energy consumption (kWh):			**418.19**	**465.65**	**497.92**
Annual energy consumption (kWh/m².a):			**23.90**	**26.55**	**28.45**

3.4. Comparison of WFG and SWFG scenarios

The final results are summarized in Table 5 and Figure 20 for each city. The results show that the SWFG saves more energy than transparent WFG (WFG_0%) and has significant energy savings compared to standard window technology (Base_2G).

The data shows that the changing transparency of SWFG has different impact on each climate condition. Compared to the standard double glass window (Base_2G), the energy savings are between 47.41-78.01% depending on location. This shows significant energy savings for every studied climate. The Table 5 also shows that this is not always the case if SWFG is compared with WFG_0%. In case of cities with insolation SWFG performed slightly better showing Abu Dhabi (5.28%) the highest, followed by Dubai (4.83%) and Torrance (3.47%). In case of Singapore, the performance was almost the same (-0.24%). In case of storage-based climates, the energy consumption was slightly higher for SWFG than WFG_0% (-2.15%, -1.77% and -1.72% for New York, Shanghai and Beijing respectively). This was because the absorbed energy (Q_useful) was not used to lower energy consumption (i.e. for domestic hot water or heating). In that case the energy consumption would have been lower for both WFG_0% and SWFG and the difference between the two would be higher. In case the absorbed energy is used to lower heating load, the energy savings for most of the insolation-based cities (Singapore, Abu Dhabi, Dubai) do not change since there is no heating demand that would have effect on the results. In case of Torrance, there is low heating demand, which is covered both by WFG_0% (71.77%) and SWFG (75.59%) effecting both energy savings and the difference between the two (3.81%). As it can be expected, the energy savings increase for storage-based scenarios and savings in all three cities increase at least by 10%: New York (77.76% and 78.81%), Shanghai (63.09% and 62.06%) and Beijing (74.57% and 77.96%). The difference between WFG and SWFG does not change significantly however: New York is almost the same (0.25%), Shanghai is still negative (-1.03%) and Beijing shows slight difference (3.39%). This is because WFG_0% already absorbs sufficient heat to cover the heating demand and therefore the additional absorption of SWFG cannot be utilized effectively for further energy savings. All the simulation results are not shown in the Table 5, and we included them in our upload file in Research Repository of Loughborough University. [38]

Considering the results, it can be concluded that insolation-based countries are less viable for SWFG technology because the energy savings are minimal, which would not justify economic viability of changing transparency. In these climates, transparent WFG seems already a sufficient scenario. In case of storage-based climate, SWFG technology can have better viability than WFG if the additional absorbed heat can be used effectively. Both WFG and SWFG perform significantly better than double glass window (Base_2G) in any climate.

Table 5 and Figure 20 show the economic value of energy savings for each city. (ROI was not calculated as the market price of WFG or SWFG is not known yet). The following coefficients of performance (COP) were assumed for calculating the total end-use energy (site energy): COP =1.0 for artificial lighting (electricity), COP = 4.2 heat pump system (for heating), and COP = 4.0 chiller system (for cooling). And in order to convert site-energy to source-energy (primary) constant primary energy factor (f_P) equal to 3.31 was considered for electricity (EN 15603). Finally, the total annual carbon dioxide emission was estimated in this study by considering the specific CO_2 emission factor equal to 0.469 $KgCO_2e/kWh$ for electricity production mix factor in Germany (carbonfootprint.com). One may argue that these factors should be considered individually based on the selected cities and energy production situation in those locations. However, for the sake of compression in this study, it seemed reasonable to use the same energy factors for all different locations.

Table 5: The total annual energy consumption, CO_2 emission, and annual electricity cost for base cases, WFG and SWFG system for seven cities
Please follow our Repository upload for detailed Excel data [38]

City	Glass	Case Name	Total Annual Energy Intensity [kWh/m².a]	Primary Energy [kWh/m².a]	CO_2 Emission [KgCO2e/m².a]	Electricity cost [US$/m².a]	Electricity cost factor [US$/kWh]	Savings compared to Base case (B_2G)
Singapore, SIN	B_2G	Base case: always clear	**180.7**	**150.3**	**70.5**	**27.0**	**0.18**	**0.00%**
	B_2G+PS	Base case: permanent shading	**125.3**	**104.6**	**49.0**	**18.8**		**30.40%**
	B_2G+AS	Base case: controlled shading	**92.9**	**141.7**	**66.4**	**25.5**		**5.72%**
	B_SHGC0.2	Base case: low SHGC	**104.4**	**94.0**	**44.1**	**16.9**		**37.41%**
	B_3G	Base case: Triple glass	**143.1**	**120.0**	**56.3**	**21.6**		**20.13%**
	B_EC	Base case: Electrochromic	**105.3**	**100.9**	**47.3**	**18.2**		**32.87%**
	B_EC4st	Base case: Electrochr. 4states	**108.0**	**106.7**	**50.1**	**19.2**		**28.95%**
	WFG_0%	Water-filled Glass	**91.0**	**78.7**	**36.9**	**14.2**		**47.65%**
	SWFG	Smart Water-filled Glass	**86.8**	**79.0**	**37.1**	**14.2**		**47.41%**
Dubai, UAE	B_2G	Base case: always clear	**291.9**	**243.9**	**114.4**	**22.0**	**0.09**	**0.00%**
	B_2G+PS	Base case: permanent shading	**144.5**	**123.1**	**57.7**	**11.1**		**49.56%**
	B_2G+AS	Base case: controlled shading	**110.9**	**156.6**	**73.4**	**14.1**		**35.82%**
	B_SHGC0.2	Base case: low SHGC	**156.1**	**133.9**	**62.8**	**12.0**		**45.13%**
	B_3G	Base case: Triple glass	**229.5**	**193.9**	**91.0**	**17.5**		**20.50%**
	B_EC	Base case: Electrochromic	**126.7**	**129.7**	**60.8**	**11.7**		**46.84%**
	B_EC4st	Base case: Electrochr. 4states	**156.0**	**146.5**	**68.7**	**10.7**		**51.16%**
	WFG_0%	Water-filled Glass	**138.3**	**119.1**	**55.9**	**10.7**		**51.16%**
	SWFG	Smart Water-filled Glass	**123.9**	**107.4**	**50.4**	**9.7**		**55.99%**
	B_2G	Base case: always clear	**282.5**	**235.8**	**110.6**	**21.2**		**0.00%**

	B_2G+PS	Base case: permanent shading	**132.4**	**114.6**	**53.8**	**10.3**	**0.09**	**51.38%**
	B_2G+AS	Base case: controlled shading	**100.2**	**147.7**	**69.3**	**13.3**		**37.38%**
	B_SHGC0.2	Base case: low SHGC	**156.3**	**134.0**	**62.8**	**12.1**		**43.18%**
Abu Dhabi, UAE	B_3G	Base case: Triple glass	**219.1**	**184.7**	**86.6**	**16.6**		**21.69%**
	B_EC	Base case: Electrochromic	**126.7**	**129.7**	**60.8**	**11.7**		**45.00%**
	B_EC4st	Base case: Electrochr. 4states	**145.0**	**137.4**	**64.4**	**12.4**		**41.75%**
	WFG_0%	Water-filled Glass	**130.8**	**112.3**	**52.7**	**10.1**		**52.38%**
	SWFG	Smart Water-filled Glass	**115.2**	**99.8**	**46.8**	**9.0**		**57.66%**
	B_2G	Base case: always clear	**171.8**	**147.3**	**69.1**	**24.6**		**0.00%**
	B_2G+PS	Base case: permanent shading	**27.2**	**28.6**	**13.4**	**4.8**	**0.17**	**80.58%**
	B_2G+AS	Base case: controlled shading	**46.0**	**102.1**	**47.9**	**17.1**		**30.68%**
	B_SHGC0.2	Base case: low SHGC	**32.3**	**34.2**	**16.0**	**5.7**		**76.81%**
	B_3G	Base case: Triple glass	**114.0**	**100.9**	**47.3**	**16.8**		**31.53%**
	B_EC	Base case: Electrochromic	**23.1**	**42.0**	**19.7**	**7.0**		**71.53%**
	B_EC4st	Base case: Electrochr. 4states	**48.0**	**56.9**	**26.7**	**9.5**		**61.37%**
	WFG_0%	Water-filled Glass	**45.2**	**44.8**	**21.0**	**7.5**		**69.58%**
Torrance, CA	SWFG	Smart Water-filled Glass	**37.2**	**39.7**	**18.6**	**6.6**		**73.06%**
	B_2G	Base case: always clear	**140.1**	**122.3**	**57.3**	**25.7**		**0.00%**
	B_2G+PS	Base case: permanent shading	**58.1**	**54.4**	**25.5**	**11.4**	**0.21**	**55.47%**
	B_2G+AS	Base case: controlled shading	**99.9**	**144.8**	**67.9**	**30.4**		**-18.48%**
	B_SHGC0.2	Base case: low SHGC	**76.7**	**70.7**	**33.1**	**14.8**		**42.19%**
	B_3G	Base case: Triple glass	**97.5**	**89.6**	**42.0**	**18.8**		**26.69%**
	B_EC	Base case: Electrochromic	**65.7**	**74.7**	**35.0**	**15.7**		**38.87%**
	B_EC4st	Base case: Electrochr. 4states	**67.0**	**74.2**	**34.8**	**15.6**		**39.31%**
New York, NY	WFG_0%	Water-filled Glass	**39.6**	**42.4**	**19.9**	**8.9**		**65.33%**

	SWFG	Smart Water-filled Glass	**40.7**	**45.0**	**21.1**	**9.5**		**63.17%**
	B_2G	Base case: always clear	**114.7**	**105.8**	**49.6**	**8.9**		**0.00%**
	B_2G+PS	Base case: permanent shading	**57.1**	**58.8**	**27.6**	**4.9**		**44.44%**
	B_2G+AS	Base case: controlled shading	**80.5**	**130.0**	**61.0**	**10.9**	**0.08**	**-22.88%**
	B_SHGC0.2	Base case: low SHGC	**66.0**	**69.1**	**32.4**	**5.8**		**34.71%**
	B_3G	Base case: Triple glass	**85.8**	**86.7**	**40.7**	**7.3**		**18.01%**
	B_EC	Base case: Electrochromic	**58.1**	**68.3**	**32.1**	**5.7**		**35.39%**
	B_EC4st	Base case: Electrochr. 4states	**58.0**	**67.3**	**31.5**	**5.7**		**36.40%**
	WFG_0%	Water-filled Glass	**36.2**	**47.8**	**22.4**	**4.0**		**54.83%**
Shanghai, CN	SWFG	Smart Water-filled Glass	**35.3**	**49.6**	**23.3**	**4.2**		**53.06%**
	B_2G	Base case: always clear	**150.2**	**130.8**	**61.4**	**11.0**		**0.00%**
	B_2G+PS	Base case: permanent shading	**69.1**	**63.8**	**29.9**	**5.4**	**0.08**	**51.26%**
	B_2G+AS	Base case: controlled shading	**106.8**	**150.5**	**70.6**	**12.6**		**-15.00%**
	B_SHGC0.2	Base case: low SHGC	**85.0**	**79.2**	**37.2**	**6.7**		**39.45%**
	B_3G	Base case: Triple glass	**107.1**	**98.0**	**46.0**	**8.2**		**25.12%**
	B_EC	Base case: Electrochromic	**75.3**	**81.1**	**38.0**	**6.8**		**38.01%**
	B_EC4st	Base case: Electrochr. 4states	**72.0**	**78.3**	**36.7**	**6.6**		**40.16%**
	WFG_0%	Water-filled Glass	**46.5**	**48.8**	**22.9**	**4.1**		**62.68%**
Beijing, CN	SWFG	Smart Water-filled Glass	**47.8**	**51.1**	**24.0**	**4.3**		**60.97%**

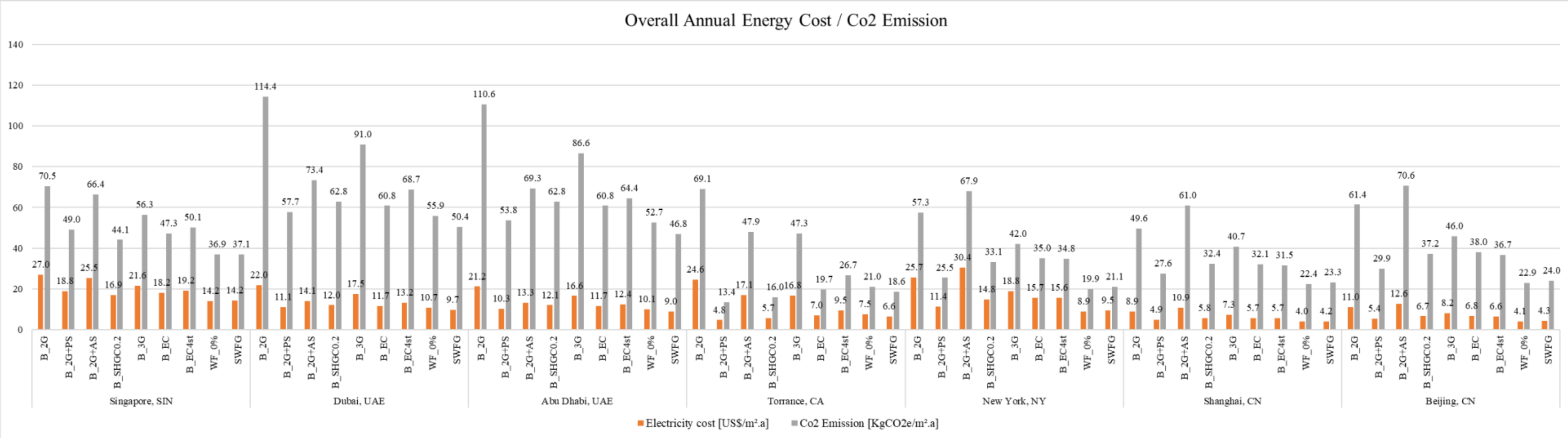

Figure 20: The total annual electricity cost and equivalent CO_2 emission for base case, WFG and SWFG systems for seven different cities. Please follow our Repository upload for detailed Excel data and chart [38]

4. Conclusions

Energy consumption of glass buildings, glass envelopes and windows are major contributors to climate change and ecological footprint of buildings. This paper reflects on the emerging critical dialogue towards glass buildings with an innovative approach that turns glass surfaces from a liability to an opportunity to save energy. Smart Water-filled glass (SWFG) technology builds on the existing Water-filled glass (WFG) system and takes it further by changing the transparency of the fluid as a response to changes in the environment, which improves the overall thermal and energy performance of the WFG system further.

The paper evaluates two kind of possible operational method depending on climate and potential of energy savings: *insolation-based* and *storage-based* approach. The first focuses the impact of SWFG on visual comfort (shading effect) and the second on the increased absorption of SWFG with higher opacity (darker glass surface).

Insolation-based approach is more ideal for climates without significant heating demand where the absorbed heat is much higher than the heating load. Storage-based approach is more ideal for climates with high heating load.

The results of insolation-based scenario present that the most ideal scenario from an energy consumption perspective is to have highest opacity settings for the whole year. This option however is not viable for windows and glass facades, especially because the energy savings between the different settings are not significant.

Storage-based approach would suggest high opacity during heating period but the results show that this is not validated by the model because absorption is high enough for low opacity settings already.

The results show that the ideal opacity settings for both approaches are basically the same, even if the starting design criteria is very different. This is mainly because of three reasons: viability of glazing (transparency is preferred whenever possible), the impact of absorption (which lowers both heating and cooling load) and the relatively small difference in energy consumption for the different opacity scenarios.

The final operational setting divides the year into four periods: 40% opacity (between 15th November and 15th January). 20% (between 15th January – 15th April and 15th September – 15th November) and clear glass/0% (between 15th April – 15th September).

The results show that both Smart Water-filled Glass (SWFG) with changing transparency and Water-filled Glass (WFG) with clear transparency performs better than standard double glass window. SWFG saves about 47.41-78.01% energy compared to standard double glass.

SWFG and WFG have relatively the same performance in insolation-based climates (mainly Köppen-Geiger A and B regions). The savings are 4.83%, 5.28% and 3.81% for Dubai, Abu Dhabi and Torrance respectively. The results are about the same for Singapore, which can be explained due to lower proportion of solar gain in the overall radiation load. SWFG performs similarly than WFG in storage-based climates (cities with relevant heating demand): both New York and Shanghai present similar results. Beijing shows 3.39% difference, which can be explained with higher solar load. The results somewhat change if we consider the energy savings of the absorbed energy. The energy savings for WFG/SWFG increase in each city with heating demand: Torrance (by 2.19%/2.53%), New York (by 12.43%/14.84%), Shanghai (8.26%/9.00%) and Beijing (11.88%/16.99%). The difference between WFG and SWFG in these scenarios does not follow this trend because absorption of WFG can already cover most of the heating demand: the difference between the two is 3,47%, -2.15%, -1.77%, -1.72% respectively.

Considerations for future research:

The results present that the use of absorbed energy of the water layer plays an important role in the performance of the system. Considerations on using this potential in the most effective way is an aspect of WFG that should be examined in the future. The current studies also don’t use coatings on WFG cases or evaluate a whole floor/building, which are elements in the simulation that should be evaluated by future research.

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