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Global carbon viability of glass technologies: Life-cycle assessment of standard, advanced and water-filled glass (WFG) building envelopes

Matyas Gutai [a,*], Brandon Mok [a], Giulio Cavana [b], Abolfazl Ganji Kheybari [c]

[a] *School of Architecture, Building and Civil Engineering, Loughborough University, Epinal Way, LE11 3TU Loughborough, United Kingdom*
[b] *Politecnico di Torino, Corso Castelfidardo 39, 10129 Torino, TO, Italy*
[c] *Transsolar Energietechnik GMBH, Landwehrstraße 60/62, 80336 München, Germany*

HIGHLIGHTS

- Glass options should be ranked on LCA instead of just operational energy.
- Paper presents life-cycle carbon for seven glass options across all major climates.
- Viability of advanced glass options is affected by their high embodied carbon.
- Glass option ranking depends on length of representative study period (RSP).
- Glass Viability Index is created, which ranks carbon impact independently of RSP.

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ABSTRACT

The construction sector is responsible for around 39% of global greenhouse gas emissions, with building envelopes playing a significant role in this carbon footprint. This is particularly relevant for building facades with large window-to-wall ratios (WWR), because higher proportions of glass increase both operational and embodied carbon. In light of the contemporary demand for such glazed envelopes, there is an emerging legislative trend that measures not only operational carbon, but also embodied via utilizing life-cycle assessment tools (LCA). To this effect, there is a great demand for techniques that can effectively lower the former carbon without increasing the latter. To contribute to this effort, this paper presents a whole LCA across seven cities for standard and advanced glazing solutions, including Water-Filled Glass (WFG). WFG is a novel technology that utilizes water in the cavity of insulated glass units (IGU), to improve thermal comfort, energy and acoustic performance of buildings. The paper utilizes energy simulation modelling through TRNSYS, and provides a comparative analysis of different glazing techniques. The significance of this paper is that a comprehensive cradle-to-grave LCA analysis of standard and advanced glass techniques is presented here for the first time, across all major Köppen-Geiger climates. The results show that WFG presents considerable carbon savings against all other options e.g., 31–53% compared to double glass, underlining the possibility of reducing operational and embodied carbon simultaneously. A second novel outcome of the paper is introducing the Glass Viability Index (GVI) for the first time, which presents the 'carbon payback' period required to offset an embodied carbon increase with operational savings. This is because the short lifespan of glass makes embodied carbon a large driver in LCA, and as such the prioritisation of operational carbon when selecting a technique can lead to a unsustainable practice.

1. Introduction

The construction sector is responsible for a major part of greenhouse gas (GHG) emissions, with 39% globally [1], 39.35% in European Union [2] and 41.4% in the United Kingdom [3]. Whilst there was an overall decrease of emissions during the COVID-19 pandemic, global trends indicate a quick rebound is taking place, with an increasing proportion of energy used for cooling of buildings, even in colder climates such as the UK [4]. The increasing demand for cooling is further driven by multiple historical heat records being surpassed globally in recent years

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* Corresponding author.
E-mail address: M.Gutai@lboro.ac.uk (M. Gutai).

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[5].

Glass plays a great role in the energy consumption of buildings: glazed areas are responsible for a major share of energy loss from the building envelope, culminating to 47% total heat loss in a typical residential building [6] and for 20–40% wasted energy in buildings in general [7]. This impact is further increased by the nature of the manufacturing process of glass, which is holistically energy intensive: the glass industry worldwide is reported to be responsible for 86 Mt. of CO_2e emissions, and produces 150 Mt. of glass a year - 42% of this is float glass used in construction industry (36.12 Mt) [8]. Whilst these values may appear modest when compared to the steel or concrete industries, the emissions are rapidly increasing due to contemporary advanced glazing products that have a higher embodied carbon output and steadily expanding market share, e.g., electrochromic glazing (6 times expected increase of market share between 2016 and 26 [9]) and photochromic (about 5 times between 2016 and 26) [10]. The embodied carbon increase of such products is significant in magnitude, as techniques such as electrochromic are suggested to have up to 28 times higher embodied carbon than float glass (sheet-by-sheet basis) [11]. This increasing proportion of advanced glazing and their high embodied carbons present two issues: firstly, there is a substantially increasing carbon impact of the glazing industry overall, and secondly, the viability of advanced glazing is challenged, especially considering the increased embodied carbon they require to achieve higher operational savings compared to standard glass units.

Considering the GHG impact of glass in building envelopes, there is an emerging global dialogue on curtailing glass use in buildings [12,13], culminated in proposals such as the ‘glass building ban’ by the Mayor of New York City [14]. The idea was later translated into legislative action in form of Local Law 97 [15], which introduces taxation on carbon emission of buildings. The law itself does not explicitly name glass, but targets buildings with high window-to-wall ratios (WWR), as their energy consumption is considerably higher [16]. Similar legislation has been approved by the European Union under the EU Emissions Trading System (ETS), that, albeit excluding buildings in its first implementation, will now directly tax carbon impact of buildings and transportation from 2025 [17,18], and is expected to become a driver of carbon savings in built environment. Additionally, there are novel legislative approaches in Europe for building codes, that consider life-cycle assessments (LCA): the Netherlands, Denmark and France have already introduced such measures for most of their newbuilds, with Finland and Sweden currently planning to do so, and others such as the UK, Germany and Switzerland having LCA limits for public buildings [19]. There are additional national regulations, including carbon limits on newbuild homes in the UK, which mandates a 30% lower carbon limit as part of national efforts towards net zero [20]. These measures target glazing both in terms of high embodied and operational carbon, which again limits the viability of advanced glazing. Here, this suggests that in order to meet ambitious national and global carbon targets, there is a great demand for innovation in glass, especially solutions that can significantly lower operational energy consumption without increase in embodied carbon. This underlines the importance of LCA as a tool to evaluate both.

Life-cycle assessments (LCA) have been implemented to both monitor and assess the environmental impact of products or services, enabling comparative evaluation in order to favour one alternative over another. This concept was initially explored in product design [21] and later in other fields, including construction [22]. Considering the latter, LCA has the advantage of evaluating a construction project through multiple stages (material production, construction, use, end of life), which offers a comprehensive view on the carbon impact of a building and avoids undocumented environmental loads passed between different phases of the building life-cycle, or from one construction project to another [23]. There are currently several guidance frameworks for LCA calculations, with the fundamental standard being ISO 14025 for LCA calculation, and 140040 for Environmental Product Declarations or EPDs [24]. A similar standard has been implemented in the European Union as EN 15804 [25]. Additional national guidelines have been issued to support country/region specific calculations, e.g., the one issued by Royal Institution of Chartered Surveyors (RICS) [26]. In each case, a ‘cradle to grave’ LCA calculation includes multiple assessment stages from manufacturing until end of life. The majority of the impact is related to the use of materials (materials production stage) and to operational energy consumption (use stage) due to carbon intensive processes of the former and the long reference study period for the latter (RSP, typically 50–70 years) [27]. Until recently, most policies focused on the reduction of operational energy consumption, which was also justified with LCA results showing operational carbon as the major driver of environmental impact (typically 80–85%) [28]. However, the impact of stricter policies saw a constant decrease in operational carbon, which in turn highlighted the previously disregarded equal importance of embodied carbon, particularly within the product manufacturing stage [29]. This concept can be appreciated in certain net-zero energy buildings (NZEB), where the investment in passive and active measures led to a decrease in operational energy, but an increase in embodied carbon, leading to a higher overall LCA, even when compared to low energy buildings (a concept that NZEB aimed to usurp and develop) [30]. Here, this strongly suggests that the use of energy-saving measures should always be carefully considered, and their embodied energy consequence taken into account.

Such an ethos regarding sustainable design also applies to glass, as advanced glass options are subject to a similar predicament; whilst they may offer operational savings, these must justify and offset the considerable embodied carbon of these techniques. Despite that, the current focus on glass option evaluation mainly focuses on metrics that simultaneously assess the operational energy, along with other aspects of the building performance related to user comfort. Apart from the impacts of the transparent element on the overall energy consumption of the building, the parameters used to optimize the glazing design also belong to the visual comfort domain: (Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Daylight Factor (DF), unified glare ratio (UGR), mean workstation horizontal illuminance (HI)), and also thermal comfort (Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD) Mean Radiant Temperature (MRT), Weighted Discomfort Time (WDT)) [31]. Other trends deal with the possible use of short term metrics (assessed in certain time and position), long term spatial analysis (considering the evolution of such metrics in time and space) [32], or effects of high levels of transmitted sunlight in the internal environment [33]. The above suggests that while energy consumption reduction is considered, the assessment of the resulting increasing or decreasing levels of embodied carbon are usually missed in certain phases of the evaluation [34].

The increasing embodied carbon of advanced glass technologies points to the need for a proper evaluation of such. Whilst using LCA methodology to choose the best glass option for any project provides some merits, it can produce a misleading evaluation if used by itself. This is because it does not directly consider the embodied carbon difference between the glass options. This can create an equivocal evaluation and result. Here, the lifespan of a glass façade is relatively short (30–35 years), and hence in a traditional LCA the overall carbon result is driven by the selected representative study period (RSP), which varies between 50 and 120 years, depending on user calculations since no universal RSP standard is available. This means that the actual ranking of glass façade options in any climate greatly depends on the selected RSP, because depending on the length the glazing could be replaced multiple times. For example, advanced glazing has a higher embodied carbon than most, and with a longer RSP they become an increasing liability for the overall evaluation. Hence, it is crucial that a mathematical method is presented that offers an objective and comprehensive tool that can supplement an LCA, which eliminates the associated liabilities of the RSP.

For these reasons, the authors of this paper introduce the ‘Glass

Viability Index' (GVI), which highlights the relationship between the increase of embodied carbon in a glass unit, and the resultant operational carbon saving. The GVI is calculated by using the embodied carbon increase of the glass unit, divided by its annual carbon savings and compared to a base case, producing a 'carbon payback' period. Practically, GVI shows how many years of operational carbon savings are required to balance the increased embodied carbon. The GVI can be used for 1) comparison of different glass unit options, 2) to identify the best climate scenario(s) for any glass option, and 3) ascertaining the viability of any glass technique for a climate. The third point is particularly relevant, because it is something that conventional LCA techniques do not show: if the GVI value is close or higher than the lifespan of a typical glass façade, then it is likely that another glass unit option should be pursued instead. GVI is useful to recognise whether a glass option is viable at all, meaning whether the invested embodied carbon of the advanced glass can actually be justified by the offered OC savings throughout its lifespan of 30–35 years. Again, this is something that a traditional LCA does not necessarily show, since the RSP here is dependent on the user. GVI is useful for the second point as well: as the results will show below, in the case of LCA the ranking of glass options in any particular location depends on the RSP, which is not the case for GVI. Hence, the ranking for LCA and GVI may not be the same.

To assess the impact of GVI, the paper evaluates seven different case study options, including widely used technologies (standard + advanced glazing) and innovative options such as water-filled glass (WFG) and smart water-filled glass (SWFG). By conducting the study in such a manner, the options for this paper cover the four main approaches towards energy management that are currently present within the glass industry. The first approach focuses on improving insulation or U-value, typically through additional layers of glass [35]. The second option can be categorised as a radiation control measure that improves the SHGC, typically by utilizing a coating that can be permanent (e.g., Low-E [36]), dynamic (e.g., electrochromic or EC [37], suspended particle device window or SPD [38], or polymer dispersed liquid crystal or PDLC [39]). Thirdly, techniques focus on combining glazing with solar control e.g., fixed or automated shading [40]. Finally, the fourth category relies on a fluid medium within the window, typically air (ventilated inside [41] or outside [42]) or water [43].

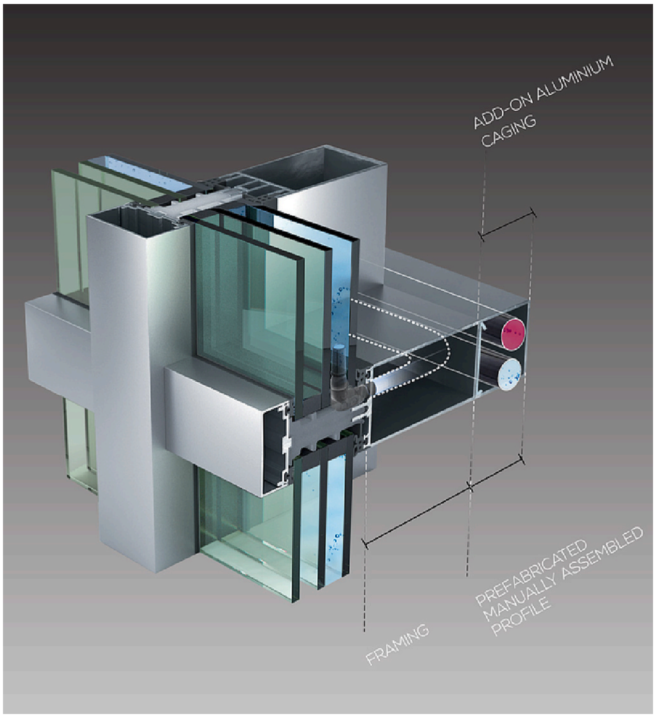


Fig. 1. Water-filled Glass (WFG).

In particular, Water-filled glass or WFG (shown in Fig. 1) was introduced first in 2007 [44], then in 2009, [45] and patented [46,47] by the author Matyas Gutai. The technique consists of an innovative IGU that utilizes an external argon layer and an internal water layer in the glass, that is connected to external mechanical system to improve thermal comfort, acoustic and energy performance in buildings, particularly ones with high WWR. The technology is being researched by various institutions, including research groups in Madrid [48,49], and in China [50]. Two real world case prototypes have been built by the author [44,51], and provide validation for the energy models on energy consumption [52] and construction aspects of WFG, including concerns of leakage, transparency, and other risks [53]. The existing research gives a good overview on the energy performance of water-filled glass technology. However, there is limited information on global life-cycle assessment of water-filled glazing, especially in an operational setting. This presents a significant gap in research, especially when considering the 1) existing challenges in CO_2 emission cuts, 2) legislation in LCA, and 3) need for advanced glazing that lowers operational carbon without increase in embodied carbon. Accordingly, it can be concluded that there is a great demand on more understanding of life-cycle assessment of glazing in general and of WFG.

The significance of this paper is that the global viability of glass solutions are evaluated, considering how the increase of embodied carbon of any glass option is translated into a 'carbon payback period', when using the annual equivalent operational savings of the same glass. As mentioned earlier, the increasing embodied carbon and short lifespan of advanced glass technologies points to the need for such evaluation, especially in light of different operational savings for the same glass unit in various climates. It should be noted that whilst the paper evaluates embodied carbon here, the focus is primarily on energy consumption. Firstly, the embodied carbon of glass is driven by energy consumption, as the manufacturing process requires high temperatures and controlled environments. Secondly, whilst evaluating embodied carbon payback, the goal is to highlight the possible unconscious bias towards operational energy, which is the main aim of the paper.

Novelty is also introduced via the paper offering a global comparative analysis of the life-cycle assessment for Water-filled glass (WFG) in an operational setting (office building), compared against other standard and advanced glazing scenarios (presented here for the first time). Finally, as a third novel aspect, the research presents a global evaluation of glazing options from cradle-to-grave, and strongly highlights the importance of the embodied component.

2. Methodology

The paper follows the standard methodology approach for Life-cycle assessments, in line with ISO 14025 and EN15804. The embodied carbon is calculated using the Inventory of Carbon and Energy (ICE), and guidance from the Royal Institute of Chartered Surveyors (RICS, [26]). The operational carbon calculation is based on the dataset from a previous publication, where energy consumption was simulated for the same glass options [54]. Once this and the present datasets are combined into an overall LCA, the research evaluates the results by calculating the Glass Viability Index (GVI), which is the increase of embodied carbon divided by the annual operational carbon savings, compared to the baseline of a standard double glass window. The GVI is then presented to reflect on both environmental impact and viability of each glass option in seven cities.

The Methodology chapter is divided into two main parts. The first part introduces the considerations for energy simulation including simulation model, selected cities, climates and glass cases. The second part presents the considerations for the LCA calculation, e.g., assumptions for product calculation, transportation, construction, use and end of life stages.

2.1. Considerations for energy simulation

2.1.1. Office setting (annual dynamic simulation setup)

The simulation method for this paper followed the same model and framework as in previous publications on WFG. Here, TRNSYS dynamic simulation software was used to determine the operational energy consumption for each scenario [52,55]. A prototype of WFG panels and an experimental building titled Water House 2.0 was used for validation of the model, which is presented in earlier publications [52]. Additionally, the full dataset of the first simulations and for this article is available with Open Access, referenced in the Appendix below. As shown in Fig. 2, an office room of 17.5 m^2 gross area with 3 m height was used for the simulation, with one of the external walls being part of the glass façade of the building; the rest of the surfaces (interior walls, ceiling, floor) were considered adiabatic. The orientation of this façade was assumed to be equatorial (South-facing in Northern hemisphere, for all seven cities). The size of the room was 3.5 m by 5.5 m, and the glass façade was 3.3 m by 2.8 m (9.24 m^2 area). The properties of internal walls, floor and ceiling are shown in Fig. 2, with simulated U-values of 0.3, 0.6 and 0.6 W/m^2K respectively. The U-values and SHGC for the glass façade are also shown in Table 2 below (Chapter 2.1.3.).

The room was designed to be a functional office environment for one employee. Internal heat gains were set for working hours (Mon-Fri: 8:00–18:00) as 130 W/m^2 for a person, 140 W/m^2 for a computer and 5 W/m^2 for artificial lighting (controlled by available daylight lighting setpoint of 300–500 lx). Infiltration was assumed as $n = 0.25$ ACH, with an increase to $n = 1.45$ ACH during working hours. Optional night ventilation was assumed as an efficient cooling alternative during summer, as outdoor temperature fell below room temperature.

In terms of the mechanical system, it was assumed to have a setpoint temperature of 25 °C for cooling, and 21 °C for heating; these periods were limited to operational hours. Outside of the operational period, the room was permitted to have higher range for indoor temperature (29 °C for cooling, and 15 °C for heating). In case of Water-filled Glass (WFG) and Smart Water-filled Glass (SWFG), the TRNSYS model also factored in the energy required for heating-cooling the water, which was assisted with ground heating-cooling. Accordingly, the model also includes ground temperature in each location to adjust changes in temperature over the year.

2.1.2. Considerations for climate and cities

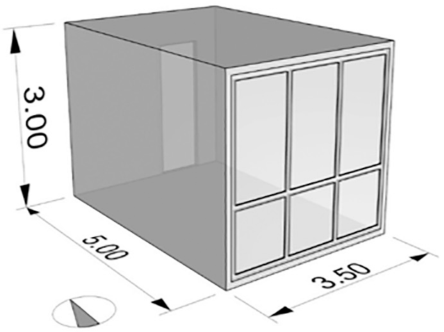
The cities for the simulation were selected based on climatic considerations and urban context.

In case of the former, it was important that the research identifies and includes a city from each major inhabited Köppen-Geiger climate region. Previous research identified that WFG is not viable in the Cold climate region (Köppen-Geiger E) [54], and therefore was not included in the study. The remaining areas were covered, as shown below in Table 1 and Fig. 3.

In the case of urban context, the cities within each climate region were chosen based on their existing building stock characteristics: preference was given to locations where high-rise buildings with high WWR is a likely scenario (and therefore would be a good representation of the study). Among the seven selected cities, there was one exception to this context: Budapest was a preferred option to represent the continental climate category, as the city is close to a WFG factory. However, due to a lack of accessible weather data, another Hungarian city (Debrecen) was used instead. Table 1 shows data of the selected cities with the end column 'Climate' providing the relevant Köppen-Geiger classification for the chosen cities.

2.1.3. Consideration for glass options

The study investigates two sub-options for water-filled glass (WFG): in addition to the transparent version known simply as WFG (which has the same appearance as any clear window), another version is also considered with a specific water infill that can incrementally change its colour to black, to provide shading and respond to change in daylight conditions. This technology is coined smart water-filled glass (SWFG), and has been introduced in a previous publication [52]. Here, SWFG can change its colour from clear (0%) to semi-dark (20%) and dark (40%) opacity. The two water-filled glass options are compared with five base cases. The first is a standard double glass option with Low-E coating, assumed to represent industrial standard for newbuild projects in each city of this study. The next base case is the same window in terms of composition but features an automated shading system with a 75% shading fraction (Fc = 0.25); this follows German Industry Norm or DIN as standard (DIN 4108–2, where solar irradiation (IT) is higher than 200 W/m^2). This base case is unique compared to the other options because the glass is combined with a shading device and the performance of the façade is influenced twofold. Whilst this difference was acknowledged by the authors, the inclusion of this case was still deemed beneficial as it offers a valuable control reference to the other options with inbuilt shading functions (e.g., EC or SWFG). The third option is a standard triple glass façade, the final standard glass option of this study. In terms of the advanced glass options, two are included in the study: The SHGC option is a solar protective glass with a selective coating (SHGC = 0.2), that aims to control the solar gain experienced by the façade, to minimise the need for corrective temperature control. This option differs from other glasses in sense that it is a dark mirror glass and is not as transparent as the others. The fifth glass option of this study is an electrochromic glass with Low-E coating and 4-step illuminance-based control. The seven glass options also cover the four energy



Component	Material	Thickness (m)
External wall	Expanded polystyrene	0.15
	Reinforced concrete	0.25
	Gypsum	0.0125
Dry wall	Steel structure	0.1
	Acoustic insulation	0.1
	Plasterboard	0.025
	Paint (double coat)	-
Ceiling/Floor	Finishing (timber MDF)	0.012
	Expanded polystyrene	0.03
	Reinforced concrete	0.25
	Gypsum	0.0125
	Paint (double coat)	-
Door (0.9x2.4m²)	Veneered Door	-
Window	See options in Table 2	

Fig. 2. Simulation Model (shoebox cube).

Table 1
Selected cities and climates.

City	Country	Latitude	Longitude	Altitude (m)	Avg. ground temperature (C)	Climate
Singapore	Singapore	1.37	103.98	16	27.5	Af
Dubai	United Arab Emirates	25.2	55.27	44.2	27.2	Bwh
Madrid	Spain	40.42	−3.7	807	14.1	Csa
New York	United States	40.78	−73.97	40	12.2	Cfa
Milan	Italy	45.46	9.19	321.5	11.4	Cfb
Beijing	China	39.8	116.47	32	12.5	Dwa
Debrecen	Hungary	47.48	21.63	112	10	Dfb

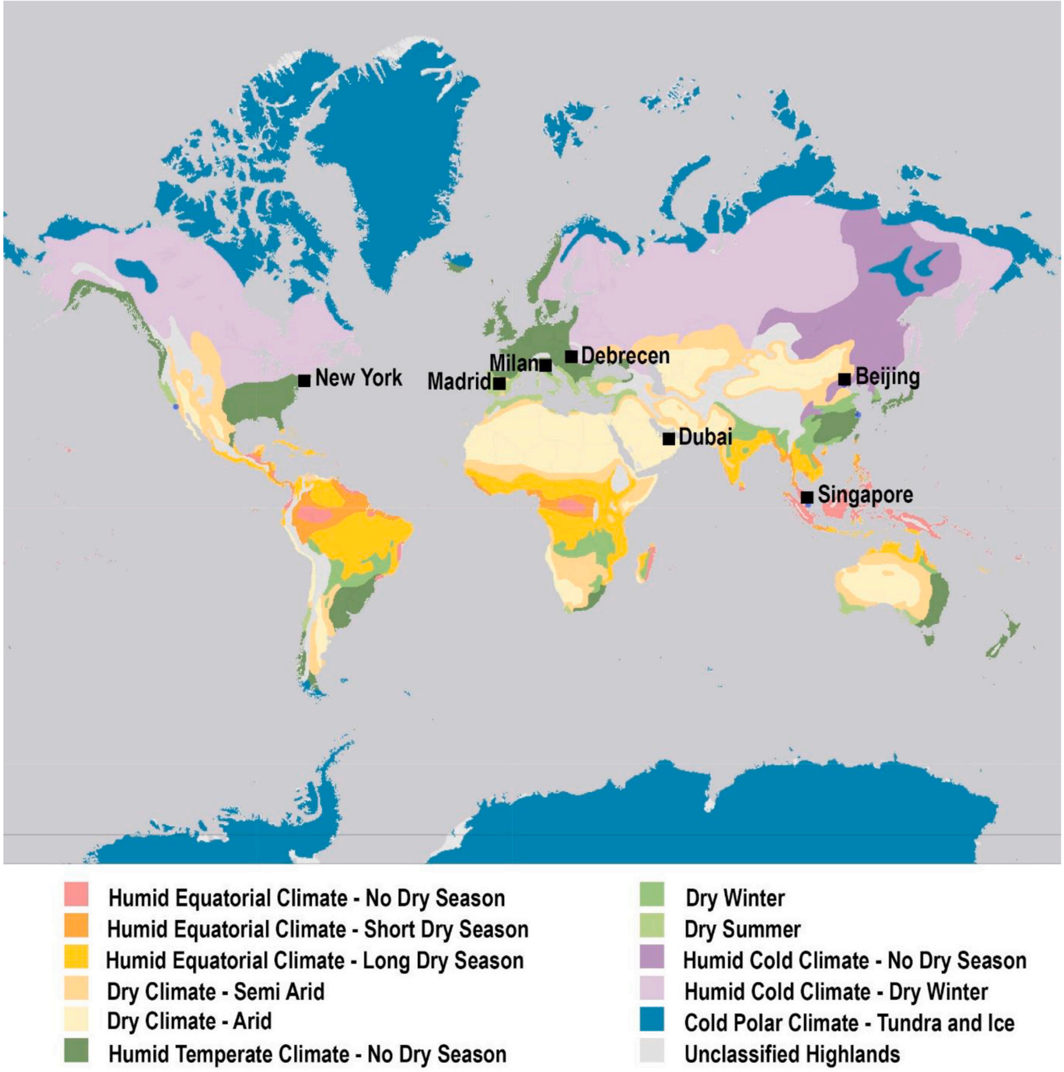


Fig. 3. Selected cities and climate regions (world map).

management strategies for glass: Insulation (modifying the U-value), Shading (internal/external devices preventing solar incident radiation), Incorporated Radiation Control (controlling solar gains), and Fluid Flow (integrating a dynamic layer into the fixed unit). The options with their parameters and energy management category are listed below in Table 2.

2.2. *Considerations of LCA calculations*

The location of the project drives not only the operational carbon output (through climate conditions), but also embodied, due to the carbon impact of local manufacturing processes, and the transportation of materials (product stage) and products (construction stage). Here, this applies especially to products with higher weight and manufacturing requirements, as significant increases in carbon may result in these cases. For each city and glass option, the calculations followed the current recognised practice of each respective local construction industry (as far as is practicable). Calculations were quantified through each major stage of the cradle-to-grave LCA calculation (Modules A, B and C, see Fig. 4).

In each city, the LCA calculation has been performed for seven different scenarios. These scenarios share the same construction elements specified in Fig. 2, while varying in regard to the seven glass options displayed in Table 2.

Table 2
Glass options.

Case Name	Window Type	Glazing System Settings	Shading / Switchable Window Control	U_g	SHGC [%]	T_{sol} [%]	T_{vis} [%]	Energy Management Category
DG	Insulating double glazing (SHGC ≥0.4)	16 mm Gap filled with argon, Low-E	No shading, always transparent	1.4	62%	43%	62%	Insulation
DG+AS	Insulating double glazing (SHGC ≥0.4)	16 mm Gap filled with argon, Low-E	Automatic 2-step radiation-based control, When IT <200 W/m2 = Clear, When IT ≥200 W/m2 = Shaded (Fc = 0.25)	1.4	62%	43%	62%	Insulation + Shading
TG	Triple Glazing	15 mm Gap filled with air	No shading, always transparent	1.2	50%	33%	51%	Insulation
SHGC_0.2	Solar protection double glazing (SHGC ≥0.2)	16 mm Gap filled with argon, solar protection	No shading, always transparent	2.16	20%	15%	20%	Incorporated radiation control
EC	Electrochromic Window	Double glazing system 16 mm Gap filled with argon, Low-E	Automatic 4-step illuminance-based control, When E < 600 lx = Clear, When 600 lx ≤ E < 800 lx = Low-tinted When 800 lx ≤ E < 1000 lx = Mid-tinted When E ≥ 1000 lx = Full-tinted	1.3	43%	29%	44%	Incorporated radiation control
WFG	Water Filled Glazing	15 mm Gap filled with clear water	Always clear, 0% dyed	2.9	55%	27%	44%	Fluid Flow
SWFG	Smart Water Filled Glazing	15 mm Gap filled with dyed water	Always clear, 0–40% dyed Automatic 3-step illuminance-based control 0% (Clear), 20%, and 40%	2.9	54%	22%	35%	Fluid Flow

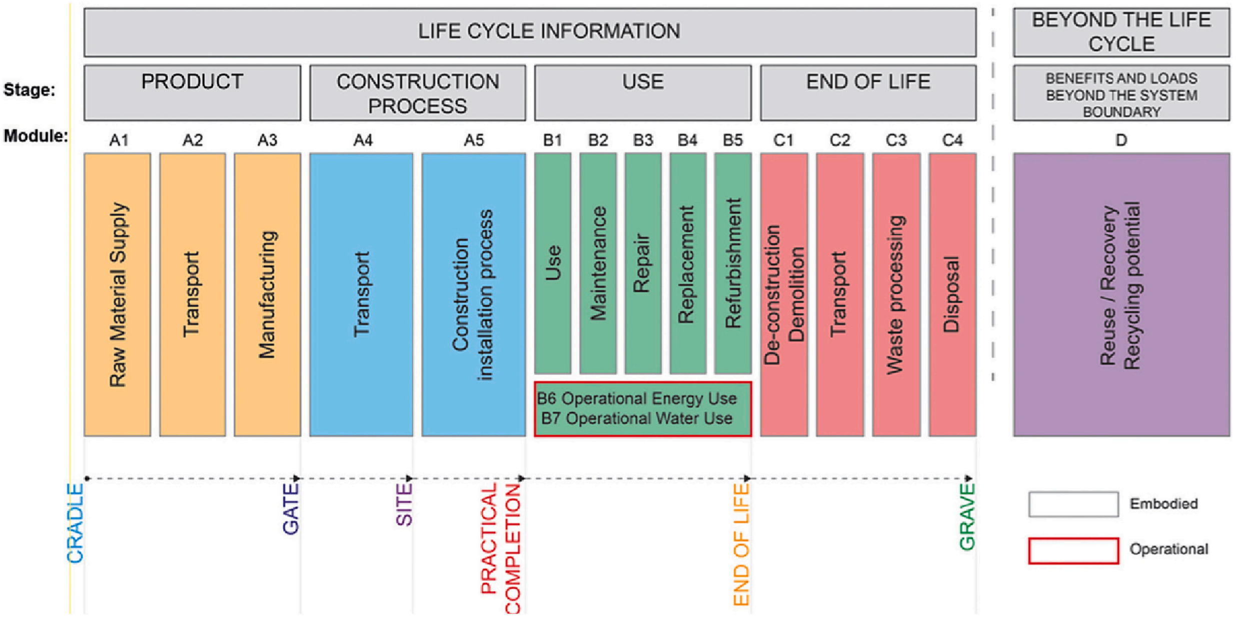


Fig. 4. Stages and Modules of Life-Cycle Assessment (LCA). Source: Institute of Structural Engineers.

2.2.1. *Embodied carbon calculation (product, construction and use stages): Considerations and assumptions (LCA stages A1-A3, A4-A5, B1-B5)*

Within the Product stage (A1-A3), the 'Inventory of Carbon and Energy' or ICE carbon data is utilized to calculate the embodied carbon for the building materials used in each scenario, where possible. This applies to generic elements in the model that are widely available (e.g., plaster walls and ceiling, door, floor, and slab).

For the glass façade in the Product Stage, EPDs were used as a basis for the calculation where appropriate, for standard glass options (shading [56], double [57–60] and triple glass [61]), advanced glass options (solar protective glass [62], EC [11,63,64]), and the curtain wall framing (Schüco [65]). With this, the recycled content for these products is assumed as what is provided within the EPDs. All calculations completed in this stage use the 100:0 method, to assume recycled potential during the product stage as 100%, which creates a twofold benefit. Firstly, it avoids an erroneous duplicate calculation of accounting for recycling potential 'twice' (e.g., discounting carbon impact of recycling steel both during End of Life (EoL) stage and during Product stage in the next project). Secondly, this approach also helps provide complete and correct data, as this aligns with the EPDs used, which considered recycled content during Product stage. In the case of WFG and SWFG, EPDs are not available since these are existing but relatively new products. Therefore, to calculate the environmental impact, a collaborative effort was undertaken directly with the manufacturer. The calculation recognises that WFG and SWFG comes with additional components compared to a triple glass unit (e.g., unique spacers, pipes, heat exchanger etc), which are included in the calculation. This creates a higher embodied carbon for WFG and SWFG, compared to standard glass options. These technologies are patented, which limits the amount of information that can be revealed at this stage. Additional technical information about these technologies are available in previous publications [52,53]. We also published our calculations in detail on Loughborough University Research Repository with open access [66], which provides details on our calculations, including WFG and SWFG.

For the Construction stage (A4-A5), the calculations had to assume distances for transportation of the finished product to the final construction site (A4). Generic materials and standard IGUs have been considered as nationally supplied, with the distance calculated as an average across the seven cities. In case of specific products such as EC glazing the calculations considered international shipping due to the specificity of manufacturer location (in this case Sage located in Fairbault, US).

Whilst this is justified, new glass innovations require bespoke manufacturing processes and factories, which limits the supply chain scope considerably; this results in an increase of embodied carbon. This concept highlights an important aspect of glass innovation, as limited supply points lower the viability of such technologies. This does not apply for WFG and SWFG, which have been developed with a manufacturing process that can be adopted by any glass factory with existing IGU manufacturing processes, and hence was assumed to be produced locally in every city.

The construction process (A5) has been calculated based on the recommendation of RICS [26] for each case. While it is recognised that the actual carbon impact may differ in each city, it has been also assumed that these values are close in reality because we are considering the same modern construction technology for all sites, while the weighting of the value itself is relatively low in percentage. This approach also gives fair comparison across cities.

The calculation of embodied carbon during Use Stage (B1-B5) was divided into two parts: the first part is carbon for use (B1), maintenance (B2), repair (B3) and refurbishment (B5), the second part is carbon for replacement (B4). Following guidance of RICS and Institution of Structural Engineers (ISE), the calculation focuses on the second part. The first part is assumed as a small percentage of embodied carbon because: i) B1 is “generally insignificant” for structural materials, B2 and B3 is assumed to be minimal, and B5 is assumed not to take place during the studied period. The percentage assumed for this part is set to 3% of the Product stage, which correlates with results from RICS [26] and other studies [67].

2.2.2. *Operational carbon calculation: Considerations and assumptions (B6, B7)*

The operational carbon calculation has been set for each city with respective data on carbon coefficient for the local energy supply [68]. The study assumes an energy-efficient heating-cooling system that utilizes heat pump and electricity consumption for the building. The same system was assumed for the hot water supply. While heat pumps are not considered to be the standard solution in any of these cities, it is a competitive energy-efficient option in all of these locations, hence it was an ideal option for a fair comparison across countries.

Operational water consumption has been assumed based on data on water use for office buildings [69]. Additional water consumption has been calculated for WFG and SWFG in stage A1-A3. It should be noted that these systems are closed loops, so their water demand is minimal (the system needs to be filled up only once during its lifetime).

3. Results

The following section will be categorised into four components, in accordance with guidance provided by the Royal Institute of Chartered Surveyors (RICS) [26]. By using such a framework, potential improvements and existing shortcomings can be easily identified for each LCA stage; this promotes the efficient implementation of resources for each stage of the supply chain.

3.1. *Product stage (A1-A3)*

Fig. 5 shows the calculated carbon contributions from the Product Stages A1-A3. The carbon coefficients were taken from Schüco and Uponor Environmental Product Declarations (EPDs). Detailed calculation results are available in Loughborough University Research Repository with open access [66]. It is worth underlining that this component of LCA is location-independent according to data from ICE.

As shown in Fig. 5, the glazing technique with the largest emission output here is Electrochromic (EC) and Double Glazing with Automatic Shading (DG + AS), with 9744 and 6221 $kgCO_{2e}$ respectively. The lowest contributors in this stage are DG and SHGC 0.2 (5123 and 5173 $kgCO_{2e}$). It is noteworthy that depending on the glazing technique chosen, 22–58% of the embodied carbon at this stage is accredited to the glazing (the rest is associated with the remaining elements of the room).

3.2. *Construction stage (A4 – A5)*

The carbon impact of transportation (A4) considered distances for each component as an average distance of the construction site from the manufacturer among the different cities (as located in the geolocation of each analysed city given by Google Maps). The only exception to this is represented by EC: for this specific product, the distance from the specific manufacturer location and the construction site has been calculated individually, resulting in slightly different results for this technology depending on location (location-dependent difference is marked in light-green in Fig. 6). Details of the calculation are available in the tables updated to the Loughborough University Repository with open access [66]. These have been made available, as this study promotes the ethos that innovations in embodied carbon especially for glazing technologies should be flexible globally, and accessible by all manufacturers. This is because the estimated current contribution of the building sector to global anthropogenic GHG is around 40%; pooling of resources and knowledge must become a common practice, if we are to achieve the collective goals around climate change. In terms of the contributions from the common fixing elements, the calculation utilized a disaggregate breakdown as shown in tables of the Research Repository [66]. For Stage A5, a construction cost of £2900/m^2 and a carbon coefficient of 1400 kg/£100 k was simulated following recommendations of RICS, resulting in a carbon emission of 710.5 $kgCO_{2e}$ for each location. Fig. 6 shows the overall results of modules A4-A5.

3.3. *Use stage, embodied carbon (B1-B5)*

Within this stage, refurbishment (B5) was assumed not to occur at any point within the Representative Study Period (RSP). The RSP was determined to be 60 years, in line with recommendations of RICS. As mentioned earlier, B1-B3 was assumed to be a low value, in line with RICS and Institute of Structural Engineers; the calculation here assumes this to be 3% of the Product stage as shown in Fig. 7. For EC, these values are location dependent only in the stage B4 (Replacement), explained previously in Section 3.2.

3.4. *Use stage, operational carbon (B6-B7)*

Operational energy consumption (shown in Fig. 8) followed the same approach as undertaken in the previous publication. The carbon

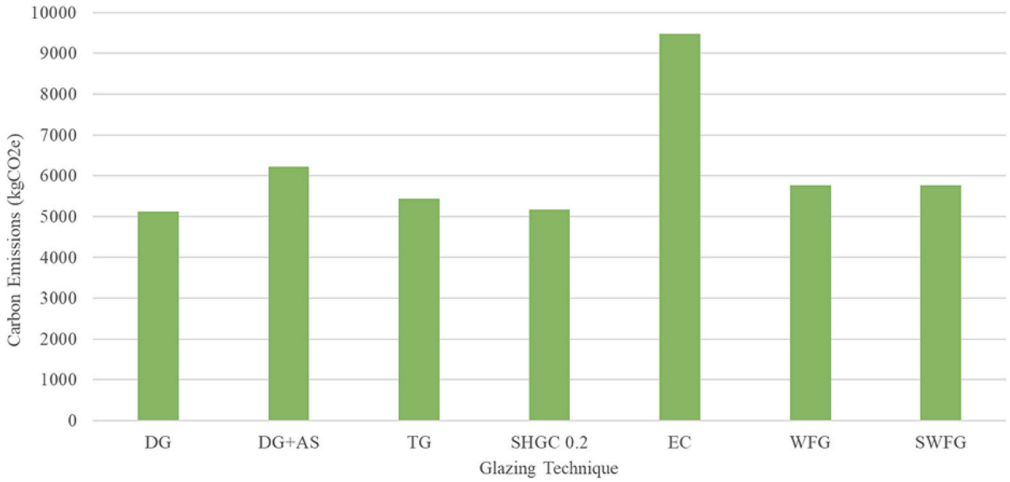


Fig. 5. A1-A3 Stages of LCA ('Cradle to Gate'): A1(Material extraction and Supply), A2 (Transport to plant), A3 (Manufacture and fabrication).

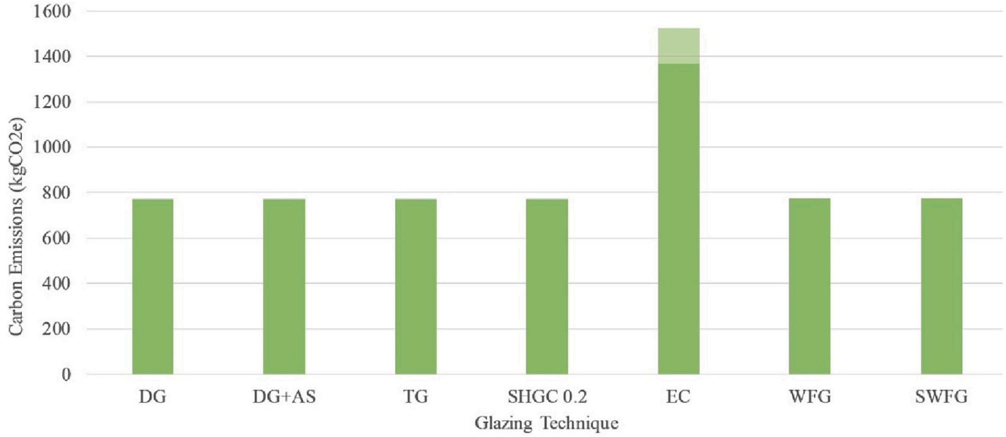


Fig. 6. A4-A5 Stages of LCA ('Gate to Practical Completion'): A4 (Transportation to site), A5 (Construction).

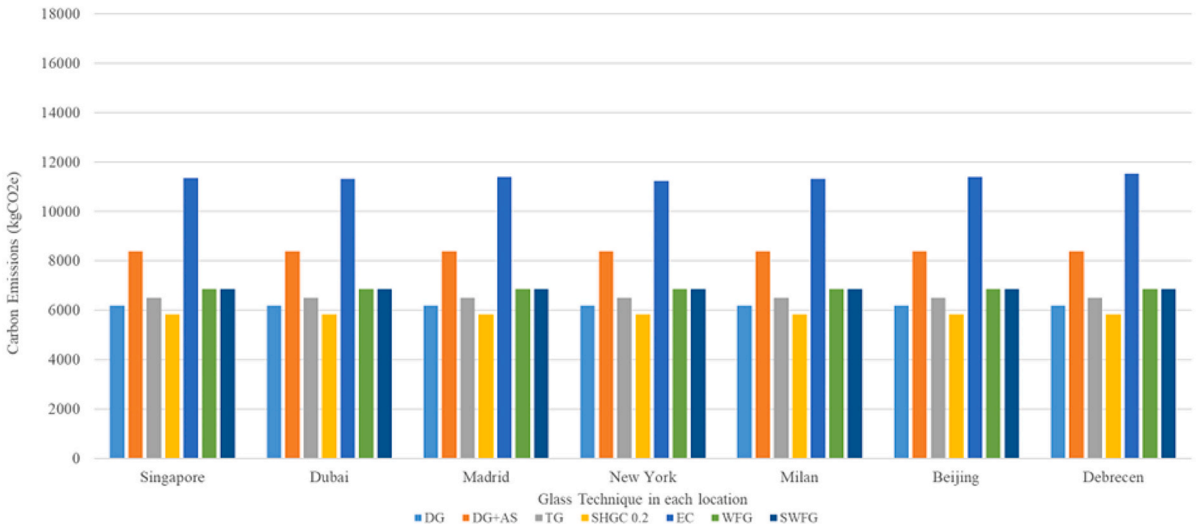


Fig. 7. Use stage, embodied carbon for specific structural elements (B1-B4 Stages: B1(Use), B2(Maintenance), B3 (Repair), and B4 (Replacement)).

emission factor for the electricity supply was different for each city, and was determined using the local data. The Site-to-Source conversion factor for electricity and COP was assumed to be the same, as well as the mechanical system for each location. In Table 3 the CO_2 conversion factors (f_{el}) for electricity production is displayed. Details of the simulation as well as results are uploaded to the Research Repository of

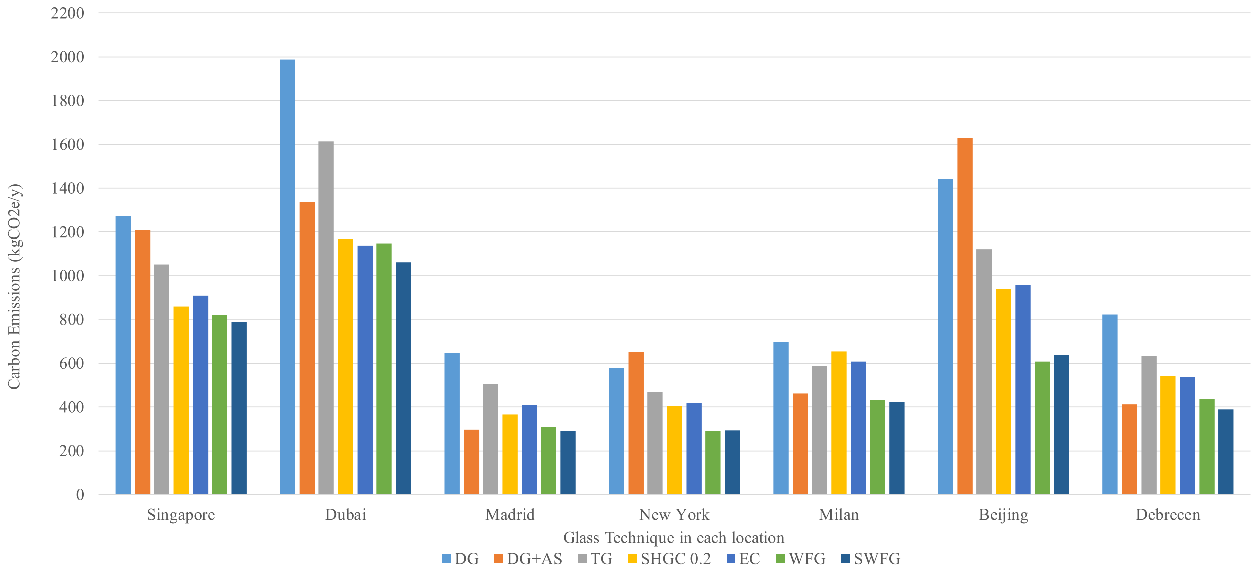


Fig. 8. Operational carbon (B6 and B7) for seven cities and glass scenarios.

Table 3
CO_2 conversion factors (f_{el}) for electricity from the national grid.

Location	Singapore	Dubai	Madrid	New York	Milan	Beijing	Debrecen
f_{el} (kg_{CO2eq}/kWh)	0.4188	0.4258	0.22026	0.18991	0.33854	0.555	0.25298

Loughborough University with open access [70]. Apart from being determined by the specific energy consumption in each location, the high values of operational carbon are also greatly influenced by the conversion factors of each location's electricity grid.

B7 (Operational water use) was calculated as 170.29 $kgCO_{2e}$, when a water consumption value of 1.55 l/m^2 and a carbon coefficient of 0.000344 $kgCO_{2e}/l$ were simulated. Fig. 9 shows the carbon impact between modules A1-B7 (Product, Construction and Use stage); note that this only includes operational emissions for a singular year, not over the entire life cycle.

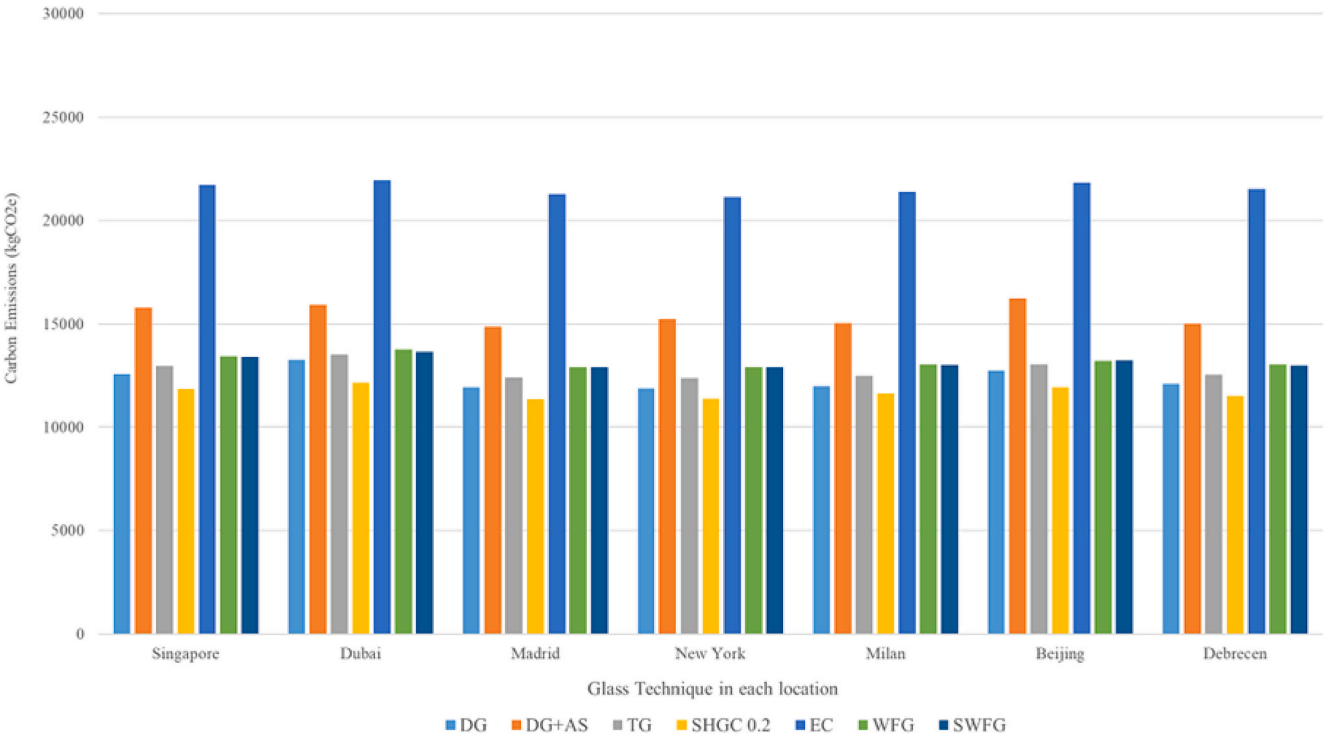


Fig. 9. ('Cradle to End of Life): Operational and embodied carbon (A1-B7) for seven cities and glass scenarios.

3.5. End of life stage C1-C4

Within C3, the '100:0' approach by RICS was assumed, meaning that no recycling measures were simulated for End-of-Life stage. This is to provide a conservative estimate for emissions, by assuming all components end up in landfill or otherwise. This was also justified by the use of the EPDs, which were calculated with recycled content in the Product stage.

C1 (Demolition) was calculated using RICS method and was assumed to be the same for each city. Fig. 10 shows the C1-C4 LCA stages for glazing: C2 (Transportation of waste), C3 (Recycling), and C4 (Landfill Disposal). Distances for transportation to waste management facilities were determined for each city (two closest facilities to each city centre was selected, and the average across all the locations was used for the calculation). Details of this calculation are available on the Loughborough University Research Repository with open access [66]. It is noteworthy that for C1-C4, these are quite similar for each technique studied.

4. Discussion

The results of the calculation are shown below in Fig. 11 for each glass option and each city. The results highlight the following observations:

In every single location, WFG and SWFG provide the lowest carbon impact. This can be expected since 1) the technology offers operational energy savings with a minimal increase in embodied carbon, 2) is available locally in any glass factory (which lowers carbon in shipping) and 3) its unique additional components (pipes, water, spacer) are not energy intensive. It should be noted that the energy consumption of WFG and SWFG is calculated as a conservative scenario, which means an operation mode where the heat captured by the water (Q_{useful}) is not utilized in any manner. As such, the consumption could be even lower than the data presents.

Regarding the second-most carbon advantageous technique, this is the automated shading one for Debrecen and Madrid, which is not surprising because of the high solar radiation experienced in these regions. However, this shading option performs worse than standard double glass in Beijing and New York, which is a result of its high carbon and loss in solar gain that would normally lower overall heating demand of the building.

Solar protective glass comes second in Singapore, Dubai, Beijing, which matches initial expectations as radiation management is critical in these climates. In the case of regions like Beijing, solar control glass would lower the solar gain in winter, but to a lesser degree compared to automated shading.

Solar protective glass, automated shading, and WFG exhibit similar results in Madrid, which again highlights the importance of solar gain. However, to ensure a fair and representative comparison, it should be noted that WFG does not have either shading nor coating in this study and adding those to WFG would improve its performance even further, which begins to display in SWFG to a certain extent. In addition to WFG, solar protective glass also performs well overall, with a limited increase/trade-off of embodied carbon.

Triple glass presents the third best option, in Madrid, New York, Milan, and Debrecen. In the cases of Singapore and Beijing, its performance is very close to EC. For climates such as Dubai, triple glass unsurprisingly performs the worst, as the improved insulation offers significantly limited benefits in cooling dominated climate.

In regard to the holistic performance of EC, it presents as the 4th–7th most favourable option across all climates: its best performance is in Singapore (4th), Dubai (4th) and Beijing (4th), followed by Madrid (6th), New York (6th), Debrecen (6th) and Milan (7th). Here, this is because of three factors: 1) the high embodied carbon of EC compared to other glass products, 2) the limited energy savings of EC during heating periods, 3) the high carbon impact of shipping EC (due to the specific location of its manufacturer). The combination of these lead to a considerably higher environmental impact, which makes EC less competitive and viable.

4.1. Importance of embodied carbon

Fig. 11 presents the proportion of embodied carbon for each glass scenario (represented by the respective darker section on each bar). The results show that embodied emissions play a less dominant role in hot climates (Singapore and Dubai), whereby the operational energy demand is higher. This is theoretically sound, considering that the façade in this study is almost completely glazed and south facing. However, embodied carbon emissions become more dominant in other regions; this is shown in the percentage of embodied carbon for each city and scenario, presented in Table 4. The results also reinforce the significance of the increasing embodied carbon for current advanced glazing techniques, such as EC.

Fig. 11 highlights the overall life-cycle impact of each glass scenario and offers a comparison for overall environmental impact. This graph strongly indicates the need for more attention on embodied carbon, and

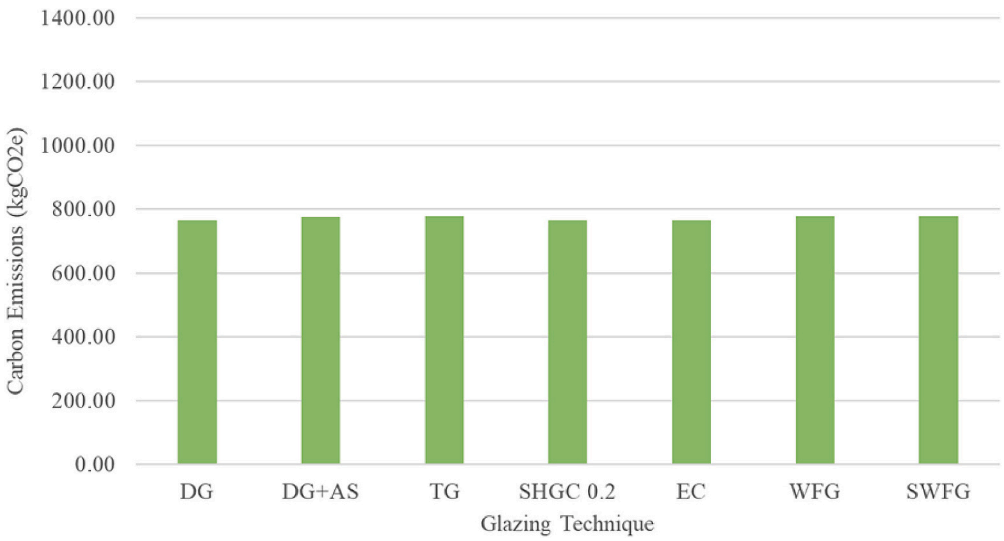


Fig. 10. End of Life stages for glass scenarios (C1 (Demolishment), C2 (Transportation), C3 (Recycling), and C4 (Landfill Disposal)).

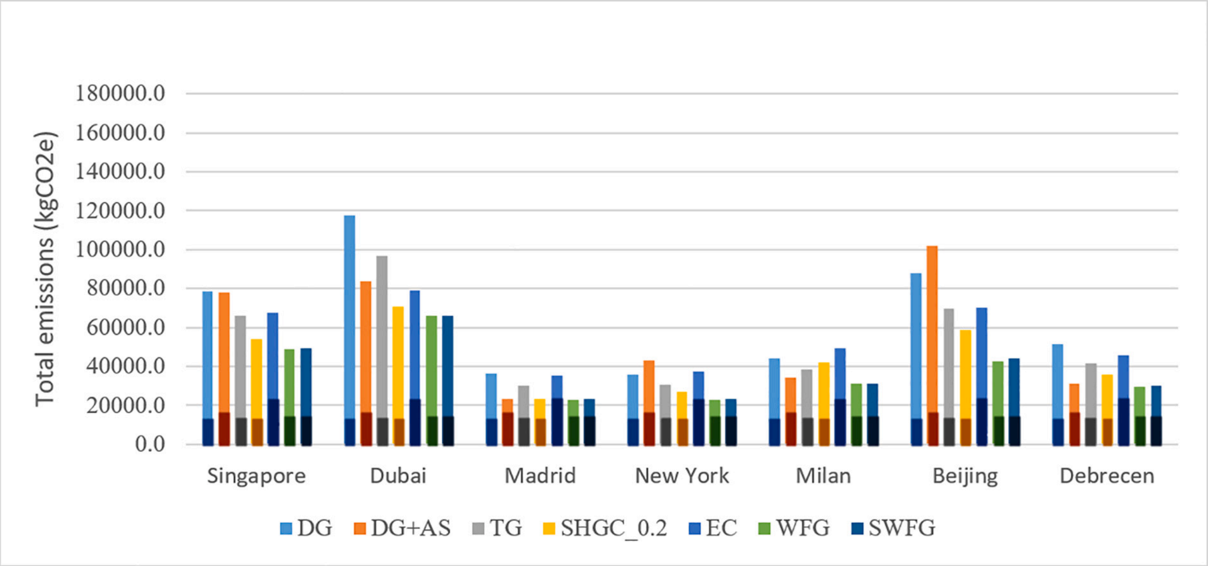


Fig. 11. Life-Cycle comparison of seven glass options in seven cities.

Table 4

Life-cycle assessment of seven glass options in seven cities *(DG)% refers to the emissions with respect to Double Glazing*.

City	Technique	Total Emissions (kgCO2e)	OPERATIONAL (OC) (kg(CO2e)	EMBODIED (EC) (kg(CO2e)	OC%	EC%	OC compared to DG (%)	EC compared to DG (%)	TOTAL compared to DG (%)	Glass Viability Index (GVI)
Singapore	DG	78358.1	64534.5	13823.7	82.4%	17.64%				
	DG+AS	77959.0	60850.2	17108.8	78.1%	21.95%	-5.7%	23.8%	-0.5%	18.24
	TG	65995.0	51554.0	14441.0	78.1%	21.88%	-20.1%	4.5%	-15.8%	1.45
	SHGC	54295.5	40415.6	13879.9	74.4%	25.56%	-37.4%	0.4%	-30.7%	0.07
	EC	67390.7	43371.5	24019.2	64.4%	35.64%	-32.8%	73.8%	-14.0%	14.67
	WFG	48995.6	33861.0	15134.5	69.1%	30.89%	-47.5%	9.5%	-37.5%	1.32
	SWFG	49124.1	33989.6	15134.5	69.2%	30.81%	-47.3%	9.5%	-37.3%	1.29
Dubai	DG	117457.6	103634.0	13823.7	88.2%	11.77%				
	DG+AS	83700.9	66592.1	17108.8	79.6%	20.44%	-35.7%	23.8%	-28.7%	1.81
	TG	96859.7	82418.7	14441.0	85.1%	14.91%	-20.5%	4.5%	-17.5%	0.89
	SHGC	70840.3	56960.4	13879.9	80.4%	19.59%	-45.0%	0.4%	-39.7%	0.04
	EC	79151.2	55178.3	23972.9	69.7%	30.29%	-46.8%	73.4%	-32.6%	6.38
	WFG	65815.2	50680.7	15134.5	77.0%	23.00%	-51.1%	9.5%	-44.0%	0.77
	SWFG	65815.2	45716.3	15134.5	69.5%	23.00%	-55.9%	9.5%	-44.0%	0.68
Madrid	DG	36218.0	22394.3	13823.7	61.8%	38.17%				
	DG+AS	23098.8	5990.0	17108.8	25.9%	74.07%	-73.3%	23.8%	-36.2%	4.10
	TG	30252.3	15811.3	14441.0	52.3%	47.74%	-29.4%	4.5%	-16.5%	2.85
	SHGC	23146.1	9266.2	13879.9	40.0%	59.97%	-58.6%	0.4%	-36.1%	0.13
	EC	35419.3	11295.9	24123.4	31.9%	68.11%	-49.6%	74.5%	-2.2%	28.26
	WFG	23029.4	7894.9	15134.5	34.3%	65.72%	-64.7%	9.5%	-36.4%	2.80
	SWFG	23065.1	7930.6	15134.5	34.4%	65.62%	-64.6%	9.5%	-36.3%	2.73
New York	DG	36001.8	22178.1	13823.7	61.6%	38.40%				
	DG+AS	43340.3	26231.5	17108.8	60.5%	39.48%	18.3%	23.8%	20.4%	-16.57
	TG	30728.3	16287.3	14441.0	53.0%	47.00%	-26.6%	4.5%	-14.6%	3.19
	SHGC	26762.4	12882.5	13879.9	48.1%	51.86%	-41.9%	0.4%	-25.7%	0.18
	EC	37418.4	13603.1	23815.4	36.4%	63.65%	-38.7%	72.3%	3.9%	35.50
	WFG	22918.8	7784.3	15134.5	34.0%	66.04%	-64.9%	9.5%	-36.3%	2.82
	SWFG	23387.2	8252.6	15134.5	35.3%	64.71%	-62.8%	9.5%	-35.0%	2.83
Milan	DG	44250.4	30426.8	13823.7	68.8%	31.24%				
	DG+AS	34018.9	16910.2	17108.8	49.7%	50.29%	-44.4%	23.8%	-23.1%	4.97
	TG	38623.2	24182.2	14441.0	62.6%	37.39%	-20.5%	4.5%	-12.7%	3.01
	SHGC	41859.9	27980.0	13879.9	66.8%	33.16%	-8.0%	0.4%	-5.4%	0.70
	EC	49188.9	25229.9	23959.0	51.3%	48.71%	-17.1%	73.3%	11.2%	59.40
	WFG	30900.5	15766.0	15134.5	51.0%	48.98%	-48.2%	9.5%	-30.2%	2.77
	SWFG	31284.7	16150.1	15134.5	51.6%	48.38%	-46.9%	9.5%	-29.3%	2.76
Beijing	DG	87776.1	73952.5	13823.7	84.3%	15.75%				
	DG+AS	102177.4	85068.6	17108.8	83.3%	16.74%	15.0%	23.8%	16.4%	-6.04
	TG	69885.4	55444.4	14441.0	79.3%	20.66%	-25.0%	4.5%	-20.4%	1.01
	SHGC	58716.1	44836.1	13879.9	76.4%	23.64%	-39.4%	0.4%	-33.1%	0.06
	EC	70032.3	45908.3	24124.1	65.6%	34.45%	-37.9%	74.5%	-20.2%	11.18
	WFG	42816.9	27682.3	15134.5	64.7%	35.35%	-62.6%	9.5%	-51.2%	0.88
	SWFG	44114.7	28980.2	15134.5	65.7%	34.31%	-60.8%	9.5%	-49.7%	0.88
Debrecen	DG	51664.2	37840.6	13823.7	73.2%	26.76%				
	DG+AS	31354.1	14245.3	17108.8	45.4%	54.57%	-62.4%	23.8%	-39.3%	2.85
	TG	41432.5	26991.5	14441.0	65.1%	34.85%	-28.7%	4.5%	-19.8%	1.73
	SHGC	35563.4	21683.5	13879.9	61.0%	39.03%	-42.7%	0.4%	-31.2%	0.11
	EC	45859.5	21498.2	24361.4	46.9%	53.12%	-43.2%	76.2%	-11.2%	19.63
	WFG	29816.5	14681.9	15134.5	49.2%	50.76%	-61.2%	9.5%	-42.3%	1.75
	SWFG	29927.7	14793.1	15134.5	49.4%	50.57%	-60.9%	9.5%	-42.1%	1.71

subsequently the consideration of carbon savings over time within glazing.

Naturally, each glass option investigated within this paper saves operational energy compared to the baseline (double glass). However, they mostly achieve this at a cost of increase in embodied carbon. Compared to double glass, the operational savings and embodied trade-off are not directly correlated, i.e., some options achieve more operational savings with less embodied carbon. This difference in embodied carbon is important, because of multiple reasons, such as 1) the short lifespan of glass (35 years) and 2) the short deadlines in carbon savings: embodied carbon is emitted at the beginning of a project while operational carbon is spread over the RSP, e.g. 60-year lifespan. This means that the viability of a glass option may not correlate with the comparable position of LCA savings (shown in Fig. 11 and Table 4), because of longer time required to compensate the initial increase in embodied carbon through operational carbon savings, which makes the option less desirable.

4.2. LCA-based comparative analysis: Glass Viability Index (GVI)

The results indicate that it is crucial to consider whole life carbon, and not just simply operational carbon: some of the options can be attractive from an operational perspective, but perform worse in LCA. For example, if Double Glass is considered as a baseline standard, higher embodied carbon is particularly prevalent if the operational savings needed to compensate this increase is longer than 8–13 years (which would pass national emission cut deadlines of 2030 and 2035) or >35 years (lifespan of a glass façade). To complicate the choice of glazing technique even further, each glass option offers different savings in different climates. Finally, another issue is the LCA being dependent on RSP: because of short service life of glass, the ranking of best glass options for each case depends on whether the RSP is set to 50 years or 70, mainly because the glass options are replaced once or twice respectively. To overcome these difficulties in selecting the most appropriate glazing technique, the authors suggest the use of a new Glass Viability Index (GVI) based on the concept of payback period, which expresses the number of years that are required for any glass option to balance its increase in embodied carbon by reduced operational energy consumption, without any dependence on the user defined RSP. This can be observed in eq. 1:

$$GVI = \frac{\Delta EC_{i-b}}{\Delta OP_{y,b-i}}\ [\mathrm{y}] \tag{1}$$

$$\Delta EC_{i-b} = EC_i - EC_b\ [\mathrm{CO_2}] \tag{2}$$

$$\Delta OP_{y,b-i} = OP_{y,b} - OP_{y,i}\ [\mathrm{CO_2/y}] \tag{3}$$

where EC_b and EC_i are the embodied carbon of LCA phase A1-A5 of the baseline option (in this paper DG), and alternative i respectively, while $OP_{y,b}$ and $OP_{y,i}$ are the annual operational carbon emission of baseline and alternative i respectively.

With this, the shorter the period calculated, the more carbon viable the glass is, expressed through the unified value contained within the GVI. This index value is significant for a twofold reason: it is clear to observe whether the glass can balance 1) the increased embodied carbon before national or international carbon goals, and 2) the carbon within a typical lifespan of the glass façade. A negative index value suggests that the operational carbon of option i is higher than the base case, (assuming that the "embodied carbon investment" ($EC_i - EC_b$) will be positive for higher performance glazing techniques).

Figs. 12–18 present the carbon interactions between the seven case study cities and seven glass options, with DG as a baseline comparison across a 100-year timeframe. In the graphs, the glazing is replaced every 35 years, as per RICS guidance.

The advantage to this presentation is of particular relevance, as it highlights that due to the heterogenous definition/standard of the length of an RSP, the total carbon emissions of a glazing technique can drastically change. This is due to the embodied-operational split of carbon emissions, as advanced glazing techniques usually possess higher embodied carbons; if the RSP is longer, these techniques may become less viable than initially presented by shorter RSPs, since more replacements will occur. As such, this study suggests that some RSPs may be systematically biased to promote certain techniques; the authors recommend using an RSP-independent metric such as GVI.

Another advantage of presenting the results in such a manner is that one can observe how small changes in operational efficiency can result in large impacts over the building's lifespan, and vice versa for embodied carbon changes. This is linked to a glazing's GVI, whereby the quicker a technique overcomes the initial embodied carbon increase, more savings can be achieved over a longer timeframe.

The results and figures highlight the importance of embodied carbon as well as GVI for glass facades. The former is relevant because the high embodied carbon of advanced glass options makes a difference in the overall carbon impact, especially because the short lifespan of the façade. The latter is relevant because it presents the viability of glass by evaluating whether a glass option is feasible to use compared to DG. GVI

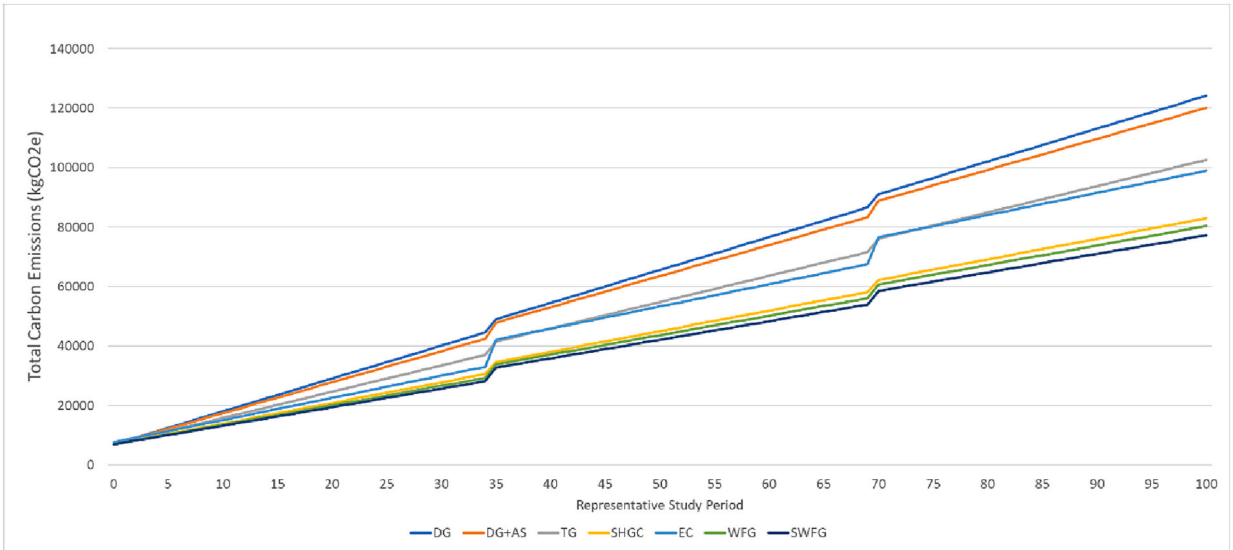


Fig. 12. Carbon emissions for seven glass options in Singapore.

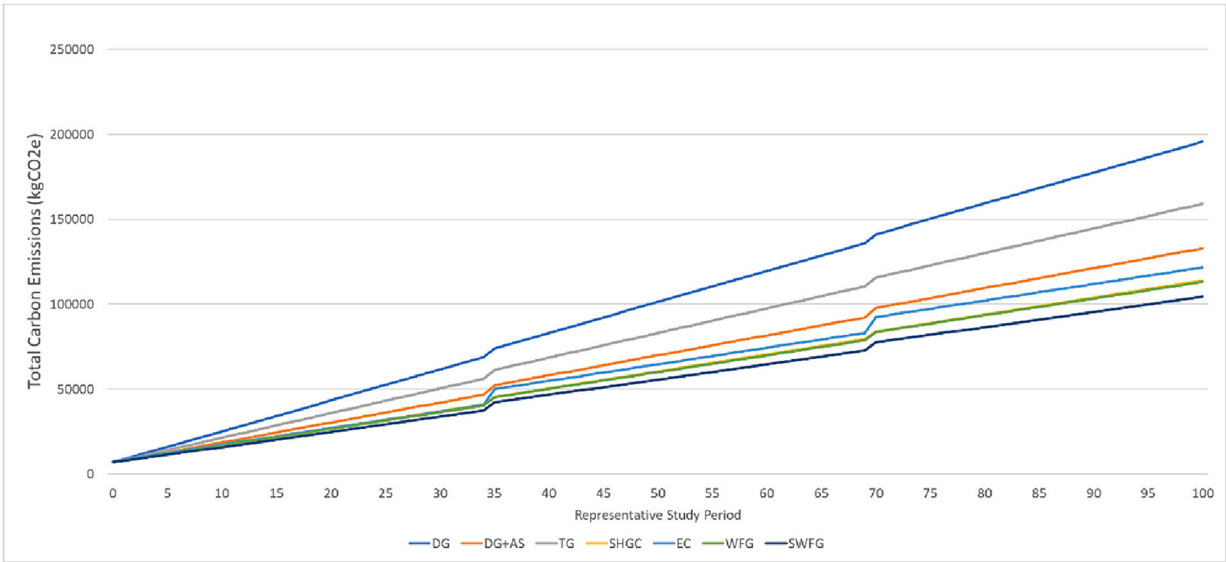


Fig. 13. Carbon emissions for seven glass options in Dubai.

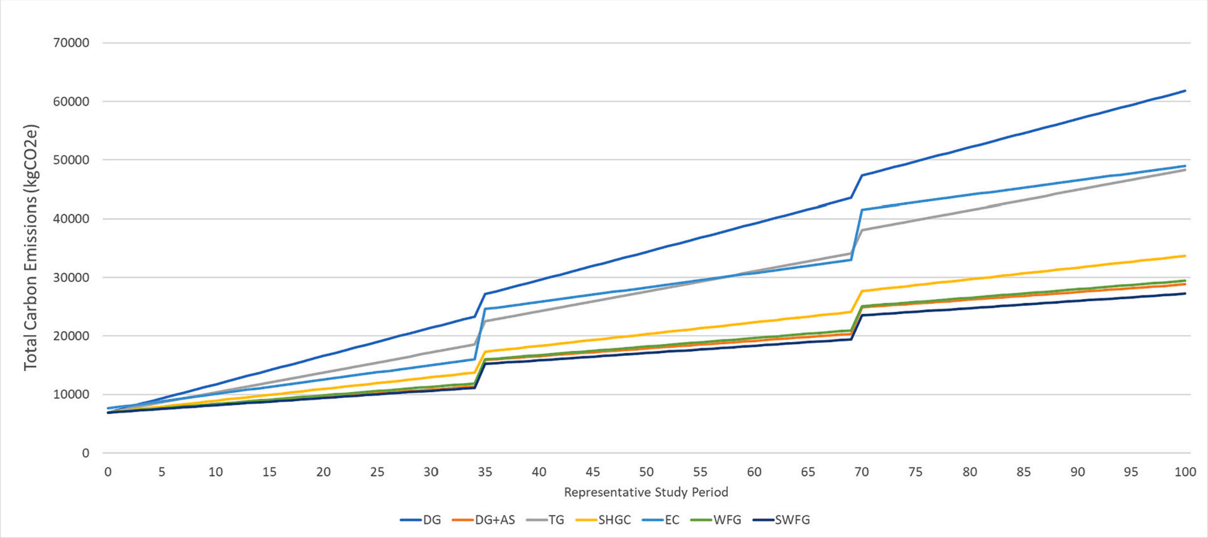


Fig. 14. Carbon emissions for seven glass options in Madrid.

effectively makes the study period an independent variable, and can provide rankings for any glass options in any climate.

However, as Table 4 shows, the favourable order for the glazing techniques changes when GVI is considered. These results are quite informative for multiple reasons. Firstly, a more accurate assessment of viability can be made. For example, the index quantifies EC as having a high value, suggesting that the option is less viable than initially thought, making achieving climate goals difficult. Secondly, the weighting between operational and embodied carbon can be evaluated for each technique and climate, presenting a whole LCA across a typical 60-year lifespan of a building. This presents a unique advantage to designers or stakeholders at the outset stage of a project, allowing the quantification of the carbon impact of a structure, as well as providing evidence for which glazing to choose on a multi-criteria decision-making basis.

The results show that WFG and SWFG present effective solutions in all climates, due to their low embodied carbon and good operational performances. This finding is presented in the right-hand side of Table 4, which expresses the net savings achieved by using WFG instead of any other technique (green represents a net saving). In addition, GVI values for each glazing technique with double glazing as a base case have also been provided, for each individual climate scenario. Whilst solar protection glass presents a good performance, it should be noted that it is practically a dark mirrored glass, and therefore it drastically compromises the transparency of the glazing, when compared to other techniques studied here. WFG in these results initially appears to offer a better performance than SWFG; this is due to the non-inclusion of $Q_{\_useful}$ as mentioned previously.

A significant result is also found in this study; embodied carbon can represent anywhere from 11 to 74% of the total carbon of a glazing technique, when measured across a 60-year RSP. Embodied carbon represents more of a share in Csa (Madrid) and Cfa (New York) climates, where operational carbon occupies a smaller amount.

4.3. *Implications of Glass Viability Index (GVI): Impact of renewable energy on glass viability*

The impact of GVI enables a more holistic analysis of relationship

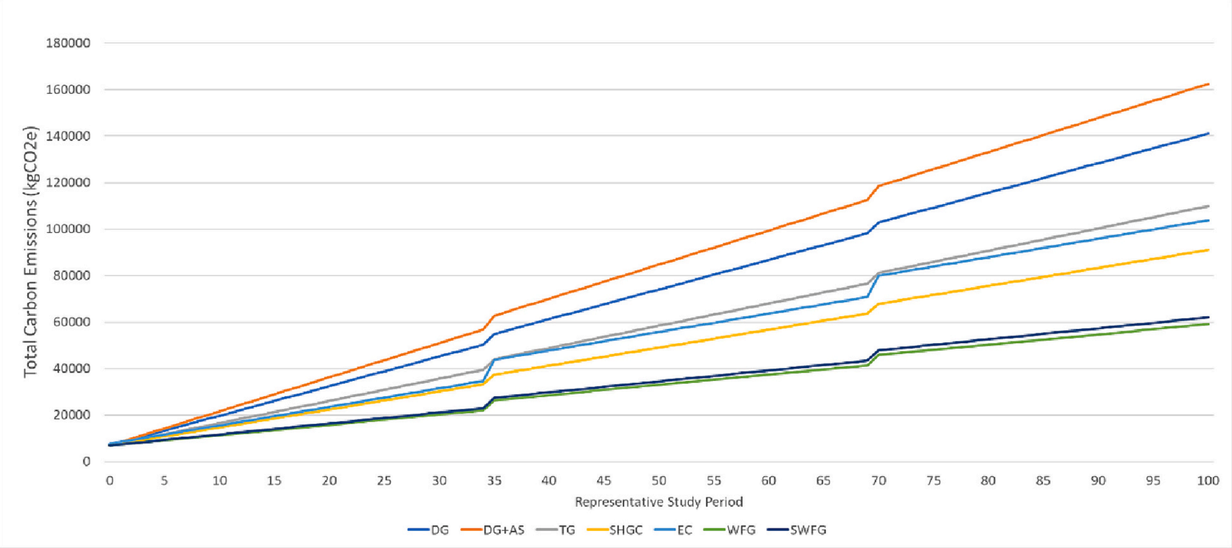


Fig. 15. Carbon emissions for seven glass options in New York.

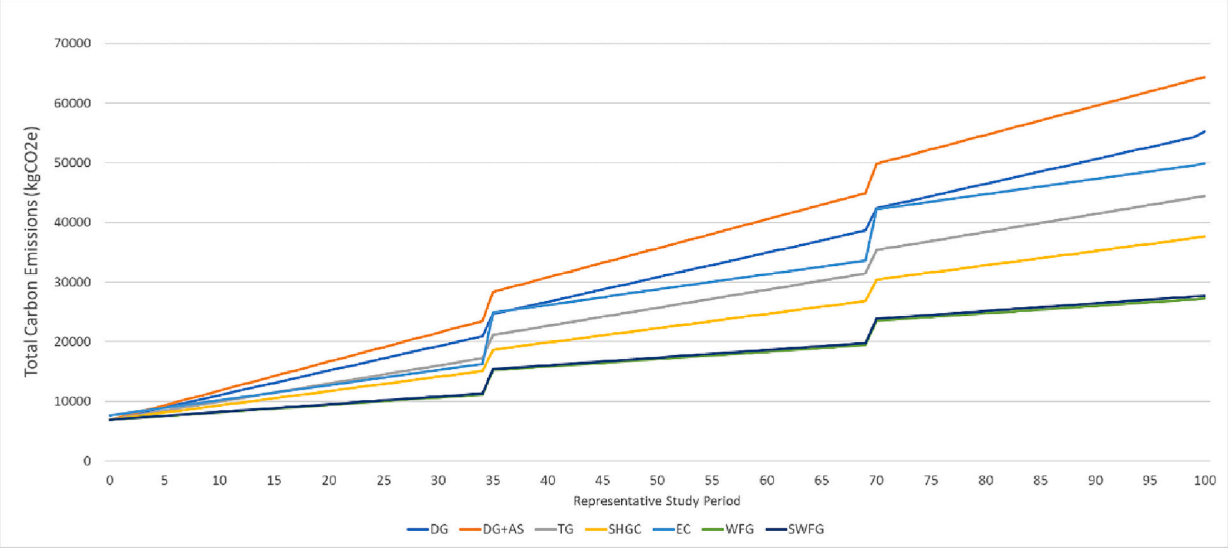


Fig. 16. Carbon emissions for seven glass options in Beijing.

between properties of a glass option (i.e. embodied and operational carbon) and other drivers of environmental impact, specifically the impact of renewable energy use. LCA is typically performed as a projection in the future where variables of the energy supply (e.g. carbon coefficient of an energy source) are assumed to be constant over time. However, in reality this is not the case as renewables are playing an increasing role in national energy production as well as energy supply of individual buildings. For both cases, the higher proportion of renewables mean that the same decrease in energy use for any window will yield less operational carbon savings over time, which results in longer GVI. This underlines three significant outcomes.

First, the main driver of GVI over longer periods is not actually the performance of the window (expressed in energy savings) but the carbon coefficient of the energy supply: as the OC impact for the same energy demand decreases, the performance of the window becomes less relevant. This is already shown in Fig. 8, where the difference between carbon coefficients are relevant factors in the OC savings and eventually the GVI.

The second outcome is the importance of embodied carbon. The decreasing OC savings over time render the importance of energy savings less relevant compared to embodied carbon, especially considering that itremains 'locked in the building' during construction. This is particularly relevant because the embodied carbon of glass products is difficult to lower with renewables as most of it comes from materials and heat (the latter may be electric in the future but based on the current uptake of electric foundry in the glass industry, this is likely a long-term goal at best). This highlights the importance of GVI as using it for the evaluation of glass options assures that the overall embodied carbon investment (compared to the double glazing base case) brings sufficient carbon savings overall.

The third outcome is the result of the first two above: considering a 'dynamic' GVI where an increasing use of renewables is considered and the carbon coefficient of energy supply changes over time, it can be concluded that practically each glass alternative becomes obsolete at a point of time in the future when the OC savings become significantly low and the GVI exceeds the lifespan of the glass. Furthermore, at a point in time all glass alternatives become obsolete compared to the Base Case, which is what the authors defined as a 'GVI Breakpoint'; improvements

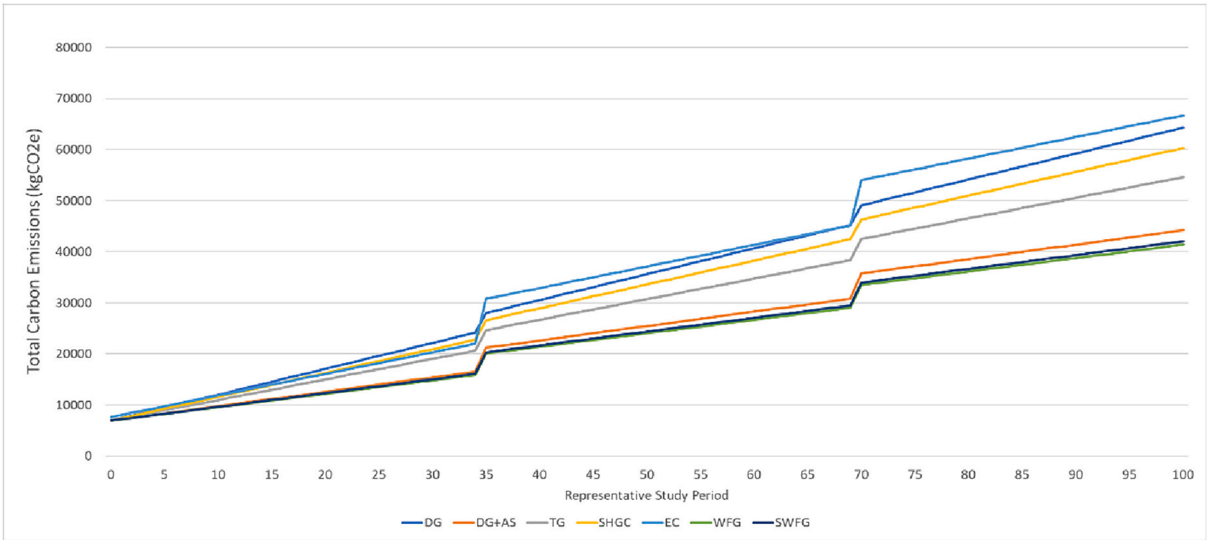


Fig. 17. Carbon emissions for seven glass options in Milan.

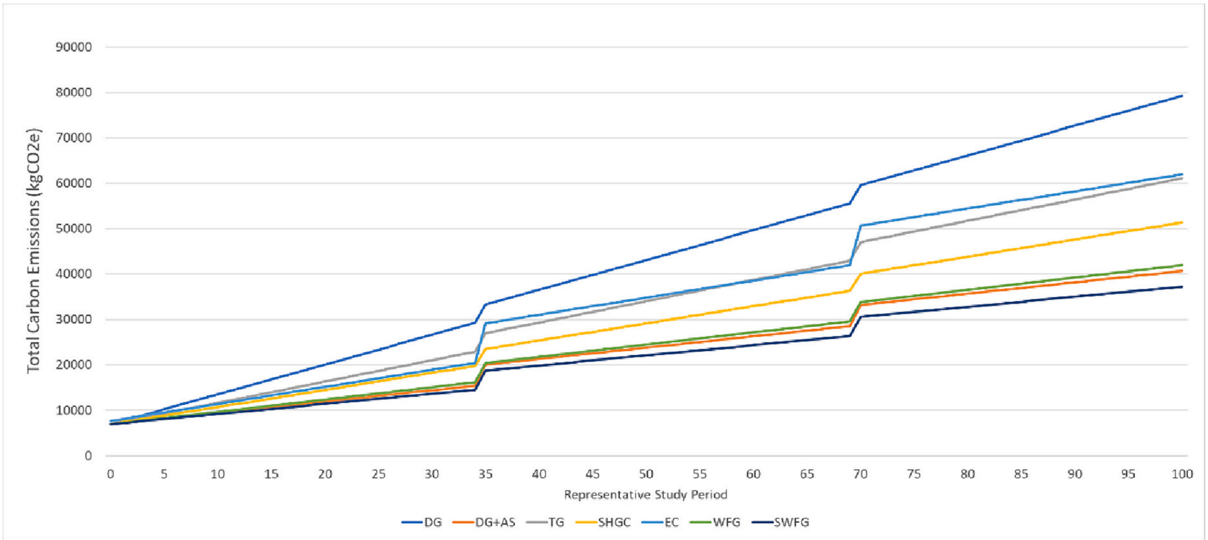


Fig. 18. Carbon emissions for seven glass options in Debrecen.

or alternative glass technologies must thus be used instead. Here, the challenge is that one should not stop using alternatives at the Breakpoint but sooner: ideally a whole lifespan before the Breakpoint or at least a period of full carbon payback before the Breakpoint.

These three outcomes underline an additional significance of GVI: the variable not only shows (and assures) if the glass option is carbon viable today, but also the estimation of the GVI Breakpoint assures that the option remains viable in the future too. This means that the GVI of the glass option has to: 1) be shorter than the service life of the glass, 2) have a sufficient carbon payback before the GVI Breakpoint, and 3) have a sufficient carbon payback before the national and international carbon goals. GVI can effectively present all of these considerations in a single variable. This is demonstrated in Fig. 19 (variation of grid conversion factor based on data from the International Energy Agency (IEA)), and Figs. 20–24 (carbon viability changing with conversion factor) below. The graph for SWFG has been omitted, since it is similar to WFG. For any carbon coefficients that are above 35 years on the y-axis (denoted by the horizontal line), means that the operational savings in that scenario will not be enough to offset the relative embodied carbon increase, and is carbon unviable.

From these results, assuming that there are no drastic changes to glazing production or operation, it can be estimated the year at which each technique becomes unviable, as it surpasses the 'breakpoint' for that climate. The closest breakpoints are shown in Table 5 below: for techniques reasonably far away from reaching their breakpoints, these have been omitted, as this far an extrapolation into the future is likely to be inaccurate and unreliable. In addition, it is unclear whether the carbon coefficient of the energy supply will decrease low enough to permit these scenarios (nonetheless, it is worth nothing that no local renewable generation is considered in this study, that might render the reaching of the GVI Breakpoint project-specific).

As shown, the main technique with challenges around future carbon viability is electrochromic glazing, in all seven climate studied. The suggested year in which this happens ranges from 2024 to 2042. Since this study assumes static carbon coefficients for energy during the lifespan of the glazing (35 years), electrochromic in its current state has up to 18 years before it becomes wholly unviable from a carbon perspective. For New York, Milan, and soon Madrid, this study proposes that EC should not be used from a carbon perspective, as the breakpoint is around the current date of publication.

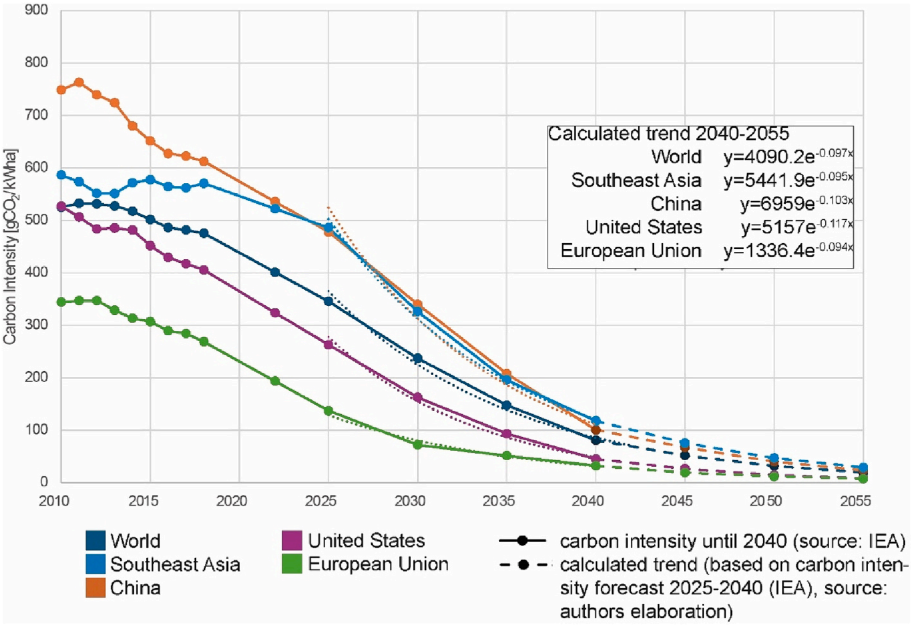


Fig. 19. Carbon intensity of electricity grid forecast.

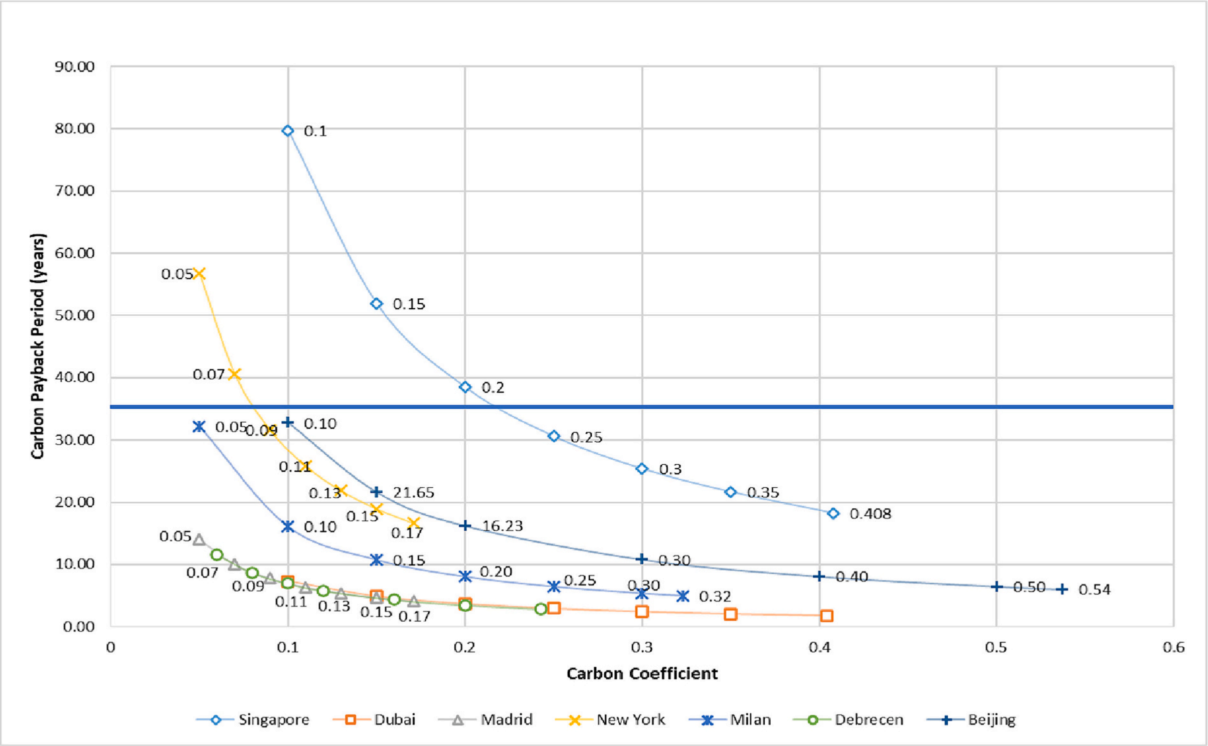


Fig. 20. Effect of carbon intensity on payback period for DG + AS in each location, showing GVI Breakpoint in years 2032 for Singapore, and 2035 for New York.

A similar observation is found but to a lesser extent for DG + AS, with 2032 and 2035 breakpoints for Singapore and New York respectively. The rest of the techniques (SHGC, TG, WFG, and SWFG) are not suggested to become unviable solely based on changing carbon coefficients in the future for operational performance.

4.4. Implications of Glass Viability Index (GVI): Impact of cost and changes in ROI

The analysis of 'dynamic' GVI has another significant implication on the future viability of glass options; the increase of renewables in energy production does not result in decreasing energy prices. Looking at the countries with highest electricity cost [71], the countries listed at the top are all characterized by high renewable energy production, the top five being Denmark (79%), Germany (40.1%), United Kingdom (40.4%), Austria (79.9%) and Italy (41%) respectively [72]. Whilst it is acknowledged that the pricing of electricity is subject to a variety of factors in addition to use of renewables (e.g. private vs. public ownership, taxation, etc.), based on the data it is still reasonable to assume that the increase of renewables will not lead to a global decrease of energy

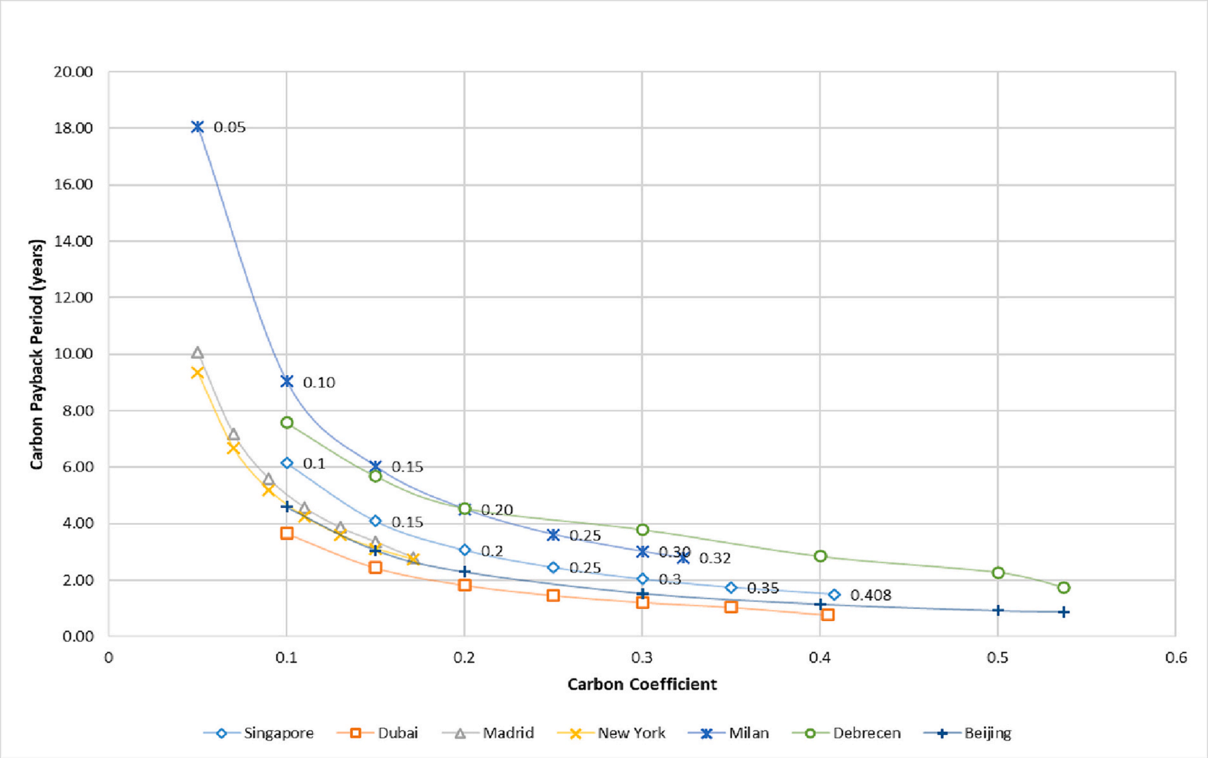


Fig. 21. Effect of carbon intensity on payback period for WFG and SWFG in each location.

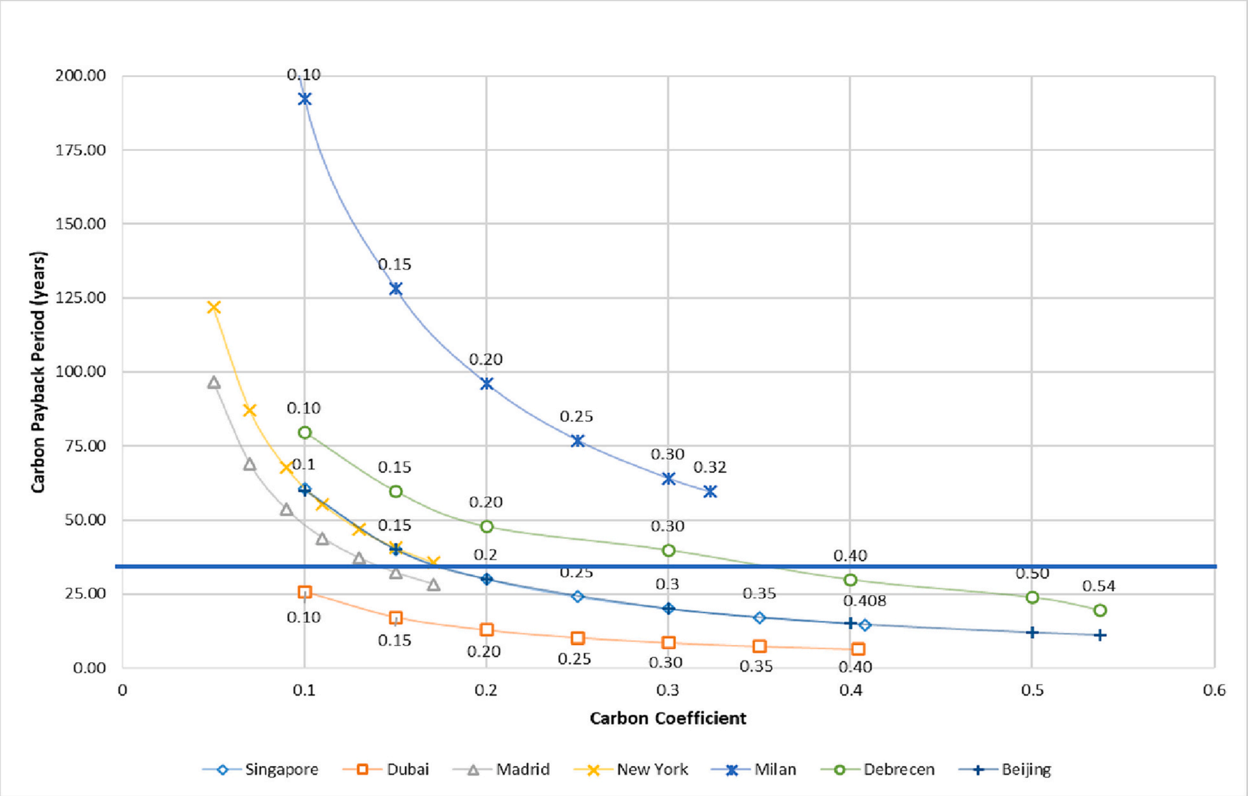


Fig. 22. Effect of carbon intensity on payback period for EC in each location, showing GVI Breakpoint in years 2024 (New York and Milan), 2026 (Madrid), 2029 (Debrecen), 2035 (Singapore), 2038 (Beijing), and 2042 (Dubai).

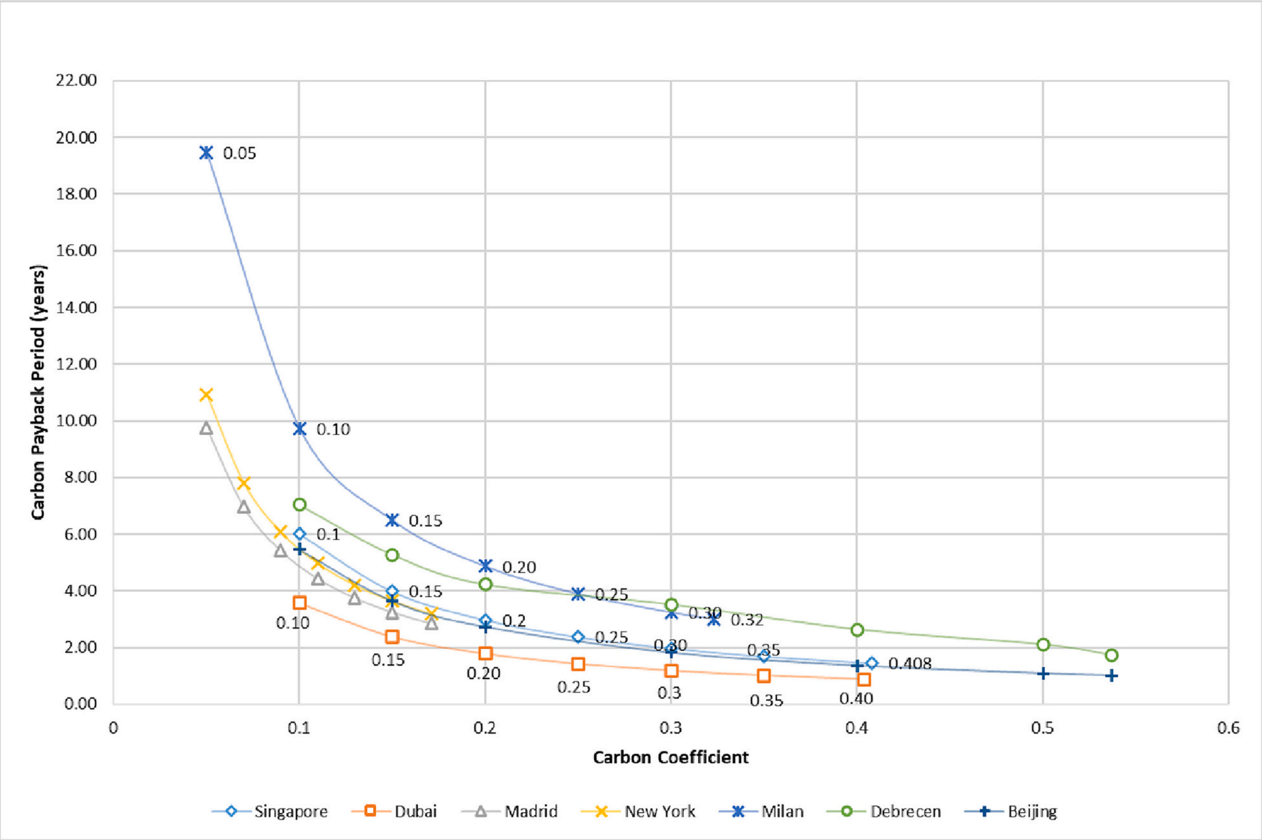


Fig. 23. Effect of carbon intensity on payback period for each location (TG).

prices in every country. This leads to a significant concern highlighted by 'dynamic' GVI which should not be underestimated: as stated above, the GVI Breakpoint marks a point in time when glass alternatives become unviable from a carbon standpoint, however, this does not account for economic viability. In short: savings in energy demand are permanent in the model, which translates into decreasing OC savings and increasing operational cost savings each year. This means that GVI Breakpoint may refer to a point in time when replacing windows in retrofits or investing in better ones for newbuild would result in cost savings but would produce higher carbon and result in pollution. Highlighting this point in time complements GVI. Table 6 below summarises the annual financial energy savings, when alternative glazing options are adopted. This is done via using the energy consumption and cost of electricity for each technique and climate respectively. Due to a lack of accessible information, differences in manufacturing technique and locations etc., the cost and payback period could not be reliably provided here, and as such has been omitted. However, for reference, it is reasonable to assume a cost of \$500–\$1200/m^2 of window as construction cost globally. (Note that the area of a window is not the same as the m^2 shown below, which refers to Gross Internal Area. The typical ratio between the two is 1:4–5 in a commercial building.)

5. Sensitivity analysis

The project uses RICS guidelines and ICE database for LCA calculations to determine carbon impact of the glass options. The mathematical model highlights several elements that should be considered as important factors that affects the overall results.

Transportation (A4) is a significant component that varied greatly among the glass options. This affected results when a glass is being supplied only from one location, which was the case for EC. Here, results show 8.23–13.40 kgCO$_{2e}$ for local products, and 58.90–401.73 kgCO$_{2e}$ for EC. It shall be noted that whilst this shows a significant difference proportionally, its impact on the overall carbon is very low (<1% overall). Therefore, this was deemed a suitable process.

A significant element was the product stage (A1-A3) for every product, which contributes a great proportion to the overall embodied carbon. To avoid potential errors in calculating carbon, the carbon for glass options relied on EPDs when possible. This specifically applied to EC, which has a higher carbon than the other options. The calculation includes risks in terms of using the same ICE database for all cities, when calculating the product stage for common elements in the model (e.g., concrete slab and walls). As noted earlier, it was assumed that these common materials have similar carbon impact when produced in different countries, which made this simplification possible. Additionally, since the same common elements were used in all glass scenarios, it is not expected that it affects the comparative analysis significantly. The same applies for carbon of construction process (A5), which was the same for all cases. A similar assumption was taken for B1-B3 and B5; it shall be noted that these elements are deemed to be insignificant for most projects as also pointed out by ISE guidance on LCA.

Furthermore, the CO$_2$ emissions related to the operational energy consumed during the life of the building is highly influenced by the conversion factor of each country's national grid, with this factor also determining higher differences among technologies used within the same location. As a result, these were calculated for each location respectively. Indeed, the energy generation is a relevant factor for the project because the use of renewables affect both operational and embodied carbon emissions. In case of the former, the increase of renewable energy production, both for energy supplied by the grid and by distributed generation, is expected to significantly lower the carbon impact of operational energy use (B6) especially for cities where use of renewables is currently limited. The effect of higher renewables is considered in detail in Section 4.2 above. Considering that the

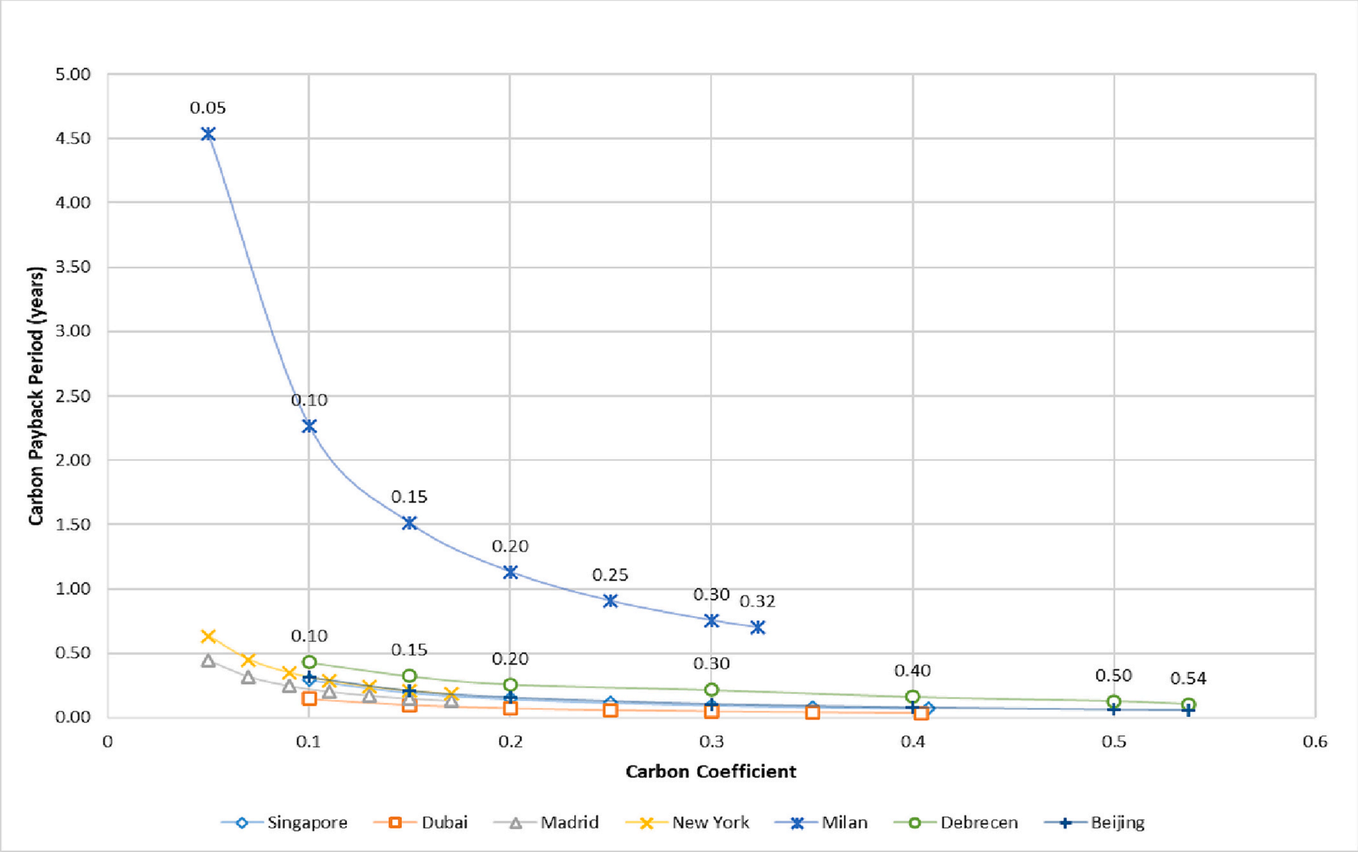


Fig. 24. Effect of carbon intensity on payback period for each location (SHGC).

Table 5
List of glazing techniques that reach their breakpoint soonest.

Technique	Location	Breakpoint Year
DG + AS	Singapore	2032
DG + AS	New York	2035
EC	Singapore	2035
EC	Madrid	2026
EC	New York	2024
EC	Milan	2024
EC	Beijing	2038
EC	Debrecen	2029
EC	Dubai	2042

Representative Study Period (RSP) is 60 years, it can be assumed that the percentage of operational carbon will be significantly lower by the end of the RSP. In case of embodied carbon of glass, it should be considered that much of the embodied carbon of glass production is energy related, as the manufacturing process requires high temperatures. With the advance of renewable energy use, this may be lowered as well. It should be noted however, that much of the process is heating related which relies predominantly on gas and that for advanced glass options (e.g. electrochromic glass) much of the embodied carbon is resulted by material use and not of energy as stated in EPD [11].

Finally, recyclability of glass is another aspect that can affect the results. In this calculation tempered glass was assumed for all glass options, which would be the typical case for glass facades with larger glass units. Since tempered glass is not recyclable, there was no recycling calculated at the End-of-Life stage. This also corresponded with the 100:0 calculation approach which was implemented in the model. However, in case of smaller glass unit size, a different calculation model (0:100 or 50:50) would benefit more standard glass options (DG, TG, DG + AS) as these can be made potentially of float glass that can be recycled. It shall be noted that recycling would have a relatively small impact on the results and that glass recycling in the construction industry is relatively low, which would further prompt towards disregarding recycling component.

Among the parameters influencing LCA, a great impact is represented by the RSP and, consequently, the lifespan of the building elements. In particular, during the considered 60 RSP, the glazing façade is replaced only once due to its 35 years lifespan. Considering a different RSP would change the relative impacts of embodied carbon and operational carbon. On the one hand, with a shorter RSP for instance, the impact of embodied carbon would be higher, while longer ones would determine a bigger impact related to operational carbon. On the other hand, changing the RSP from 60 to 80 years would determine the necessity to replace two times the glazing façade, resulting in poorer LCA performance of certain technology characterized by high embodied carbon (EC for instance). This aspect represents a limitation of comparability among techniques being the result deeply influenced by the considered RSP. The use of GVI mitigates this issue by providing a metric that is RSP-independent.

6. Conclusion

The paper analysed the LCA results of seven glass options in seven cities. The LCA calculation was cradle-to-grave, and considered all stages of life cycle: Production, Construction, Use and End of Life. The results highlighted the importance of embodied carbon in the overall LCA: its proportion is noticeably increased in advanced glass options. This increase in embodied carbon for the latest glass options suggests a possible conflict in carbon savings: such options require more embodied carbon, which is released in the environment at the beginning of the project, to create higher operational savings. To measure this, the authors suggest the use of a Glass Viability Index or GVI, to measure the

Table 6
Energy consumption expressed as relative cost savings per technique and climate.

Location	Technique	Energy Consumption (kWh/m2.a)	Saving vs. DG (kWh/ m2.a)	Electricity cost (USD/ kWh)	Savings (USD/ year)
Singapore	DG	150.3			
	DG + AS	141.7	8.60	0.24	2.06
	TG	120.0	30.30	0.24	7.27
	SHGC 0.2	94.0	56.30	0.24	13.51
	EC	100.9	49.40	0.24	11.86
	WFG	86.9	63.43	0.24	15.22
	SWFG	82.7	67.65	0.24	16.24
Dubai	DG	243.9			
	DG + AS	156.6	87.30	0.08	6.98
	TG	193.9	50.00	0.08	4.00
	SHGC 0.2	133.9	110.00	0.08	8.80
	EC	129.7	114.20	0.08	9.14
	WFG	138.4	105.51	0.08	8.44
	SWFG	125.9	117.96	0.08	9.44
Madrid	DG	123.9			
	DG + AS	32.5	91.35	0.37	33.80
	TG	87.2	36.66	0.37	13.56
	SHGC 0.2	50.8	73.10	0.37	27.05
	EC	62.1	61.80	0.37	22.87
	WFG	47.1	76.83	0.37	28.43
	SWFG	39.7	84.23	0.37	31.16
New York	DG	122.3			
	DG + AS	144.8	−22.50	0.18	−4.05
	TG	89.6	32.70	0.18	5.89
	SHGC 0.2	70.7	51.60	0.18	9.29
	EC	74.7	47.60	0.18	8.57
	WFG	39.6	82.72	0.18	14.89
	SWFG	41.2	81.13	0.18	14.60
Milan	DG	89.1			
	DG + AS	49.3	39.75	0.58	23.06
	TG	70.7	18.36	0.58	10.65
	SHGC 0.2	81.9	7.20	0.58	4.17
	EC	73.8	15.28	0.58	8.86
	WFG	46.3	42.77	0.58	24.81
	SWFG	44.3	44.74	0.58	25.95
Beijing	DG	130.8			
	DG + AS	150.5	−19.70	0.25	−4.93
	TG	98.0	32.80	0.25	8.20
	SHGC 0.2	79.2	51.60	0.25	12.90
	EC	81.1	49.70	0.25	12.43
	WFG	46.5	84.30	0.25	21.07
	SWFG	49.6	81.22	0.25	20.31
Debrecen	DG	147.3			
	DG + AS	55.1	92.19	0.12	11.06
	TG	104.9	42.39	0.12	5.09
	SHGC 0.2	84.2	63.13	0.12	7.58
	EC	83.4	63.85	0.12	7.66
	WFG	62.4	84.92	0.12	10.19
	SWFG	51.3	95.96	0.12	11.52

necessary amount of time for any glass option to balance the increased embodied carbon with its respective operational savings. This value is important because if the GVI is above 6–11 years, then it compromises carbon goals as of 2024 (goals in 2030 or 2035). If GVI is above 35 years than the glass may not be a viable option altogether. For such cases, the climate goals may be achieved better with another glass alternative. Additionally, GVI recognises the possible decrease in operational carbon impact due to increase in renewables in the electricity production. Building on this, the authors also offer 'dynamic' GVI, which takes the increase of renewables into account. The 'dynamic' GVI presents a point in time described as the 'GVI Breaking Point', whereby the renewables lower the operational carbon to a level where the invested additional embodied carbon compared to a Base Case cannot be balanced within the 30–35 years lifespan of a window. From the authors perspective, GVI should not be seen as an alternative indicator to LCA, but might be used as a tool to better support the decision towards one solution or another. Analogous to economic evaluation, the use of the two indicators might provide a better understanding of the carbon investment (GVI).

Results show that WFG and SWFG results in significant LCA savings compared to other options available. This is because WFG and SWFG saves operational energy with limited increase in embodied carbon. The results also show that EC has difficulty in maintaining viability: it has a significantly higher LCA than other options, partially due to its high embodied carbon during both manufacture and international transportation, the latter due to the glass only being available in one location. This is reinforced by the GVI for EC being poor, falling between 6 and 59 years payback depending on climate.

7. Consideration for future research

The paper highlights the importance of embodied carbon of glass and its impact on viability, especially for advanced glass options with higher embodied carbon. Future research would have to evaluate the Glass Viability Index (GVI) for more glass products and settings, especially for additional advanced glass products.

Additionally, there are some significant elements around operation of WFG that are worthy of further investigation: the effect of the condensation-evaporation cycle in lifetime duration of the product, optical properties variation due to water alkalinity, specific title description of the building typology, and investigations around ideal operational temperature settings in respect of thermal comfort, glass orientation and climate.

CRediT authorship contribution statement

Matyas Gutai: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Brandon Mok:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giulio Cavana:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abolfazl Ganji Kheybari:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

Matyas Gutai and Abolfazl Ganji Kheybari have equity ownership in Water-filled Glass Ltd, which owns patents for water-filled glass. The other authors have no interest to disclose.

Data availability

Data will be made available on request.

Appendix A. Validation of TRNSYS model

As mentioned earlier, the simulation was conducted with TRNSYS and LBNL Window, which followed the method introduced in previous publications [52,53]. The model was validated in two stages. Please see summary from previous publication below:

Concerning optical characteristics, the Beer Lambert law enables the computation of water layer absorption and transmission based on the absorption coefficient of pure water and the layer's thickness. These variations in thickness offer a method to selectively control the transmission of solar and visible radiation while managing heat absorption. Previous research has demonstrated the heat collection potential of different water layer thicknesses. For instance, a 1 cm water layer absorbs 30% of solar heat (wavelength: 300–2500 nm) while allowing 99% of visible light (380–780 nm) to transmit, whereas a 10 cm layer absorbs 45% of solar heat and transmits 92% of visible light, assuming (ASTM E-490 AM0 Standard Spectra). The thermal properties of water, such as molecular weight, conductivity, viscosity, and specific heat coefficient, have been characterized across temperatures ranging from zero to 50 °C in earlier studies. Various configurations of water-filled glass systems were established using LBNL Window software (v. 7.6) to evaluate their thermal and optical behaviours. The optical properties of water layers, including absorption and reflectivity, were initially defined in Optics 6 and then integrated into Window as a new shading material. The thermal conductivity of water, also defined across different temperatures (0–50 °C), was introduced into Window's Gap library as a new gas. The table below presents the steady-state performance of window systems with water layers under CEN environmental conditions, focusing on the centre of the pane. To facilitate annual dynamic simulations, window properties for each configuration need to be imported into TRNSYS as BSDF (Bidirectional Scattering Distribution Function) datasets, alongside other thermal layer and gap information, using the trnBSDF tool. The BSDF data generated by Window contains solar and visible transmission and reflection values in the Klems matrix format (145 × 145). This modelling approach is considered one of the most accurate for complex fenestration systems, enabling precise calculation of radiative heat flux through glazing systems.

Appendix Table 1
U-value and optical properties of different window types base case and water-filled glazing [52].

Type of Water Filled Glazing	Case Name	U-value [W/m2.K]	SHGC [%]	Tsol [%]	Tvis [%]
Gap filled with argon, Low-E, 16 mm (base case, no shade)	Base_0	1.4	62	43	62
Gap filled with argon, Low-E, 16 mm (base case, auto shaded, Fc = 0.25)	Base_1	1.4	46	32	46
Gap filled with air, 15 mm (base case, no extra shade)	WFG_0	1.2	50	33	51
Gap filled with water, 15 mm (no extra shade)	WFG_1	2.9	55	27	44
Gap filled with water, 100 mm (no extra shade)	WFG_2	2.9	54	24	42

The intricate window model implemented in TRNSYS enables precise calculation of absorbed solar radiation and temperature for individual layers and gaps. Field tests and monitoring conducted on the Water House 2.0 pavilion in Taichung, Taiwan, have confirmed the cooling effect of water flow in an optically transparent setting. During the monitoring period, the building's temperature, both indoors and on surfaces, notably decreased when the pump was operational compared to when it was turned off. This cooling effect was solely attributed to the water flow, as no other cooling system was in operation, and ambient temperature and solar gain remained consistent in both scenarios. Additionally, the assumptions were validated through absorption measurements using a small prototype that can be filled with water, as illustrated in the figure below. The simulation utilized a Klipp and Zonen SP Lite pyranometer model.

Appendix Fig. 1. Water-filled Glass prototype used for measurements [52].

The water layer thickness in the prototype matched WFG_1 in the simulation, both being 10 mm thick. Measurements were conducted outdoors to assess natural solar gain, employing both horizontal and vertical settings. The glass was measured both with and without water infill. The observed change in Solar Heat Gain Coefficient (SHGC) after water infill closely correlated with the estimated 5% difference from the simulation. Additionally, the amount of changes in the visible spectrum was confirmed using an LP Standard Pro spectrometer, which indicated no difference in absorption within the visible spectrum. This method's significance lies in its ability to evaluate the performance of water-filled glass as an integral part of the entire building envelope and at the scale of the entire building, rather than focusing solely on a window. Furthermore, the simulation method presented here is readily available through Window and TRNSYS, unlike previous simulations that required bespoke coding. For detailed results, they are accessible at the Loughborough University Research Repository with open access [66,70].

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