IJBES

International Journal of Built Environment and Sustainability
Published by Penerbit UTM Press, Universiti Teknologi Malaysia
IJBES 7(2)/2020, 57-65

Glass Curtain Wall Technology and Sustainability in Commercial Buildings in Auckland, New Zealand

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ABSTRACT

Glass curtain wall provides an attractive building envelope, but it is generally regarded as unsustainable because of the high energy needed to maintain thermal comfort. This research explores the advances in the technology of glass cladding and the complex issues associated with judging its sustainability. It assesses the technology and sustainability of glass curtain wall on a sample of thirty commercial buildings in Auckland, New Zealand. Field observations of the glass-clad buildings, coupled with surveys of the building occupants and of glass cladding professionals are used to investigate the cladding characteristics, operational performance, sustainability aspects and future trends. The majority of the sample buildings are low-rise office buildings. The occupants like the aesthetics and indoor environment quality of their glass-clad buildings. However, continuous heating, ventilation and air conditioning are needed in order to maintain thermal comfort within the buildings and this has high energy consumption. The increasing use of unitized systems with double glazing instead of stick-built systems with single glazing improves the sustainability of the cladding through less material wastage and better energy efficiency. Inclusion of photovoltaic modules in the curtain wall also improves energy efficiency but it is currently too expensive for use in New Zealand. Environmental sustainability is also improved when factors such as climate, the orientation of glazed façades, solar control, ventilation and the interior building layout are considered. Any assessment of glass curtain wall sustainability needs to consider the economic and social aspects as well as the environmental aspects such as energy use.

Article History

Received : *31 October 2019*
Received in revised form : *16 January 2020*
Accepted : *30 January 2020*
Published Online : *30 April 2020*

Keywords:

Glass curtain wall, Stick-built, Unitized, Energy use, Sustainability

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DOI: 10.11113/ ijbes.v7.n2.495

1. Introduction

Glass curtain wall (GCW) is a popular cladding material and is commonly used on iconic commercial buildings worldwide. It gives the exterior view of the building a pleasing, glossy appearance and the occupants enjoy the view outside and the bright interior that comes from penetration of sunlight inside the building. However, these properties come with some disadvantages. Firstly, in the construction phase of a building, GCW is a relatively expensive form of cladding that needs skilled installation. Secondly, in the operating phase of the building, the heating ventilation and air conditioning (HVAC) costs are high because they need to counteract the effects of solar radiation penetrating the glass. The attempts of the construction sector to become increasingly sustainable means that attention is being focused on the greater energy use for the HVAC systems in GCW buildings. New types of glass and new GCW systems are being developed to improve the energy efficiency of GCW buildings but these innovations are expensive and not necessarily more sustainable over the building life cycle. Finally, the occupants' perspective on GCW buildings is very important since it is related to occupant productivity and the cost of occupant salaries is much greater than the HVAC energy costs during the operation of the building.

GCW was first used in New Zealand in the early 1980s, with the first three buildings located in Auckland (Bennett, 1987), a city of about 1.6 million people that covers an area of 531 square kilometers and has a temperate climate. Standard GCW is unsuitable for buildings in earthquake-prone regions but although earthquakes are common in New Zealand, Auckland is a region with little seismic activity. Consequently the density of buildings with GCW is higher in Auckland than in other New Zealand cities.

This research reviews the published studies on the technology and sustainability of GCW and summarizes the findings in sections 1.1 and 1.2. It then assesses GCW in New Zealand using a case study of thirty commercial buildings with glazed façades in Auckland's central business district. The technology of the GCW is based on identification of the building characteristics (curtain wall system, glass type, building use, age, size and maintenance). The sustainability of the GCW is examined using the occupants' perspectives on their buildings and the opinions of industry experts on the use of GCW in New Zealand. The expected future use of this type of façade in Auckland is discussed in the context of its sustainability.

1.1 The Technology of GCW systems

There are several different GCW systems including the stick-built, unitized and frameless systems (Bedon and Amadio, 2018; Mehta, Scarborough and Armpriest, 2018). The stick-built system was the earliest GCW system with a metal framework of vertical mullions and horizontal transoms attached to the building and supporting glass panels. This was followed by the unitized system, where preassembled modular units of glass in aluminium or steel frames are interlocked with adjacent units and fixed to the building with rigid brackets. Frameless GCWs are relatively new and aim to give the outside view of the building the appearance of continuous glass, unbroken by frame elements. The three most common types of frameless GCWs are metal structure supported (MSS) GCW, Suspended Glass Assemblies (SGA's) and cable net supported (CNS) GCW (Mehta et al., 2018).

The choice of curtain wall system and materials has a significant impact on the aesthetics of a building and can account for 15-25% of total construction costs. There is a high risk associated with innovative GCW systems so that designers tend to favour GCW systems they are familiar with and those that have the most secure warranties and technical backup (Kassem, Dawood and Mitchell, 2012).

Aside from the system classification above, GCWs can have many different characteristics such as place of assembly, curtain wall function (for example fire rated or blast resistant), glass type (for example reflective, low emissivity), glass attachment, glass configuration (single pane, double skin, freeform) and curtain wall heat transfer performance (for example, with the inclusion of thermal breaks). These are discussed in Pariafsai (2016) and Kazmierczak (2010). The latter also gives the common performance failures for GCWs such as poor heat flow (causing condensation), glare, inadequate noise control, moisture leakage, glass breakage, falling curtain wall components and cosmetic defects (in the glass itself, in the coatings, from corrosion or from poor maintenance). In addition to these, the local climate has to be considered when making the decision to use GCW; they may not be appropriate for certain buildings in tropical climates. For example, in Singapore many residential condominiums have GCWs that have very high electricity costs, excessive glare and poor privacy (Maheswaran and Zi, 2007). Simmler and Binder (2008) discuss the use of venetian blinds to offset the overheating problems that are common with unshaded glazed buildings.

GCW has two conflicting requirements; it should allow as much natural light into the building as possible while at the same time having minimal heat transfer across the building envelope. Glass has generally poor thermal performance characteristics – it transfers heat into and out of the building readily so that GCWs tend to have a significant effect on building operation costs and energy efficiency (Cuce, Cuce and Young 2016; Kassem et al., 2012). The greater the area of glass the worse the problem (Cuce, Young and Riffat, 2015a) and the higher the frame ratio (area of the metal frame/area of the GCW) the greater the heat transfer and the poorer the thermal performance of the curtain wall (Bae, Oh and Kim, 2015).

The heat transmission (or U-value) of a single pane of clear glass is about 5.8 W/m^2K. Double glazing with argon in the gap and low emissivity glass has a U-value of 1.1 W/m^2K, meaning that its heat transfer is only about one fifth of that for single clear glass panes. Thus, with considerably increased cost, a GCW can have acceptable thermal performance. However, when light transfer is considered the picture changes. A single pane of clear glass in a room transmits about 85% of incoming solar radiation to the inside of the room. It reflects about 10% and it absorbs about 5%. The absorbed radiation makes the glass hot so that it becomes a low temperature radiator; it transmits heat (by radiation and convection) to each of its faces. The proportion transmitted to each face depends on the face temperature – the lower the face temperature, the greater the proportion of heat transmitted to it. If both faces of the glass are at the same temperature, then 50% of the absorbed 5% radiation (i.e. 2.5%) is radiated inside the room so that a total of 87.5% of the incoming solar radiation goes into the room. In practice it is slightly worse than this because for a cooler exterior, the outside surface is cooler and more heat is transferred out of the building while, for a hotter exterior, the inner surface is cooler and more heat is transferred into the building. Expressed as a fraction, the solar radiation transmissivity of a single pane of clear glass is 0.87 (Bouden, 2007; Mehta et al., 2018). By comparison, the solar radiation transmissivity of double glazing with argon in the gap and low emissivity glass is 0.64 (Manz, 2004) i.e. about 75 percent that of a single pane of clear glass.

Tinting the glass makes it absorb more heat (which it will then re-radiate); it does not change the U-value of the glass but it does lower the amount of light transmitted through the glass (Mehta et al., 2018). People are particularly sensitive to radiant heat, so although sunlight passing through tinted glass does not heat the room up much, it makes the occupants feel hot (Baggs, 2016). Applying a reflective coating to the glass lowers the transmissivity, for example to 0.12 for double glazing with an air gap and reflective coating but this has poorer thermal transfer (a U-value of 2.3 W/m^2K) and potentially unacceptable glare on neighbouring buildings (Manz, 2004). In summary, there is a trade-off between U-value, transparency and radiant heat; the lower the U-value (and heat transfer), the less transparent the glass (Cuce et al., 2015a) and the greater the re-radiated heat, with implications on GCW cost, building operation costs and occupant comfort.

The main innovation in GCW systems is building integrated photovoltaics (BIPVs), i.e. the inclusion of semi-transparent photovoltaic (PV) modules in those parts of the glass façade that get the most sunlight in order to generate power (Young, Chen and Chen, 2014). This has led to the production of heat insulation solar glass (HISG) – a glass product that can generate electricity (like photovoltaic panels), has good thermal insulation (a U-value of 1.1 W/m2K), is self-cleaning, aesthetic and has good acoustic properties. It only transmits a small fraction of the visible light (7%) instead of 87% for ordinary clear glass. HISG glass curtain walls have 100% ultraviolet light blocking rate, which is important for occupants' health. Additionally, thermal radiation problems are greatly reduced (Cuce, Riffat and Young, 2015b). There are also double skin modular facade systems with glass and photovoltaic panels – the latter folded into various configurations (saw tooth, multi-fold/faceted geometries) to increase the PV area (Hachem and Elsayed, 2016). Folded facades have greater heating loads (a disadvantage) but this is compensated by their smaller cooling loads as well as some electricity generation.

There have also been innovations in the design of GCW itself. With specialized design of the connectors GCWs can withstand seismic and blast events (Bedon and Amadio, 2018). Standard glass used in GCWs does not behave well in a fire. Fire resistant glazing behaves better providing all the component parts (glazing seals, beads, fixings, and frame) are appropriately designed and specified – but the cost is too great for common use (Bedon, 2017). Interactive glass façades with automated blind systems, new electrochromic glazings, automated dimmable lighting and smart lighting and HVAC controls are discussed in Selkowitz, Lee and Aschehoug (2003) and these may help minimize some of the problems with GCWs. Despite these innovations, glass claddings do not currently perform as well as opaque materials (such as concrete and brick) in terms of heat transfer, sound transfer, fire resistance and blast resistance (Kazmierczak, 2010).

1.2 The Sustainability of GCW

The concept of sustainability originally meant ensuring that present actions did not compromise future actions. Economic, social and environmental factors contributed equally to sustainability and each of these factors was assessed over an entire life cycle (which, in the case of a building façade, includes the design, construction, operation, demolition and waste treatment phases). In the 21st Century, attention has focussed on the environmental factors which include components such as use of energy and water, indoor environment quality (IEQ) and emission of pollutants such as greenhouse gases.

As one of the largest users of environmental resources and a significant polluter of the environment, the construction sector is under pressure to improve its sustainability. Any improvement needs to be quantified, and global green ratings for buildings are commonly used as the assessment tool. There are many of these tools and they are reviewed in Ding (2008); the Building Research Establishment Environmental Assessment Method (BREEAM) is the most widely used assessment tool and New Zealand uses the Green Star rating tool. Within each tool, credits are awarded for a variety of environmental categories (energy use, IEQ, water use, emissions, etc.) with different weightings; the greatest credits that may be gained are for energy use and IEQ, while there are fewer credits for emissions. The total credits gained for a building are assumed to be an indication of its 'greenness' and higher green rating implies greater sustainability. Almost all of New Zealand's green rated office buildings have high proportions of unshaded glass facades (Byrd and Leardini, 2011) and the buildings are sealed and air-conditioned.

There are several problems with green rating tools and their link with sustainability. Firstly, the tools focus on the environmental aspects and ignore the economic and social aspects of sustainability. A building that is energy efficient may be green but it will also need to be comfortable, usable and durable in order to be sustainable (Kumar & Raheja, 2016). Secondly, there is no universal consensus on the weighting of the environmental categories (although energy use usually has the highest weighting) and whether the multi-dimensional assessment criteria provides an accurate measure of sustainability (Flemmer & Flemmer, 2005). Thirdly, green certification often happens at the design phase of the building but is not met in practice during the operation of the building where energy use is higher than expected and natural light use is lower than expected (Onyeizu 2014; Shameri, Alghoul, Elayeb et al., 2013). Fourthly, the link between green certification and environmental sustainability is somewhat tenuous; Byrd and Leardini (2011) show that New Zealand office buildings (mostly glass-clad) can get green certification while barely achieving the country's building code requirements for minimum energy performance. They suggest that green certification of buildings may be aimed more at commercial marketing than at genuine environmental sustainability and Flemmer and Flemmer (2005) suggest that the same is true for green certification of many products (other than buildings). Finally, green rating tools often fail to consider factors such as climate change and the availability of resources that affect the long term component of sustainability. In the New Zealand context, Byrd and Leardini (2011) predict that in the long term there will be increased temperatures due to global warming, greater energy required to cool buildings and increased likelihood of electricity shortages. The latter would make buildings with glazed envelopes uncomfortably warm. Consequently, they recommend that the energy weighting in green rating tools should be increased to reflect what is likely to be a global energy crisis.

Buildings with glazed envelopes are usually judged to be unsustainable (Butera, 2005), based primarily on high consumption of energy needed to maintain thermal comfort during the use of the building. Heat transfer through the GCW has improved over time (Arslan & Eren, 2014) and innovative skins with PV cells (Barkkume, 2007) are reducing the net energy consumption which implies improved sustainability over the operation of the building. However, Byrd and Leardini (2011) cite several studies suggesting that the improvements in energy efficiency are small and often unquantified. Finally, the operation of a building is just one phase of the building life cycle and it is important to look at total energy use (including embodied energy) over the entire life cycle before assessing the sustainability.

The daylighting through GCW is considered a positive aspect in its environmental assessment since it is linked to improved occupant productivity and to reduced need for artificial lighting (and its associated energy use). This is not always true; if the GCW has blue-green tinted glass (the most common tint) then the light transmitted through the façade is too cold (i.e. it has a high correlated colour temperature) and additional energy is used in artificial lighting to compensate for this (Butera, 2005). Moreover, researchers argue that daylighting can be provided thorough strategically placed windows rather than fully glazed envelopes (Kumar & Raheja, 2016) and that productivity itself is hard to assess (Onyeizu & Byrd, 2011).

It is apparent that judging the sustainability of GCW is complex. Focussing just on the environmental aspects and the operation phase of the building lifecycle there is consensus that GCW is not very sustainable but is 'more sustainable' when factors such as the climate, orientation of glazed facades, solar control, ventilation and the interior building layout are considered (Kumar & Raheja, 2016; Barkkume, 2007; Lim & Gu, 2007). There is however a need to consider the broader economic and social aspects of its sustainability. The economic aspects are obvious and include initial cost, running cost, rental revenue, etc. The fact that the economic calculus is positive is clearly demonstrated by the increased prevalence of GCW buildings. The social aspects can be complex and can themselves impact on the environmental and economic aspects. For example, there is a trend in big cities towards high-rise buildings which can alter the sunshine and wind patterns on neighbouring spaces (Al-Kodmany, 2016). Shading from neighbouring buildings may reduce energy generation in PV façades (Futcher, Mills, Emmanuel et al., 2017). Other factors such as heritage, transportation, public spaces, pedestrian comfort and safety may also contribute to the social impact of a high-rise building. Ultimately, buildings are made for people to use so an important factor in the social aspect of the sustainability of GCW is the opinion of the building occupants. Finally, the effects of climate change and availability of resources have a strong influence on the long-term sustainability of buildings with GCW.

2. Methodology

The purpose of the research was not to inventory all the glass clad buildings in Auckland, but rather to get a representative sample of such buildings and assess their characteristics. Accordingly, the researchers inspected the Auckland central business district (CBD) in March and April 2018 and identified a sample of thirty commercial buildings with GCW. The criteria for selection was that the buildings had glass cladding covering more than 80% of the façade and that the sample of thirty buildings had a wide range of heights, ages, glass cladding systems and building uses. The address, building business use and building characteristics (number of levels, glass cladding condition) were recorded. Visual inspection of the GCW was made (by the researchers) to assess the condition and this was expressed as 'Very Good' if the GCW appeared to be pristine, 'Good' if the GCW had some dirt build-up and 'Medium' if the GCW had dirt build-up and visible deterioration of the support frame or sealant.

Over the next four months, a staff person from each building, who knew about or was involved in the building operation was interviewed to get information on two aspects namely, the building construction and maintenance details (building age, glass type, cladding system, maintenance schedule and type of maintenance) and their opinion of the building functionality. The respondents consisted of four property management agents and twenty-six tenants (managers, administrators and receptionists). The age of construction was verified from Quotable Value Limited, a state-owned enterprise of the New Zealand government that records property details associated with value.

Two building professionals with at least 15 years' experience; one in GCW manufacture and one in GCW construction were selected from organizations with a relatively large market share of the industry. They were interviewed to gain insight into the New Zealand GCW industry.

3. Results and Discussion

Table 1 shows the characteristics of the 30 buildings, including their age, height, type of glass and cladding system. The GCW on all 30 buildings was maintained by washing and Table 1 shows the wash frequency, an assessment of the condition of the GCW and the building use.

Figure 1 shows the variation in the number of GCW buildings in Auckland's CBD with the stick-built system and the unitized system over time.

Table 2 shows the staff assessment of the operational performance of the sample of 30 glass clad buildings in terms of various operational factors.

Table 3 summarizes the staff opinion of their glass clad buildings from the sample of 30 buildings.

Table 1 Characteristics of GCW buildings in Auckland CBD showing number of buildings and percentage of the sample of 30 buildings

Characteristic	Number and percentage of sample buildings				
Construction date	1970-1979 2 (6.7%)	1980-1989 5 (16.7%)	1990-1999 8 (26.7%)	2000-2009 4 (13.3%)	After 2010 11 (36.7%)
Height	1-2 levels 12 (40.0%)	3-5 levels 10 (33.3%)	6-10 levels 7 (23.3%)	11-20 levels 0 (0%)	20+ levels 1 (3.3%)
Glass type	Single layer 26 (86.7%)	Double layer 4 (13.3%)	Tinted 19 (63.3%)	Reflective 4 (13.3%)	Not tinted or reflective 7 (23.3%)
Cladding system	Stick built 11 (36.7%)	Unitised 18 (60.0%)	SGA[1] 1 (3.3%)	SF[2] 1 (3.3%)	
Wash frequency	Once a month 2 (6.7%)	Once every 2-3 months 14 (46.7%)	Once every 4-6 months 10 (33.3%)	Once every 7-12 months 4 (13.3%)	
Condition	Very Good 12 (40.0%)	Good 16 (53.3%)	Medium[3] 2 (6.7%)		
Building use	Offices 27 (90.0%)	Educational 2 (6.7%)	Other (bus station) 1 (3.3%)		

Note that percentages do not always add to 100.0% because of round-off error

1: SGA Suspended glass assembly 2: SF Semi-frameless with sealant 3: constructed in 1970 and 1980 respectively

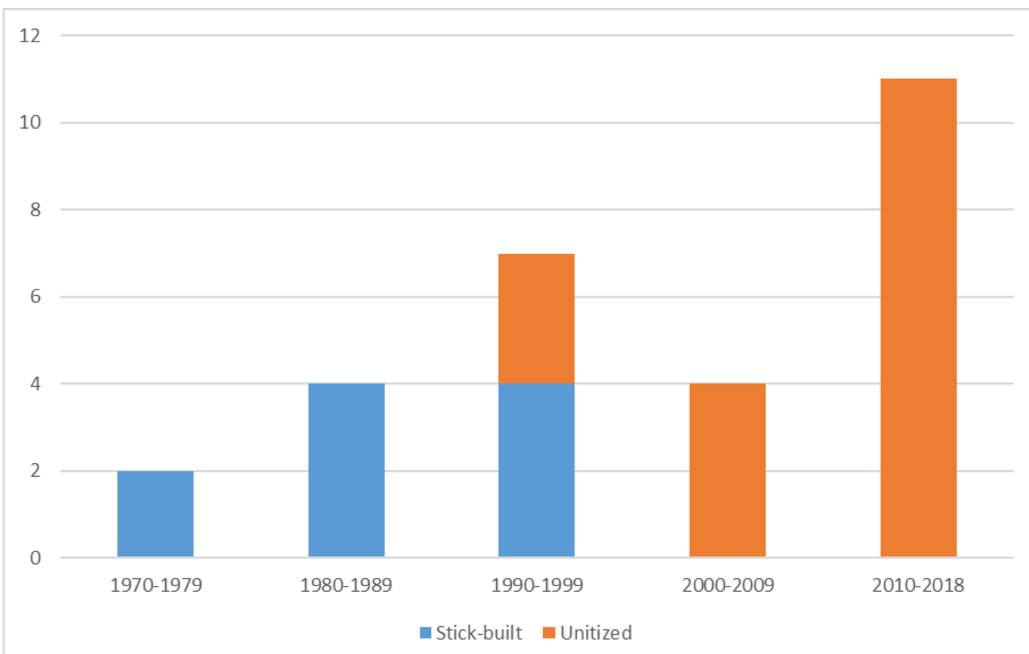

Figure 1 Variation in number of GCW buildings in Auckland's CBD having stick-built and unitized systems from 1970 to 2018

Table 2 Assessment of the operational performance of the sample of 30 buildings

Factor	Assessment, number and percentage of sample buildings			
Glare	Serious 1 (3.3%)	Acceptable 26 (86.7%)	Not noticed 3 (10.0%)	
Acoustic	Very good 14 (46.7%)	Good 16 (53.3%)	Medium 0 (0%)	Poor 0 (0%)
Thermal	Very good 3 (10.0%)	Good 22 (73.3%)	Medium 4 (13.3%)	Poor 1 (3.3%)
Impact on HVAC[1] expenditure	Large 2 (6.7%)	Medium 26 (86.7%)	Small 1 (3.3%)	None 1 (3.3%)
Use of HVAC system	All the time 30 (100.0%)	Only in summer 0 (0%)	Only in winter 0 (0%)	Never 0 (0%)

Note that percentages do not always add to 100.0% because of round-off error
1: HVAC Heating, ventilation and air conditioning

Table 3 Staff opinion of their GCW building

Staff preference for GCW?	Reason given
Yes: 28 (93.3%)	• Good view: 25 (83.3%) • Looks good/pretty/modern: 9 (30.0%) • Bright interior: 13 (43.3%)
No: 1 (3.3%)	• Poor thermal comfort: 1 (3.3%)
Indifferent: 1 (3.3%)	• No reason given: (3.3%)

Note that percentages preference does not add to 100.0% because of round-off error. The percentages listed for the reason for the preference may be greater than 100% because occupants could choose more than one reason.

Table 4 summarizes the information from the two GCW professionals from the New Zealand construction industry.

The results (Figure 1 and Table 1) show that the number of buildings in Auckland CBD with GCW is increasing. The earliest buildings used stick-built GCW systems, but modern buildings are increasingly using the unitized system. This finding was confirmed by the GCW professionals who noted that the unitized system is much quicker to install than the stick-built system. Other characteristics of the sample buildings showed the following:

- Most of the buildings are low rise, with 73% less than 6 storeys.
- Single glazing is used in 87% of the GCW systems and tinted glass is used in 63% of the GCW systems.
- 80% of the buildings use washing every 2-6 months to maintain the GCW and this agrees with the maintenance recommended by the GCW professionals.
- The visual assessment of the condition of the GCW is good or very good for 93% of the buildings and, as expected, the oldest buildings had the poorest GCW condition.
- 90% of the buildings were used as offices. This agrees with the observations made by the GCW professionals. Businesses that are concerned with corporate image can justify the expense of GCW cladding on their offices because of its significant aesthetic appeal. The design of buildings used for other purposes, such as educational facilities and bus stations, is likely to focus on less expensive, more utilitarian factors which is why GCW is less commonly used.

The staff/occupants of the buildings were mostly satisfied with the glare, acoustic performance and thermal performance of the buildings but the HVAC system was run all year round for all buildings and had a medium to high running cost (Table 2). The occupants liked the view, the aesthetics and the brightness of the GCW buildings and only one occupant suffered from thermal discomfort (Table 3). The value of these findings is limited by the small sample size; a larger sample of occupants from each building is needed before any general conclusions can be made.

The GCW professionals noted that a common misperception with GCW is that natural ventilation (i.e. ventilation from an open window) is problematic (Table 4). They confirmed that for low rise buildings, which are common in Auckland, it is easy to incorporate windows into the GCW system. Other findings from the GCW professionals were:

- Thermal performance and glare in GCW can be controlled with double glazing and specialized glass (such as low emissivity glass or reflective glass).
- GCW has acceptable seismic performance providing it has been appropriately designed and engineered.
- Research into GCW is focused on using BIPV to generate energy to partially offset the high HVAC use. In New Zealand, this is currently too expensive for practical use but is likely to be used in the future.

Table 4 Summary of information from GCW manufacturer and GCW installer

GCW Aspect	Information
Type of GCW used in New Zealand and current trends	• The older stick-built system is not used much now; 90% of current projects use the unitized system. • The unitized system has much quicker installation than the stick-built system. • Frameless GCW is mostly used in New Zealand for ground floor/shop front applications. In other countries it is used on high rise buildings but it costs 50-60% more than unitized GCW so it is very uncommon on high rise buildings in New Zealand where the construction sector prefers low-cost construction.
Provenance	• The glass is imported; the rest of the system is made in New Zealand.
Building Use	• GCW is mostly used for commercial offices and for some educational institutions.
Durability	• The average service life is 20-25 years but if the recommended maintenance is done GCW can last 70 years.
Maintenance	• Recommended maintenance is washing every 3 to 6 months. • More frequent washing is needed in coastal or industrial environments.
Energy efficiency & thermal performance	• Single glazing is less expensive than double glazing but is not very energy efficient and is being used less on new projects. • Double glazing with argon in the space between panes performs well. • Low emission glass and reflective coatings can improve thermal performance and reduce interior glare.
Ventilation	• There is a perception that natural ventilation (opening windows) is hard to incorporate in GCW. This is only true for high rise buildings. • Most buildings in Auckland that use GCW are low rise and it is easy to incorporate windows in the curtain wall.
Seismic performance	• As long as the GCW is well designed and engineered it has satisfactory seismic performance. • Auckland is a region with low seismic activity but buildings with GCW in Wellington and Christchurch (which have high seismic activity) perform well.
Sustainability	• Prefabrication of unitized GCW reduces the wasted product. • Glass is recyclable.
Future trends in GCW	• Advanced GCW technology is being developed worldwide. • GCW research aims at balancing the advantage of light penetration with the disadvantage of high HVAC use from solar radiation. • Incorporating photovoltaic systems into the glass is a way to generate energy which can be used to offset the HVAC energy requirements. Heat insulation solar glass (HISG) is one such product. In New Zealand it is called Building Integrated Photovoltaics (BIPV). It is not currently used as it is too expensive but it may be used in the future.

4. Conclusions

In Auckland, buildings with GCW tend to be low rise (less than 6 storeys) and are primarily used for offices. Low-cost GCW with single glazing dominates the sample buildings and there is a trend showing the declining use of stick-built systems with a concurrent increase in the use of unitized systems. Correct maintenance (washing every 2-6 months) is used in most of the buildings and the GCW condition is good.

The sustainability of GCW is a complex issue. From an energy perspective, GCW is generally viewed as having poor performance; continuous HVAC operation is needed to offset the effects of incoming radiation in order to maintain thermal comfort within the building. This is energy intensive and it is likely that double glazing will steadily replace single glazing in new GCW construction in an effort to save energy. The inclusion of photovoltaic modules in parts of the glass façade that get the most sunlight in order to generate power is another way to improve GCW energy efficiency, but it is currently too expensive for use in Auckland.

A complete assessment of sustainability needs to include economic, social and environmental factors and each of these factors needs to be assessed over the entire life cycle of the

GCW. An important part of the social aspect is the occupants' perspective. In the case study, most occupants seem to like their GCW buildings, in terms of both building aesthetics and building performance.

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