


Article

Life Cycle Assessment of Dynamic Water Flow Glazing Envelopes: A Case Study with Real Test Facilities

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Abstract: High initial costs hinder innovative technologies for building envelopes. Life Cycle Assessment (LCA) should consider energy savings to show relevant economic benefits and potential to reduce energy consumption and CO₂ emissions. Life Cycle Cost (LCC) and Life Cycle Energy (LCE) should focus on investment, operation, maintenance, dismantling, disposal, and/or recycling for the building. This study compares the LCC and LCE analysis of Water Flow Glazing (WFG) envelopes with traditional double and triple glazing facades. The assessment considers initial, operational, and disposal costs and energy consumption as well as different energy systems for heating and cooling. Real prototypes have been built in two different locations to record real-world data of yearly operational energy. WFG systems consistently showed a higher initial investment than traditional glazing. The final Life Cycle Cost analysis demonstrates that WFG systems are better over the operation phase only when it is compared with a traditional double-glazing. However, a Life Cycle Energy assessment over 50 years concluded that energy savings between 36% and 66% and CO₂ emissions reduction between 30% and 70% could be achieved.

Keywords: water flow glazing; dynamic building envelope; life cycle assessment



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1. Introduction

In recent years, clean energy use has steadily grown. However, energy consumption has not altered its pattern, with fossil fuels acting as the primary energy consumption and generation source. Many carbon emissions and greenhouse gases caused by conventional energy sources have severe consequences on the environment. Therefore, building codes, regulations, and energy directives consider carbon emissions' impact when evaluating energy efficiency [1]. New technologies emerge rapidly and force building designers to act without a thorough environmental impact analysis [2]. To control the construction sector's environmental impact is the most critical challenge that the architecture, engineering, and construction (AEC) industry must face soon [3,4]. Life Cycle Assessment (LCA) is a comprehensive and internationally standardized method. It quantifies all relevant emissions, resources consumed, and the related environmental aspects associated with any goods or services [5,6].

1.1. Literature Review

Extensive investigation has been conducted to study the environmental impact of building materials [7]. A Life Cycle Assessment can significantly help improve a sustainable building design by presenting how different materials or processes contribute to the

building's overall environmental impact [8,9]. According to some authors, Life Cycle Assessment considers four phases, the extraction of resources, the construction phase, the building operation, and the building's demolition [10]. The European standards (EN) standards for Building Life Cycle Assessment maintain a list of 24 total categories that describe potential environmental impact [11–13]. A broadly accepted standard of the environmental impact of buildings is energy consumption [14]. The Life Cycle Energy analysis (LCE) only accounts for energy inputs at different life cycle stages, including the operational energy and embodied energy in buildings over their lifetime. Life Cycle Energy analysis evaluates the embodied energy of products, design modifications, and strategies used to optimize operational energy. The most common period for major renovations in the residential sector in practice is, according to some authors, 30–40 years [15]. Other authors estimate the lifetime of buildings as 50 years in their LCC approach [16]. The optimization of building envelopes should examine both the energy-saving and the Life Cycle Cost goals [17]. Different authors have proposed mathematical models to calculate each envelope material's Life Cycle Cost and heating and cooling system [18]. Construction costs, return on investment, increased market value, and maintenance and operation costs are the factors that determine consumers' response to sustainable buildings [19]. Since buildings have long lifespans, the design decisions have long-term consequences, considering that upfront costs amount to less than 30% of the total Life Cycle Costs [20,21].

Global warming potential (GWP) is a measure of the amount of heat trapped in the atmosphere. This variable is measured in carbon dioxide equivalents ($\text{kgCO}_{2\text{eq}}$). This equivalency means that the total greenhouse potential of a specific emission type is given concerning CO_2 [22]. Since the calculation for global warming potential includes the residence time of gases in the atmosphere, a total time range for an assessment can be defined at 100 years [23]. Emissions are substances that are released into the environment, which includes the air, water, and soil. This, in turn, negatively impacts human and environmental health. Emissions typically enter into the environment as a waste product from different industrial processes. The most common (and therefore well-known) emissions are called greenhouse gas (GHG) emissions [24]. Some articles have studied building envelope design from its energy-saving potential, environmental consequences, and social impacts. It is of the utmost importance to optimize the balance between the cost and energy savings [25,26].

Dynamic or active buildings adapt their thermal performance according to different inputs, such as outdoor and indoor conditions, and can produce part of the building's energy over its operational life. Technical research and numerical simulation tools on active building envelopes have increased over the last decade. However, the ratio of dynamic facades in the building industry remains stable [27]. Some dynamic envelopes change their opacity or vary their transmission or reflection properties. Electrochromic glass, Polymer dispersed liquid crystal, and Suspended Particle Devices are hindered by their high cost and non-standardized manufacturing processes [28,29]. Active envelopes can also produce renewable energy on-site. Photovoltaic panels (PV) are considered the most reliable on-site renewable energy generation technology due to the wide range of electricity use and cables' flexibility that transport the energy [30]. Solar thermal collectors are considered a renewable and CO_2 free energy source. However, the pipes' stiffness transporting warm water has limitations in their applicability as a part of the building envelope [31].

This paper will examine the Life Cycle Assessment (LCA), Life Cycle Energy (LCE), and Life Cycle Cost (LCC) calculations for dynamic Water Flow Glazing (WFG) envelopes. Coupled with a plug and play piping system, it would produce a high-performance building envelope and innovative heating and cooling system [32,33]. Water Flow Glazing is a technology that can be integrated into transparent building envelopes, either in new buildings or as a retrofit for traditional glazing [34]. Flowing water through WFG panels captures an extensive percentage of the solar infrared radiation and keeps the glazing transparency [35]. WFG can absorb solar energy to provide domestic hot water to plumbing fixtures when the solar irradiance is high enough [36,37].

1.2. Objectives and Innovation

Water Flow Glazing has proven its potential for energy savings and for increasing comfort of occupants in previous studies. The main contribution of this article has been to carry out a thorough analysis of a 50-year life cycle from the energy and cost perspectives. To accomplish this task, the authors have employed a tested methodology used in previous scientific articles. This study considered two prototypes in different locations, glazing compositions and energy systems. Real-world data were collected from these prototypes and analyzed to determine the actual energy performance of WFG systems. This paper is structured into four separate parts. Section 2 of this article provides background information on Water Flow Glazing technology, a description of the WFG test facilities, and finally the methodology of Life Cycle Energy analysis (LCE) and Life Cycle Cost (LCC) calculations. Section 3 provides an analysis of the year-long data collection that occurred at the WFG facilities. This section also contains information pertaining to the embodied energy, the operational energy, and the renewable energy production of the test facilities. Section 4 is a discussion on LCE and LCC and their impact on global warming potential based on a multi-index evaluation. In addition to this, this section has a discussion on the limitations of the methodology. The fifth and final section is the conclusions section.

2. Materials and Methods

Water flow glazing can be used as both a high-performance envelope as well as an element of the heating and cooling system. The WFG module presented in this paper is made up of three components: an extruded aluminum frame, the glazing, and a circulating device. The glazing is a compound of several layers of laminated glass and coatings, with thermal and spectral properties provided by the glass manufacturers. It combines coatings and Polyvinyl butyral layers with a variable water mass flow rate to absorb or reject incoming infrared solar radiation. The circulating device is defined by a water pump, an exchanger that can regulate heat, and different sensors (such as the water flow and water temperature) to regulate the different fluid variables involved. Finally, the aluminum assembly provides the frame with structure. Although WFG can absorb and transport thermal energy, alternative heating and cooling sources might be added to compensate for the heat losses and gains and maintain comfort conditions. The initial cost of the glazing exceeds the cost of a traditional double or triple glazing panel. However, its performance has to be evaluated over its life cycle to consider potential energy savings. In addition, the water flow captures the solar infrared radiation and increases its temperature through the window. This water is transported and eventually releases the energy in buffer tanks so that thermal energy can be used in hydronic heating systems. The renewable energy integrated into the building envelope might not be enough to meet the energy needs, so it is necessary to study different energy sources and systems to compare their final energy consumption and greenhouse gas emission potential. The Life Cycle Assessment of Water Flow Glazing includes four phases. Phase 1 is the extraction, production of construction materials, and transportation of materials from the extraction point to the construction site. Phase 2 is the construction phase, including required energy to run construction machinery, any additional materials for construction, and any waste disposal. Phase 3 includes the energy required for the building's actual operation (including all energy used during the building occupation over the total lifespan of the structure), general maintenance, repairs, and finally, any required material replacement for the building. Finally, phase 4 involves demolition and transport of waste to recycling plants or landfills.

2.1. Water Flow Glazing Thermal Properties

Heat flux through any glazing depends on the difference between the indoor and outdoor temperatures ($\theta_e - \theta_i$) and the direct and diffuse solar radiation, i_0 . Equation (1) shows the heat flow, q , in glazing panels with gas chambers depending on the thermal transmittance, U , and g -factor. Equation (2) illustrates that the variable fluid's temperature and mass flow rate impact the heat flow through the glazing. Equations (1) and (2) are

valid assuming steady conditions, constant values for convective and radiative coefficients, negligible thermal resistance and thermal mass of the glass panes and the water chamber, and the uniform flow inside the water chamber.

$$q = U(\theta_e - \theta_i) + gi_0, \quad (1)$$

$$q = U(\theta_e - \theta_i) + U_w(\theta_{IN} - \theta_i) + gi_0, \quad (2)$$

where U_w is the thermal transmittance between the water chamber and the interior, U is the glazing thermal transmittance, θ_e is the outdoor temperature, θ_i is the indoor temperature, and θ_{IN} is the inlet temperature of the fluid into the WFG system. Equations (3)–(5) are taken from a previous article [38]. They show the thermal transmittances of WFG, along with the g -factor. All the parameters depend on the mass flow rate, which is estimated uniform inside the glass pane.

$$U = \frac{U_i U_e}{\dot{m}c + U_e + U_i}, \quad (3)$$

$$U_w = \frac{U_i \dot{m}c}{\dot{m}c + U_e + U_i}, \quad (4)$$

$$g = \left(\frac{U_i}{\dot{m}c + U_e + U_i} \right) \left(\left(A_1 \left(\frac{U_e}{h_e} \right) + A_2 \left(\frac{1}{h_g} + \frac{1}{h_e} \right) U_e + A_3 \left(\frac{U_e}{h_i} \right) + A_w \right) \right) + A_i + T. \quad (5)$$

Water flow glazing can change the thermal performance by varying the mass flow rate per unit of surface, \dot{m} . U and U_w are two additional thermal transmittances that depend on the mass flow rate. The product $\dot{m}c$ denotes the potential of the water to transfer energy. U_i and U_e thermal transmittances were obtained utilizing the convective heat coefficients, h_e, h_i, h_g, h_w . The thermal resistance, $(1/U_e)$ is the sum of the thermal resistances from the water chamber to the outdoors. Similarly, the thermal resistance, $(1/U_i)$, is the sum of the thermal resistances from the water chamber to indoors. Hence, U_e represents the thermal transmittance between the water chamber and outdoors, and U_i , the thermal transmittance between that water chamber and indoors. A_w is the water absorptance, whereas A_1, A_2, A_3 are the glass panes absorptances.

This study included two separate prototypes. The first one was placed in Peralveche, Spain (latitude $40^\circ 36' 42''$ N, longitude $2^\circ 26' 57''$ W, altitude 1111 MAMSL). The second one was built and tested in Sofia, Bulgaria ($42^\circ 39' 1''$ N, $23^\circ 23' 26''$ E, Elevation: 590 m a.s.l.). The Peralveche WFG cabin was made of double glazing with a water chamber. Figure 1 shows the WFG cabin and energy system schematics.

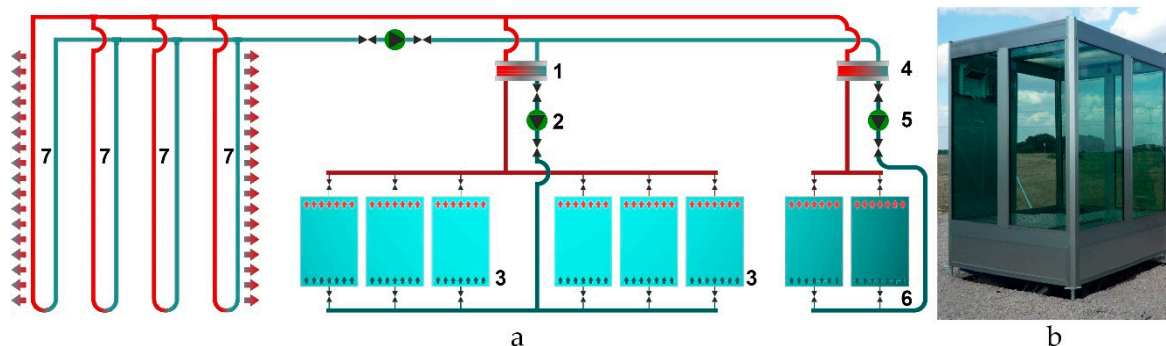


Figure 1. Peralveche prototype: (a) schematics of energy system: 1—plate heat exchanger, 2—water circulation pump and precision flow meters, 3—wall water flow glazing panels, 4—plate heat exchanger, 5—water circulation pump and precision flow meters, 6—roof water flow glazing panels, 7—borehole heat exchangers; (b) Water Flow Glazing (WFG) cabin.

The glass panes utilized to build this glazing assembly were Planiclear 6 + 6 mm with Poly-Vinyl Butyral layers (1 × 0.38 mm), a water chamber measuring 16 mm, and Planiclear 8 + 8 mm with Poly-Vinyl Butyral layers (1 × 0.38 mm). The cabin had six sides and each side was a square of 2 m × 2 m. The WFG panels were connected to four borehole heat exchangers buried 50 m underneath the cabin. The WFG cabin managed two different closed loop circulating systems. The first loop consisted of pipes that distributed refrigerant fluid from the borehole heat exchangers to the circulation pump. The WFG cabin included a second loop that circulated water through vertical facades and the horizontal roof and the mass flow rate was set to 0.9 L·min⁻¹·m⁻². Table 1 shows the glazing's thermal and spectral values from previous articles [38,39]. This WFG cabin was compared with another, referred to as Reference prototype, which had double glazing with an air cavity.

Table 1. Thermal properties of Peralveche glazing.

	Orientation	Area (m ²)	$\dot{m} = 0 \text{ L}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$			$\dot{m} = 0.9 \text{ L}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$		
			U (W·m ⁻² ·K ⁻¹)	U_w (W·m ⁻² ·K ⁻¹)	g	U (W·m ⁻² ·K ⁻¹)	U_w (W·m ⁻² ·K ⁻¹)	g
WFG ¹	S + E + W + roof	15.8	4.797	0.0	0.396	0.762	5.802	0.27
Reference ¹	S + E + W + roof	15.8	2.6	-	0.67	-	-	-

¹ Values taken from [39].

As per the Sofia prototype, the square plan dimensions were 7 m × 7 m. The walls are parallelograms of 7 m by 3.4 m comprised of five WFG modules facing east, west, and south, respectively. Figure 2 shows the unitized facade module. The circulating system incorporated a solar water pump and a plate heat exchanger connected to the water distribution pipes. The unitized WFG panels measured 3000 mm high and 1300 mm width, and the mass flow rate was set at 2 L·min⁻¹·m⁻². In the Southern glazing, the following layers were employed: a single 10 mm diamant glass pane, a 16 mm argon chamber, a low-emissivity coating Planitherm XN, Planiclear (8 mm), 2 Saflex R solar (SG41), Planiclear (8 mm), water chamber (24 mm), Planiclear (8 mm), 4 Saflex R standard clear (RB11), Planiclear (8 mm). Eastern and western glazing composition was meant to reject energy, so a highly reflective coating was included, instead of the low emissivity coating.

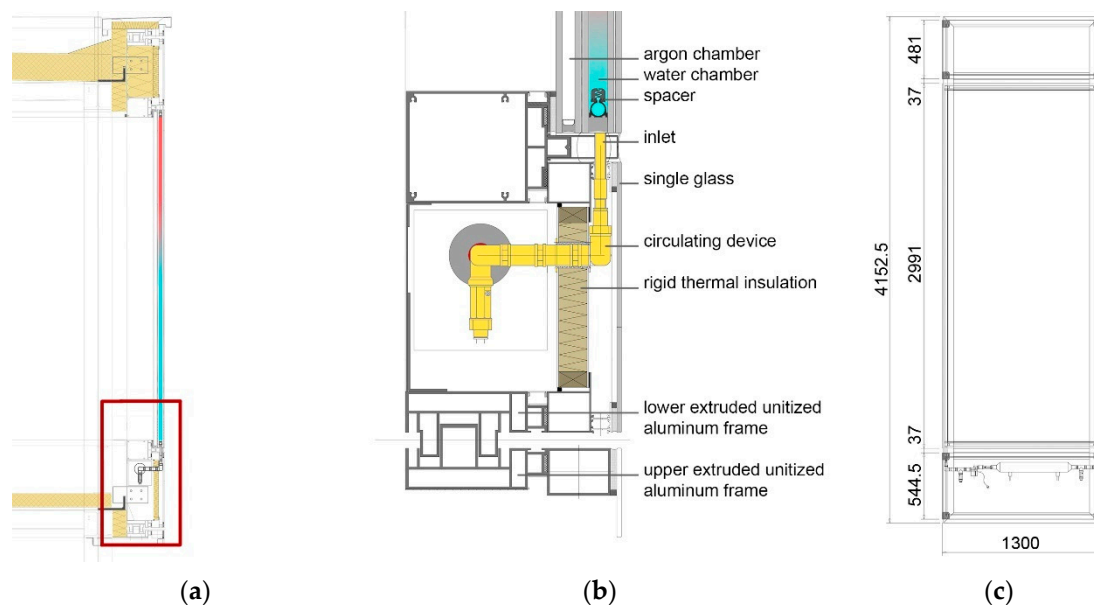


Figure 2. Sofia prototype description: (a) section; (b) detail of the unitized facade and circulating device; (c) elevation of the unitized module.

Table 2 shows the thermal properties of the glazing taken from a previous article [40]. The total glass area was 60 m². This WFG cabin was compared with another one, referred to as Reference prototype, with triple glazing with an air cavity and an argon cavity. The glass layers and coatings were the same as the WFG.

Table 2. Thermal properties of Sofia glazing.

	Area (m ²)	Orientation	$\dot{m} = 0 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$			$\dot{m} = 2 \text{ L} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$		
			U (W·m ⁻² ·K ⁻¹)	U_w (W·m ⁻² ·K ⁻¹)	g	U (W·m ⁻² ·K ⁻¹)	U_w (W·m ⁻² ·K ⁻¹)	g
WFG ¹	19.2	S Wall	1.041	0.0	0.59	0.066	6.459	0.24
WFG ¹	38.4	E–W Wall	0.995	0.0	0.27	0.063	6.462	0.22
Reference	19.2	S Wall	1.0	-	0.57	-	-	-
Reference	38.4	E–W Wall	1.0	-	0.30	-	-	-

¹ Values taken from [40].

2.2. Life Cycle Energy (LCE) Analysis

The total embodied energy of building elements involves the energy consumed directly at the primary material extraction, manufacturing, and assembly. These amounts of energy constitute the element's initial embodied energy, and the operational energy includes the heating and cooling energy consumption. Primary energy also considers the energy required to produce the final energy consumed in the building, and it varies according to fuel type and transportation losses. Primary energy is proportional to energy-related CO₂ emissions [41,42]. Life Cycle Energy comprises the building's operational energy, initial and recurrent embodied energy over its lifetime, and, finally, the energy for demolition and disposal. Equation (6) was used to calculate the Life Cycle Energy.

$$E = E_i + E_{err} + E_o(n) + E_d, \quad (6)$$

where E is the total energy of the building element, E_i is the initial embodied energy, E_{err} is the recurrent embodied energy for future maintenance and refurbishment (5% of the initial embodied energy), E_o is the total annual operational energy, n is the lifetime of the element in years, and E_d is the embodied energy required for demolition and disposal (3% of the initial embodied energy). Some LCE analysis studies include energy requirements such as lighting, cooking, hot water, and appliances. However, this study includes only the heating and cooling energy through the envelope. For the purposes of this paper, the energy absorbed by the WFG panels was considered as renewable energy production over the operational time in the final energy balance. Therefore, when calculating the total annual operational energy variable, this will be determined by taking the total energy consumption value and subtracting the amount of energy provided by the WFG panels in the structure.

2.3. Life Cycle Cost (LCC) Analysis

In addition to improving the thermal performance and reducing the environmental impact, the design of an efficient building envelope needs to pay attention to reducing the economic costs. Building owners demand the selection of cost-effective elements of the building envelope in a sustainable building design. Therefore, in terms of effective decision-making, it is essential to have a complete insight into the construction and running costs throughout the building's lifespan. The Life Cycle Cost (LCC) approach is based on optimizing design solutions and minimizing the sum of construction and operating expenses over the building lifetime. The building envelope's Life Cycle Cost has included its construction cost, C_1 , operation cost, C_2 , and demolition cost, C_3 . The present value interest factor of the annuity (PVIFA) was used to calculate the operation cost's current value. The present value interest factor (PVIF) was used to estimate the demolition and disposal cost's current value at the end of the envelope life cycle. C represents the building

envelope's total Life Cycle Cost and the heating and cooling system; r represents the interest rate; n represents the design operating life in years. Therefore, the proposed Life Cycle Cost model for building facades is presented in Equation (7).

$$C = C_1 + C_2 \left(\frac{1}{r} - \frac{1}{r(1+r)^n} \right) + C_3 \left(\frac{1}{(1+r)^n} \right) \quad (7)$$

3. Results

This section started by defining the parameters to quantify the environmental performance: primary energy, equivalent CO₂ emissions, and cost. The building reference time was defined as 50 years.

Depending on the local context, the embodied impact may surpass the operational impact. The indicators that measure energy performance can be split into economic factors and physical energy factors.

3.1. Embodied Energy Calculation

The building elements' embodied energy has been taken from different sources, whereas the operational energy was calculated with experimental data from the prototypes. It was assumed that the structures were not renovated during this time and had no change in their usage mode throughout their useable life. Energy use, in the viewpoint of the various stages of a building's life cycle, in cold-weather temperatures, the operational stage can reach upwards of 80%. In contrast, the building materials and in-situ construction account for 10–20% [43]. For simplification purposes, the energy for demolition and disposal is a percentage of the total primary energy. Embedded Energy (EE) is the total energy needed to produce goods and services, including processing, mining and extraction, manufacturing, and transport of products. Table 3 shows the emissions associated with the EE are the result of energy and emissions quantification based on the ITeC database [18]. The following assumptions have been considered: The embodied energy associated with the replacement, refurbishment, and substitution of materials and products is assumed to be 5% every ten years [44]. The embodied energy associated with demolition and disposal was assumed to be 3% of the total building Life Cycle Energy [45–47]. The considered energy for replacement, demolition, and transportation to landfill does not exceed 10 kWh.m⁻².

Table 3. Embodied Energy (EE) and Embodied Carbon (EC) of materials.

Material	EE (MJ·kg ⁻¹)	EC (kgCO _{2eq} ·kg ⁻¹)	Weight (kg·m ⁻²)	EE (MJ·m ⁻²)	EC (kgCO _{2eq} ·m ⁻²)	Cost (€·m ⁻²)
Double Reference	12.95	1.59	69.00	1500.00	110.01	120.50
Triple Reference	15.30	1.70	104.50	2002.30	180.05	220.50
Double WFG	13.25	1.63	70.00	1666.00	114.10	239.10
Triple WFG	15.90	1.75	105.00	2299.50	183.75	370.22
Extr. Al. Stick	220.00	14.76	25.8	5676.00	380.81	110.85
Extr. Al. Stick (R)	14.60	1.02	25.8	376.68	26.32	110.85
Extr. Al. Unitized	220.00	14.76	84.00	18480.00	1239.84	415.20
Extr. Al. Unitized (R)	14.60	1.02	84.00	1226.40	85.68	415.20
Circulating device ¹	-	-	-	237.20	79.68	200.00

¹ A circulating device can serve 4 m² of WFG.

The energy systems used for this study were borehole heat exchangers coupled with a ground-source heat pump for the WFG Peralveche prototype, Air-to-Water heat pump for WFG Sofia prototype, and Air-to-Air heat pump for both reference prototypes. All the heat pumps are considered to be 7 to 20 kW. The chosen system boundaries include the production of the component, starting from raw materials, the use stage, and the dismantling stage of both systems, along a temporal horizon of 50 years. Closed-loop borehole heat exchangers were made of high-density polyethylene vertical pipes with water (78%) and ethylene glycol (22%) mixture flowing. The installation process included

drilling boreholes and trenches, inserting a vertical loop, and grouting operations of the borehole with concrete and bentonite mixture [48–50]. The dismantling process included the disposal of the glycol, the sealing of the borehole, and the disposal at the heat pump's end of life. Table 4 shows the embodied energy, emissions, and cost associated with the energy systems used to operate the different prototypes.

Table 4. Embodied Energy (EE) and Embodied Carbon (EC) of energy systems.

Material	EE (MJ)	EC (kgCO _{2eq})	Cost (€)
Borehole heat exchangers ¹	9975.50	1661.98	5695.30
Ground-source heat pump	2193.60	390.30	7396.21
Air-to-Water heat pump	2210.50	350.70	8078.65
Air-to-Air heat pump	2393.70	380.50	3700.70

¹ Four 50 m borehole heat exchangers, diameter 118 mm.

The compressor and structure were made of reinforced steel and the evaporator and condenser from low alloyed steel. The pipes, cables, and expansion valves were made of copper. Pipes were insulated with a polymer and the cables were insulated with PVC. The refrigerant was assumed to be the same (tetrafluoroethane) for all the heat pumps. The heat pumps were considered maintenance-free, and their lifetime, 25 years.

3.2. Renewable Energy Production

Renewable primary energy (RPE in kWh·m⁻²) was produced as the water flowed through the glazing. The data were measured over a year. The RPE can cover part of the winter's heating needs and was subtracted from the non-renewable primary energy needed to maintain the prototype's indoor temperature within a comfort range. The heat absorption rate in the southern facades is closely related to the glazing composition and the orientation. When the solar radiation hits in the glazing units, the water chamber absorbs part of that energy. Heating was assumed to be delivered by a hydronic system using the energy absorbed by the WFG envelope. When needed, a heat pump operated to deliver the energy to keep comfort indoor conditions. Figure 3 shows the water heat gain of the prototypes' envelope. The horizontal panels in Peralveche show the largest water heat gain in July with 81.44 kWh·m⁻². When it comes to the southern facades, the Sofia prototype shows the largest heat gain. The mass flow rate was set higher than any other prototypes (2 L·min⁻¹·m⁻²), and the southern glazing properties demonstrate the highest absorptance. The peak solar heat gain in the Sofia prototype was 97.39 kWh·m⁻² in July.

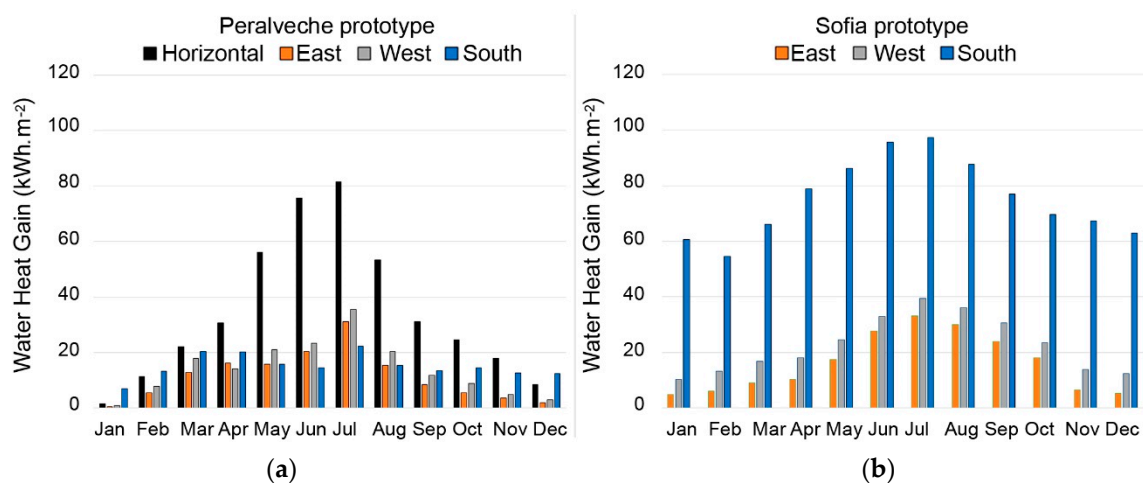


Figure 3. Experimental data. Water heat gain in WFG envelopes; (a) Peralveche prototype WFG; (b) Sofia WFG prototype in kWh·m⁻².

3.3. Operational Energy

Heating and cooling energy loads (in kWh·m⁻²) were calculated by using Equation (1) for the reference glazing and Equation (2) for WFG. The inputs were measured over a year time. Real data, obtained from the prototype throughout the year, allowed the correlation between the WFG cabin and the Reference cabin. Figure 4 shows the heating and cooling energy in kWh·m⁻² to keep the inside within comfort temperature over the year. The figure considers only the energy that goes through the transparent envelope. The cooling load of the Peralveche Reference cabin showed by far the highest energy consumption with a peak of 118 kWh·m⁻² in July.

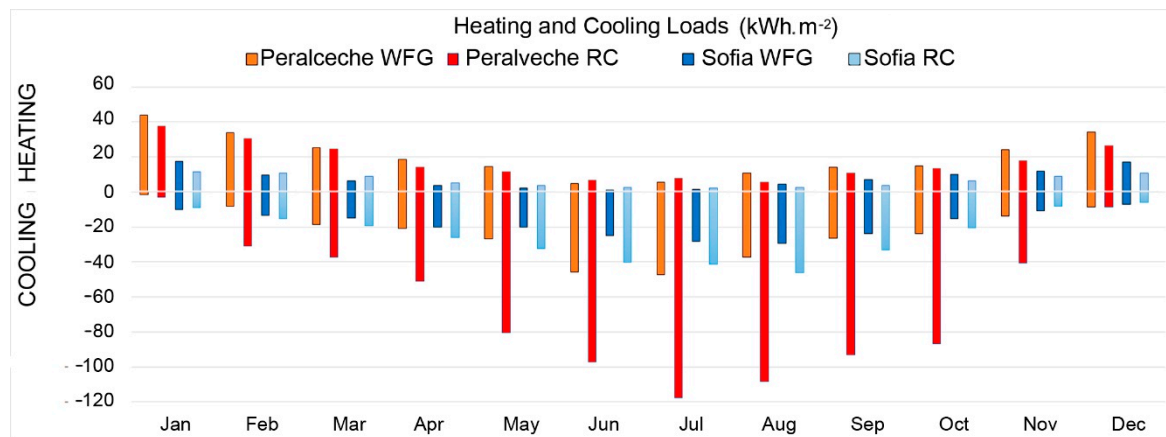


Figure 4. Experimental data. Heating and cooling energy through the transparent building envelopes in kWh·m⁻².

Table 5 shows conversion factors between non-renewable primary energy, NRPE, and final energy, FE (kWh_{NRPE}/kWh_{FE}), as well as CO₂ emissions conversion factors provided by the Spanish Regulation of Thermal Installations in Buildings [42]. The price per kWh of different energy carriers or fuels was taken from Eurostat documents [43].

Table 5. Conversion factor (f) from final energy (FE) to non-renewable primary energy (NRPE), CO₂ emissions, and price of energy carriers.

	f_{NRPE} (kWh _{NRPE} /kWh _{FE})	f_{TPE} (kWh _{TPE} /kWh _{FE})	f_{CO_2} (kgCO ₂ /kWh _{FE})	Price ¹ (€/kWh)
Mainland electricity	1.954	2.368	0.331	0.239
Fuel	1.179	1.182	0.331	0.0713
Natural gas	1.190	1.195	0.252	0.102
Biomass (pellets)	0.085	1.113	0.018	0.0462

¹ values taken from [43].

The non-renewable primary energy consumption of the existing building per unit of envelope area and year, $NRPEC$, in kWh·m⁻² per year, was calculated using Equation (8).

$$NRPE = f_{NRPE}FE_{heat} + f_{NRPE}FE_{cool}, \quad (8)$$

The equivalent CO₂ emissions of the existing building per unit of envelope area and year, in kgCO₂·m⁻² per year, were calculated with Equation (9).

$$CO_{2eq} = f_{CO_2}FE_{heat} + f_{CO_2}FE_{cool}, \quad (9)$$

Tables 6 and 7 illustrate the non-renewable primary energy consumption (NRPE) with different energy generators in Peralveche and Sofia, respectively. The conversion factor between final energy and non-renewable primary energy (kWh NRPE/kWh FE) and the factor of emitted CO₂ for electricity were taken from Table 3 for mainland electricity: 1.954

for the conversion factor between final energy and non-renewable primary energy (kWh NRPE/kWh FE) and 0.331 for CO₂ emissions for electricity. In the final energy balance, the renewable energy production was subtracted from the WFG prototype heating loads. The ground-source heat pumps' performance depends on the source inlet temperature in the heat pump, and the inlet temperature in the WFG (θ_{IN}). A typical value of source inlet temperature ranges from 20 °C in ground-source heat pumps (GSHP) to 35 °C in other Water-to-Water (W-W) heat pumps. The parameters that influence Air-to-Air (A-A) heat pumps' performance are the dry bulb exterior air temperature and the dry bulb interior return air temperature [51].

Table 6. Peralveche prototype. Final energy, non-renewable primary energy, and CO₂ emissions.

Peralveche	Heating		Cooling	
	WFG(W-W)	RC(A-A)	WFG(W-W)	RC(A-A)
Energy (kWh·m ⁻²)	42.12	206.95	279.70	755.05
COP ¹	6.60	4.20	5.90	3.30
FE (kWh·m ⁻²)	6.38	49.27	47.41	228.80
NRPE (kWh·m ⁻²)	12.47	96.28	92.63	447.08
CO _{2eq} (kgCO ₂ ·m ⁻²)	2.11	16.31	15.69	75.73
OE cost (€·m ⁻² per year)	1.53	11.78	11.33	54.68

¹ COP values are taken from [51].

Table 7. Sofia prototype. Final energy, non-renewable primary energy, and CO₂ emissions.

Sofia	Heating		Cooling	
	WFG(W-W)	RC(A-A)	WFG(W-W)	RC(A-A)
Energy (kWh·m ⁻²)	0.00	76.58	219.10	298.07
COP ¹	5.30	4.20	4.60	3.30
FE (kWh·m ⁻²)	0.00	18.23	47.63	90.32
NRPE (kWh·m ⁻²)	0.00	35.63	93.07	176.49
CO _{2eq} (kgCO ₂ ·m ⁻²)	0.00	6.04	15.77	29.90
OE cost (€·m ⁻² per year)	0.00	4.36	11.38	21.59

¹ COP values are taken from [51].

The yearly operating energy was assumed to remain steady during the entire building operation. The resource mix supplying electricity to the buildings is assumed to be unvarying. The HVAC systems' efficiency and the operation schedule were assumed to remain unchanged during the Life Cycle Assessment.

4. Discussion

WFG can be a part of hydronic heating and cooling systems, and it is compatible with ground-source heat pumps and boilers. In this study, the authors have considered only mainland electricity as the energy source, ground source heat pumps for the Peralveche WFG prototype, Air-to-Water heat pumps for the Sofia WFG prototype, and Air-to-Air heat pumps for the reference prototypes.

4.1. Life Cycle Cost Evaluation

The method to evaluate the Life Cycle Cost (LCC) has been shown in Section 2. The parameters to calculate the envelope's Life Cycle Cost and the energy system initial cost have been discussed in Section 3. The operation cost was calculated with data provided by Table 5 and energy prices for mainland electricity. Maintenance costs for the envelope over 50 years have been calculated as a percentage of the initial cost (1% for the reference glass and 5% for WFG), whereas the heat pump's lifetime was 25 years. The cost of the studied WFG unitized facade was 985 €·m⁻², whereas the price for the circulating water pump was 20 €·m⁻². Replacing the water pumps after a 10-year cycle is included in the maintenance

cost. Finally, the demolition and disposal costs were calculated as a percentage of the initial cost (3%). Therefore, the total proposed Life Cycle Cost for the building envelope and energy system was calculated according to Equation (7). The total construction costs of the envelopes and the energy systems were calculated by multiplying each envelope component's quantity by the total unit price. The operation cost was converted to the present value based on annual heating and cooling loads through the envelope. The considered demolition and disposal values were 3% of the total construction costs and converted to the present value. This article considered a discount rate of 2% calculated as an average of the harmonized consumer price index in Spain over the last 20 years. The price of energy was taken from Eurostat reports [43]. The material prices of other components come from the ITeC database [18]. Table 8 shows the cost analysis parameters for all cases.

Table 8. Cost analysis parameters.

	C_1	C_2	C_3	Total (50 Years)
Peralveche WFG	17,529	640	7921	40,611
Peralveche RC	7373	1239	3921	47,767
Sofia WFG	65,626	1320	10,046	110,865
Sofia RC	40,795	1923	4923	103,066

Water flow glazing envelopes showed a higher Coefficient C_1 . The initial cost reflected the investment in borehole heat exchangers and circulating devices. However, the coefficient C_2 reflected that the reference yearly operation cost is twice as much as the WFG cost in Peralveche and 1.5 more in Sofia. The total cost considered a 50-year life cycle by converting the operation and disposal costs to the present value. In Peralveche, the reference prototype cost surpassed the WFG one. In Sofia, the WFG is slightly higher than the reference one.

4.2. Life Cycle Energy Evaluation

Life Cycle Energy included the materials initial embodied energy, the operational energy for heating and cooling over 50 years, the recurrent embodied energy over its lifetime, and, finally, the energy for demolition and disposal. Equation (6) was used to calculate the Life Cycle Energy. Table 9 shows the initial embodied energy E_i , the recurrent embodied energy for future maintenance E_{err} , calculated as a percentage of the initial embodied energy, the total annual operational energy, and the embodied energy required for demolition and disposal E_d .

Table 9. Life Cycle Energy parameters in GJ.

	E_1	E_{err}	E_o	E_d	Total (50 Years)
Peralveche WFG	193	19	300	58	571
Peralveche RC	116	12	1553	35	1716
Sofia WFG	1216	122	978	61	2377
Sofia RC	1198	120	2230	60	3608

The most considerable initial embodied energy E_i was shown in both WFG prototypes. It was more significant in the Peralveche prototype than in Sofia because of the high embodied energy in the borehole heat exchangers. However, the lower operational energy over 50 years compensated for the higher initial energy consumption. Table 10 illustrates the CO₂ emissions, which is the parameter used to assess the global warming potential (GWP) in kgCO_{2eq}. The life cycle emissions included the same phases: manufacture and transport of construction materials, maintenance, operation of the building, and waste disposal.

Table 10. Life cycle Embodied Carbon in kgCO_{2eq}.

	EC_1	EC_{err}	EC_o	EC_d	Total (50 Years)
Peralveche WFG	10,107	707	14,133	505	25,452
Peralveche RC	8145	3654	73,080	407	85,286
Sofia WFG	83,713	2302	46,048	4186	136,250
Sofia RC	83,269	5247	104,945	4163	197,625

Improving the thermal performance of the building envelope with WFG caused an increase in the initial cost. However, the amount of energy and CO₂ emissions declined in both cases over the considered life cycle.

4.3. Multi-Index Evaluation Model

Usually, the optimum building envelope's thermal performance is often accompanied by an increase in the cost and environmental load. This study established a multi-index evaluation model, including non-renewable primary energy consumption NRPE, global warming potential GWP, and cost, as indicators of the environment's aspects to evaluate a building envelope. Figure 5 shows that the initial cost of the WFG prototype in Peralveche doubled the reference one's cost because of the investment in borehole heat exchangers. Over a 50-year lifetime cycle, the reference prototype's accumulative cost surpasses the WFG prototype, due to the operational cost difference. When it comes to the Life Cycle Energy and the global warming potential the WFG showed a better performance. The reference prototype consumed three times as much energy as the WFG. The accumulative CO₂ emissions for the WFG envelope were 25,247 kgCO_{2eq}, whereas the reference glass envelope was responsible for 85,286 kgCO_{2eq}. When the cost is increased by 100%, the total Life Cycle Energy decreased by 1145 GJ. It has been estimated that the initial investment for the WFG system would cost €17,529, while the Reference system would require an initial investment of €7373. The WFG system would require €640.88 for maintenance per year, with an end-of-product, total demolition, and removal cost of €7921. Summing together these values and the initial investment for the system, the final total Life Cycle Cost of the Peralveche WFG system is €40,611. Meanwhile, for Peralveche RC, this system would cost €1239 in maintenance costs per year, with an end-of-product, total demolition, and removal cost of €3921. Combining these values with the initial investment cost shows that the final total Life Cycle Cost of the Peralveche RC system would be €47,767. Therefore, in the Peralveche case, it is apparent that the successful construction and implementation of the WFG system would save the owner a total of €7156 over the total building life cycle period. When it comes to Life Cycle Energy assessment and global warming potential, the WFG system in the Peralveche prototype used 571 GJ of energy during its lifetime. It was also determined that the system would contain 25,452 kgCO_{2eq} during its 50 years of use. Meanwhile, for the Peralveche RC prototype, the system was calculated to use 1716 GJ of energy, while containing 85,286 kgCO_{2eq} during its 50 years of use. Therefore, the Peralveche WFG system, when compared to the RC, will save 1145 GJ of energy as well as 59,834 kgCO_{2eq} of Embodied Carbon over its entire lifetime.

Figure 6 shows that the HVAC operation cost over 50 years did not compensate for the higher initial cost of the WFG prototype. Over a 50-year lifetime cycle, the WFG envelope showed a better performance in the Life Cycle Energy and the global warming potential. The accumulative Life Cycle Energy for the WFG envelope was 2377 GJ, whereas the Life Cycle Energy of the reference glass was 3608 GJ. A model integrating Life Cycle Cost with Life Cycle Energy is used to assess the envelope schemes and select the optimal one in the decision-making process. The Sofia WFG system is estimated to initially cost €65,626, while the Sofia Reference system would cost €40,795.

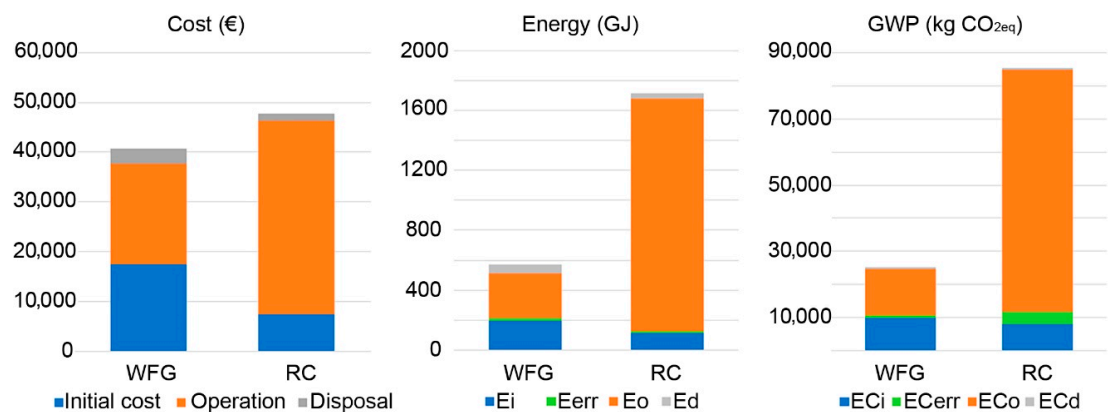


Figure 5. Life Cycle Assessment outcomes of the Peralveche prototype.

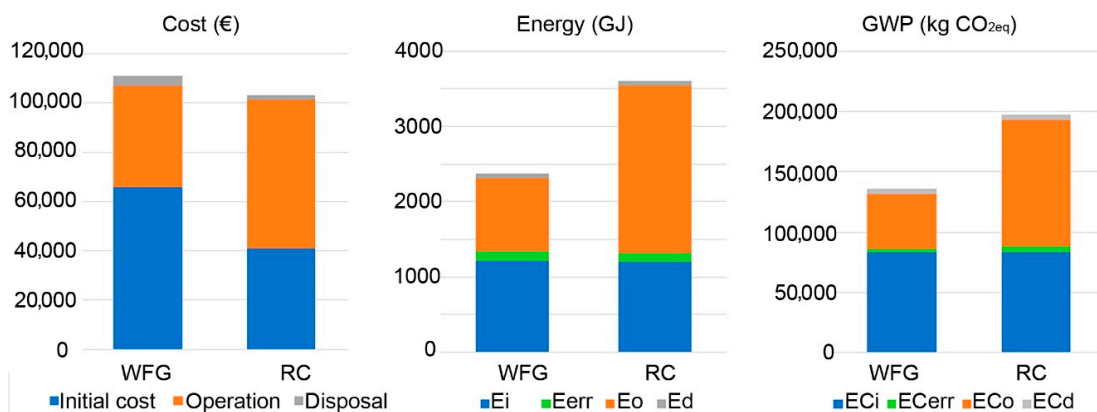


Figure 6. Life Cycle Assessment outcomes of the Sofia prototype.

For Sofia prototypes, the WFG system would require €1320 for maintenance per year, with an end-of-product, total demolition, and removal cost of €10,046. Summing together these values, as well as the initial investment for the system, it can be seen that the final total Life Cycle Cost of the Sofia WFG system is €110,865. Meanwhile, for Sofia RC, this system would cost €1923 in maintenance costs per year, with an end-of-product, total demolition and removal cost of €4923. Combining these values with the initial investment cost, the final total Life Cycle Cost of the Sofia RC system would be €103,066. The Sofia WFG system would cost an additional €33,184 compared to Sofia RC over the structure's lifespan.

The WFG system in the Sofia prototype used 2377 GJ of energy, so the system would contain 136,250 kgCO_{2eq} during its 50 years of use. Meanwhile, for the Sofia RC prototype, the system used 3608 GJ of energy while containing 197,625 kgCO_{2eq} during its 50 years of service. In this case, the WFG system will save 1231 GJ of energy while also containing 6137 kgCO_{2eq} less of Embodied Carbon over its entire lifetime as compared to the Reference system.

5. Conclusions and Limitations

This paper aimed to develop a conceptual framework to assess the building envelope energy consumption throughout their entire life cycle. By analyzing two case studies, the results can assist building designers during the decision-making process at early stages and consider water flow glazing as an option to reduce energy consumption and CO₂ emissions.

As has been demonstrated, WFG glazing technology typically retains a higher price point for initial construction than the reference prototypes, requiring a substantial investment early on. This is because of the additional equipment needed for the successful operation of WFG panels. The Peralveche reference prototype's initial cost is 42% of the

Peralveche WFG cost, whereas the Sofia reference prototype initial cost is 62% of the WFG initial cost. The steeper initial investment for WFG technology can serve as a deterrent for the technology in the eyes of building design professionals. However, when the total Life Cycle Costs of the WFG and RC are also taken into account, WFG can potentially be a much more economical option.

It is not until we consider each system's overall Life Cycle Costs that the economic benefits of WFG systems become apparent. For this study, the building lifespan was determined to be 50 years. The total Life Cycle Cost (LCC) of the Peralveche WFG is 85% of the total Reference system LCC. Meanwhile, the Sofia Reference LCC is 92% of the total WFG LCC. The conclusion derived from these findings is that selecting high-performance triple glazing is better than a WFG in Life Cycle Cost. A WFG system is better over the operation phase only when it is compared with a traditional double-glazing system, as has been demonstrated in Peralveche.

Another important factor that should be taken into account in the analysis between a much more traditional glazing system versus a WFG system is the Life Cycle Energy (LCE) and global warming potential (GWP) variables. The Peralveche WFG system, as compared to the Peralveche reference prototype, has demonstrated a savings of 66% in LCE with a 70% reduction of CO₂ emission. In Sofia, there are similar results. Sofia WFG demonstrated a 36% savings in LCE with a 30% reduction in CO₂ emissions. This analysis shows that a high-performance triple glazing system improves the Reference prototype performance, but WFG performs better in LCE and GWP in both cases.

The WFG system, however, does have several limitations. Firstly, there is an apparent lack of interoperability with the rest of the building systems present in modern structures, especially concerning the ventilation system. In addition to this, it is not always possible to retrieve all the detailed information needed as input for Water Flow Glazing operation. The maintenance of the building systems operation and the control of the building's indoor environmental conditions according to its user's comfort is of the utmost importance, and smart meters can assist in this. However, these devices pose considerable limitations concerning the quality, frequency, and accuracy of data. Therefore, taking these limitations into account, several future steps of research should be undertaken. Firstly, a development of a testing method to evaluate the performance of the unitized module components should be explored. In addition to this, more case studies in several different climate regions should be analyzed. Thirdly, the development of a management system to control the water pump in the circulating device should be realized. The life cycle of the water pump, which is another point of future research, depends on the operating hours and the on-off cycle. Finally, an integration of a whole evaluation protocol, including maintenance, environmental, and economic aspects, should be explored. This could be used by stakeholders involved in the design, maintenance, and monitoring process in future, potential projects.

After monitoring the WFG systems for a year, several uncertainties, misfunctions, and system issues must be addressed. WFG systems are limited by a high initial investment cost coupled with the need for an energy management system integrated with the other required equipment, especially if the system is coupled with borehole heat exchangers combined with a ground source heat pump. The heating and cooling devices must be adequately dimensioned to avoid misfunctions, especially the Air-to-Water heat pump. Further research must include monitoring energy performance much more accurately by attaching sensors to monitor the amount of electricity powering the heat pump to compare the actual thermal and electricity consumption. In addition to this, further standardization of the manufacturing and deployment process is required to bring down upfront investment costs and payback periods. Finally, another potential further research component would be to control indoor relative humidity, which would be achieved by integrating WFG with efficient ventilation systems.

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Abbreviations

Symbol	Meaning
AEC	Architecture, engineering, and construction.
EE	Embedded energy.
FE	Final energy.
GHG	Greenhouse gas.
GSHP	Ground source heat pump.
GWP	Global warming potential.
LCA	Life Cycle Assessment.
LCC	Life Cycle Cost.
LCE	Life Cycle Energy.
NRPE	Non-renewable primary energy.
PV	Photovoltaic
PVIF	Present value interest factor.
PVIFA	Present value interest factor of the annuity.
RC	Reference cabin.
RPE	Renewable primary energy.
WFG	Water Flow Glazing.
A_j	Absorptance of glass layers.
C_1	Construction cost.
C_2	Operation cost.
C_3	Demolition cost.
E	Total energy of the building element.
E_i	Initial embodied energy.
E_{err}	Recurrent embodied energy for future maintenance and refurbishment.
E_o	Total annual operational energy.
E_d	embodied energy required for demolition and disposal.
h_j	Convective heat coefficients.
i_0	Solar irradiance ($W \cdot m^{-2} \cdot K^{-1}$).
\dot{m}	Mass flow rate per unit of surface ($Liter \cdot min^{-1} \cdot m^{-2}$).
n	Lifetime of the element in years.
P	Heat gain in the water chamber (W).
q	Heat flow ($W \cdot m^{-2} \cdot K^{-1}$).
r	Interest rate.
θ_i	Interior temperature (K).
θ_e	Exterior temperature (K).
θ_{IN}	Inlet temperature of the water chamber (K).
U	Thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$).
U_i	Interior thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$).
U_e	Exterior thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$).
U_w	Thermal transmittance (water chamber–interior) (K).

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