Building energy simulation. Case studies with water flow glazing

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Abstract. Buildings represent complex systems with high levels of inter-dependence on many external sources. Building envelope expertise is a part of the building process, from pre-design through post-occupancy. Large glazed surfaces increase the building’s luminosity. However, the glass is a poor thermal insulator, and allows a great part of the solar radiation passing through it. The use of a glazed façade has the disadvantage of introducing an excess of energy in the building by means of solar radiation during the summer months. New glass technologies solve the energy problems raised by the use of glass in buildings: double and triple glazing, surface treatments, solar control glazing, low-emissivity glazing, etc. One of these is the water flow glazing. Due to the spectral properties of water, it captures most of the infrared solar radiation, allowing the visible component to pass through. This provides the water flow glazing with the same luminosity than conventional glazing, only lessening the heat transfer towards the interior space. Furthermore, the water circulation allows us to use, store or dissipate the captured energy as deemed appropriate. The first goal of this paper is to study the integration of the water flow glazing to evaluate its behavior in different weather conditions. Active and passive strategies will be tested in real case studies to achieve the goal of a Zero Energy Building.

1. Introduction

Improving the energy performance of buildings is a cost-effective way of avoiding rising energy costs and fighting against climate change. This paradigm benefits owners and challenges architects and building designers [1, 2]. International building codes have been focusing on prescriptive requirements mainly related to the building envelope [3, 4]. Nowadays, with the vision of transforming to a carbon-neutral economy by 2050, most countries are introducing new legislation to improve energy efficiency and add renewable energies in the building stock. The concept of a zero-energy building (ZEB) is generally understood, but there is not an internationally agreed definition [5]. In the USA, the net-zero building is a voluntary certification program established by the International Living Future Institute (ILFI) that focuses exclusively on the energy balance of a project [6]. In the European Union, the Directive on Energy Performance of Buildings (2010), focused on the Nearly Zero Energy goal, stated, “all new buildings shall be nearly zero energy buildings by 31 December 2020” [7, 8, 9]. In China, net-zero buildings are currently individual and volunteer-based, and no policy or building code has any requirements related to net-zero energy or net-zero emissions.

The first and most effective step towards a ZEB is to reduce energy consumption. A building with low energy needs would require less on-site energy generation. Expand passive measures play a crucial
role in the design of ZEBs as they directly affect the heating, cooling, ventilation and lighting loads put on the building’s mechanical and electrical systems, and indirectly reduce the sizing of the renewable energy that balance the consumption.

Some authors have elaborated on a set of passive design solutions, energy efficiency solutions, and renewable energy solutions that are used in a building to lower the energy impact of the space conditioning and building loads [10]. The highest potential for energy savings lies in the quality of the building envelope and ventilation systems. The use of PV and solar thermal panels, along with adjusting the temperature setpoints are considered effective measures in cold climates [11, 12]. Solar energy is the primary source for on-site generation of electricity, and other technologies, such as wind turbines, are rarely used in the building sector. Low wind speeds in urban areas and noise problems hinder the use of this technology on a larger scale. Users’ behavior is also crucial in this new type of building to ensure they understand the specific operating processes of the building [13, 14].

Heat losses through the external glazing account for approximately 40% of the overall heat losses in buildings. Therefore, improving the performance of glazing is essential in optimizing the building energy-saving design [15, 16]. Nowadays, it is possible to reduce the energy consumption of the window by using high-performance glazing systems, such as coatings and triple glazing, with an insulating gas between panes [17, 18]. Thermal transmittance U, solar heat gain coefficient, or g-factor and visible transmittance Tv are global glazing parameters needed to calculate the energy performance of a window, and therefore of a building. The g-factor is the most common parameter to measure the solar energy transmittance of glass panes in Europe, whereas, in the United States, it is the Solar Heat Gain Coefficient (SHGC). The g-factor usually refers to a glass panel, and the SHGC refers to a whole window, including frame material and screens.

Coatings, air, and gas between panes are passive glazing properties that building designers can use. There are guidelines, catalogs, and simplified methods that can be used to select the type of glass that fits the climate zone, the use, and occupancy of the building [19, 20]. The ratio between visible transmittance and solar heat gain coefficient is a fixed value in double and triple glass panes. In climates with severe winter, the designer should select the highest g-factor to reduce heating so that winter solar gains can provide the building with a portion of the heating energy demand. Low g-factors are desirable in warm climates. In moderate climates, with high air conditioning costs or summer overheating problems, windows with lower g-factors reduce summer cooling and overheating. However, they also minimize free winter solar heat gain.

Water flow glazing (WFG) comprises two or three glass panes with a flowing water chamber that absorbs and transports the solar energy before entering the building [21, 22]. This water chamber is connected in a closed circuit to a hydraulic pump and a heat exchanger. The flow rate of this circuit is governed by switching ON and OFF a hydraulic pump. Solar absorption depends on the spectral characteristics of each layer of the glazing. Solar radiation is absorbed, and later this heat is transported by the water in a closed circuit [23]. This heat is exchanged with a primary circuit. The possibility to control the flow rate of the water chamber allows modifying heat flux associated with the solar heat gain (g), which is entering into the building. Depending on the spectral characteristics of each layer, which comprises the glazing, the g-factor can vary between 0.2 and 0.7.

The following section of this paper evaluates different building simulation tools at the design stage. This paper aims to review commonly used strategies based on energy simulation to establish their effectiveness in cold climates. Section 4 illustrates the influence of parameters such as airtightness, natural ventilation, and passive solar heat gains. Finally, the results of traditional HVAC systems composed of air-to-air heat pumps and split units are compared with a hydronic system that integrates water flow glazing and a ground source heat pump to evaluate its behavior in summer conditions.
2. Description of the case study

The focus of this study is to understand the strategies that would help improve a building’s energy consumption in a New England Climate and progress it forward into a nearly-zero energy building. The strategies that are required to enhance this building are construction methods such as airtightness, design of external components, and window placement. Selecting the best HVAC and solar systems are also required to improve the building’s energy consumption.

The study uses a three-stage optimization plan to develop the building: Firstly, a 3D BIM model and analysis of the building that will provide information on energy consumption; secondly, a 3D energy plus model (Figure 1, 2) will be produced, focused on daily studies and different strategies; finally, the utilization of Water Flow Glazing (WFG) will improve thermal performance and comfort, in order to explore the feasibility of having a nearly-zero energy building in the New England region of America. The multipurpose residential building sits in the small town of Keene, New Hampshire.

![Figure 1. Rendered View of Building](image1.jpg)

![Figure 2. Energy Plus Model](image2.jpg)

The building holds studio apartments and a rock-climbing facility that goes up to five stories. Each apartment has a big south-facing window and smaller windows on the east and west facades. The envelope of the building begins with the timber frame construction.
The external walls are composed of (inside to outside): gypsum wallboard, air infiltration barrier, wood studs/glass fiber batt insulation, polystyrene-expanded-eps, and cherry planks. The roofs are assembled with (inside to outside): gypsum wallboard, air infiltration barrier, wood joist/glass fiber batt insulation, plywood sheathing, polystyrene-expanded-eps, metal deck. The floors (bottom to top): wood joists/glass fiber batt insulation, plywood sheathing, oak flooring. The Partitions (left to right): gypsum wallboard, wood studs, air, wood studs, gypsum wallboard. All U-values of the building’s components are recorded below in Table 1 with the Passive House (PHIUS) requirements. The building uses a split system(s) with mechanical ventilation with a high-efficiency heat pump for its HVAC. The system also utilizes heat recovery with an efficiency of 70%. The air changes per hour (ACH) of the building have three different levels to it. The importance of having a tighter construction is the amount of energy leaving the building that could be used for the heating load. Two different window types are used. Large storefront glazing occupies the south façade, and smaller windows are placed on the East and West façades. The storefront glazing on the south façade allows each of the apartments and the rock-climbing facility to utilize the solar gains coming in from the south. The smaller windows on the East and West façade are used for views and to allow a little more sunlight into the spaces.

3. Results and discussions
For the first part of the three-stage optimization strategy, two programs were used: Autodesk Revit and Green Building Studio. Revit was used to model the building, and Green Building Studio performed an energy test to determine the energy needs. Table 2 illustrates a breakdown of the energy uses between each part of the building. PE stands for Primary Energy. PEH stands for heating. PEHW stands for hot water. PEC stands for cooling. PEL stands for lighting. The primary energy consumption for the building is roughly 472 Btu/yr. and about 56% of the total is from the energy needed for water. The second biggest consumer is the lighting, with 26% of the total energy consumption.

| Insulation          | Material                  | Thickness (Inches) | U-Value btu/(hr·ft·°F) |
|---------------------|---------------------------|--------------------|------------------------|
| External Wall       | Polystyrene – Expanded - EPS | 4                  | 0.0202                 |
| External Wall       | Glass Fiber Batt          | 6                  | 0.011                  |
| Roof                | Polystyrene – Expanded - EPS | 4                  | 0.0202                 |
| Roof                | Glass Fiber Batt          | 8                  | 0.011                  |
| Floor               | Glass Fiber Batt          | 10                 | 0.011                  |

| Building | PEH   | PEHW  | PEC   | PEL   | PE    |
|----------|-------|-------|-------|-------|-------|
| Percentage | 13%   | 56%   | 5%    | 26%   | 100%  |

Figure 3 looks at some of the biggest building components that affect the heating and cooling demands. The biggest component that affects the building’s overall energy consumption is the windows. They have a heating load of 69 kBtu/h and a cooling load of 147 kBtu/h. This displays the amount of energy that the building is losing through the windows.
Figure 3. Heating and Cooling losses through Building Components (kBtu/h). Inner Circle Represents Heating Demand and Outer Circle Represents Cooling Demand

The next biggest component is the ventilation during the heating load. Roughly 113 kBtu/h are needed for the heating load. The walls and the infiltration go together because if one is improved the other will improve along with it. Infiltration is how well the walls are put together and can only be done successfully in the field of construction. However, the simulations can show how much these two components can affect the overall heating and cooling demands if they are done successfully.

Table 3 looks at the heating and cooling demands of three different spaces of the building. The rock-climbing facility, an apartment that is located on the North side of the site and an apartment located on the South side of the site. When using Design Builder, the focus is also on these three specific spaces. These spaces were chosen because of their location and uses. The two apartments are on different ends of the site. The southern apartment has a greater external envelope than that of the northern apartment that sits below another one. The rock-climbing facility has the greatest volume and requires different heating and cooling solutions.

| Space                  | Surface (SF) | Heating (kBtu) | Cooling (kBtu) |
|------------------------|--------------|----------------|----------------|
| South Apartment        | 2,322        | 10.00          | 13             |
| North Apartment        | 3,251        | 11.00          | 13             |
| Rock Climbing Facility | 9514         | 59             | 89             |

By using Autodesk Revit and Green Building Studio, a general strategy can be made to improve the building and promote it to a net-zero energy building. The focus of the general strategy will be to improve the air tightness of the envelope and a way to reduce the impact that the windows have on the heating and cooling loads. Design Builder is used to further test the building and its capabilities to perform as a net-zero energy building.

4. Strategies for improvement
To improve and push for a nearly-zero energy building, Design Builder is explored to provide a daily model of the different energy uses. By doing so, displaying differences in each test and helping us
understand how the building can be improved. Other improvements such as PV arrays and a collective solar thermal system would help greatly in dropping the energy consumptions of the different contributors. The daily tests done in the Design Builder focuses on two dates. Tuesday, February 5th is placed as the coldest day of the year with a temperature at -9.85°F. The peak of solar gains on this day is 43 kBtu/h. The Saturday, July 20th, is placed as the hottest day of the year with a temperature of 98.45°F, with peak, the solar gains 25 kBtu/h. These dates were chosen to provide different strategies in the winter and in the summer. There are several factors that make it difficult to apply similar strategies to each space. The factors may be solar gains, external surface area, volume, and purpose of space.

4.1. Ventilation strategies
The rock climbing facility is, by far, the largest space of the building. Its area of south oriented windows, the schedule of use, and the complexity of its spatial design make this space the ideal sample to test different strategies for improvement. The first day that will be simulated is Tuesday, February 5th and explore the different results that are provided for the coldest day of the year.

Figure 4 displays the amount of energy the rock-climbing facility uses within that day. The biggest factors that the results show are the heating loads and the external infiltration. The heating load is the highest at the beginning of the day at 89 kBtu/h. This is very high; however, it is 10% less than a different HVAC system without heat recovery. The external infiltration of the building on this day is -59 kBtu/h. The external infiltration is presented in a negative number because it’s the amount of energy leaving the building, cooling the space within. While the heating load, solar gains, occupancy and general lighting are heating the spaces.

Figure 4 displays the amount of energy the rock-climbing facility uses within that day. The biggest factors that the results show are the heating loads and the external infiltration. The heating load is the highest at the beginning of the day at 89 kBtu/h. This is very high; however, it is 10% less than a different HVAC system without heat recovery. The external infiltration of the building on this day is -59 kBtu/h. The external infiltration is presented in a negative number because it’s the amount of energy leaving the building, cooling the space within. While the heating load, solar gains, occupancy and general lighting are heating the spaces.

Figure 5 provided results based on the simple change of the air changes per hour from 0.7 to 0.5. By changing the ACH, the peak heating load decreased from the 89 kBtu/h to 72 kBtu/h. The external infiltration losses decreased from -59 kBtu/h to -42 kBtu/h.
In figure 6, the ACH is lowered more to 0.25. The result of the change is the peak heating load dropping down to 51 kBtu/h and the external infiltration decreasing to -21 kBtu/h. These numbers are very good at displaying the positive change to the peak heating load and peak external infiltration. They both are coming closer and closer to zero.

Figure 5. Rock-Climbing Facility in winter with Heat Recovery (ACH 0.5)

Figure 6. Rock-Climbing Facility in winter with Heat Recovery (ACH 0.25)
The rock climbing’s biggest issue was the external infiltration. To improve this parameter, the ACH of the building were dropped from 0.7 to .25. By doing this the heating loads reduced from 89 kBtu/h to 51 kBtu/h and the external infiltration from -59 kBtu/h to -21 kBtu/h. By tightening the building we can reduce the amount of energy that is escaping and ultimately reduce the amount of energy needed to keep the space heated.

Next, the hottest day, Saturday, July 20th will be simulated to test different strategies to improve the building’s performance. Figure 7 displays the results of the building with a heat recovery system and an ACH of 0.5. It is very clear to see that the big issue that needs to be solved during the hottest day is the solar heat gain. Here, the peak cooling load is -56 kBtu/h while the peak solar gains are 25 kBtu/h. These two correspond with each other reflecting one another. As the peak of the solar gains, so does the cooling load. Summer days also offer a different look into infiltration and ventilation. There are now two times during the day that infiltration peaks, at night and during the day. At night the peak infiltration is -3 kBtu/h and during the day it is 10 kBtu/h. To improve the performance of the building during the summer, natural ventilation has been added to reduce the need for cooling.

Figure 8 illustrates the thermal behavior of the facility with a night ventilation value of 0.5 ACH. The peak cooling load does not show improvement, moving to a value of -55 kBtu/h. The infiltration at night improves from -3 kBtu/h to -2 kBtu/h and during the day it stays the same at 10 kBtu/h.
Figure 8. Rock-Climbing Facility in summer with Heat Recovery (ACH 0.5) Natural Ventilation at Night

The issue that needs to be addressed to improve the building will be how to shade the building to reduce the number of solar gains. Since the cooling load and the solar gains reflect each other, reducing one will reduce the other. In figure 9, the shade is added to reduce the number of solar gains during the day. The shading device that is used is a 4.4ft Projection Louvre that helps to diffuse most of the solar gains coming into the space.

Figure 9. Rock-Climbing Facility in summer with Heat Recovery (ACH .5) Shaded (4.9 ft Projection Louvre) Natural Ventilation at Night
The most significant parameter influencing the rock-climbing facility is the solar gain coming through the windows. To help improve the energy performance, the ACH stays at 0.5 and natural ventilation is provided during the night to reduce the cooling loads. Then, a projection louver was placed to reduce the solar gains entering the space. The cooling loads were not affected until the louver system was placed.

4.2. The influence of Water Flow Glazing

Researchers of the Polytechnic University of Madrid have developed a heat transfer computational fluid dynamics tool to simulate the performance of the water flow glazing unit to establish operational parameters. In this article, the tool has been applied to the rock-climbing facility to decide a variable solar heat gain coefficient (SHGC) of WFG envelopes. Previous papers have shown a mathematical model to predict the performance of WFG, along with other radiant systems [24]. The following differential equation presents the dependency of the different design parameters and variables:

\[
m c \frac{d \theta_i}{dt} = S_B U_B (\theta_e - \theta_i) + S_F [q + h_i (\theta_w - \theta_i)] + S_G [U_G (\theta_e - \theta_i) + U_W (\theta_w - \theta_i) + g I]
\]

(1)

The design parameters are constant in time. The integral of the equation turns variables into mean values. The integral of \(d \theta_i\) is canceled under the assumption that the variation of \(\theta_i\) with time is periodical.

\[
\theta_i = \frac{S_B U_B + S_G U_G \theta_e + g S_G I + S_F h_i + S_G U_W \theta_w + S_F q}{SU}
\]

(2)

where \(SU = S_B U_B + S_G U_G + S_F h_i + S_G U_W\)

A ground-source heat pump is connected to a hydronic distribution system made up of radiant floor and WFG. Figure 10 illustrates the schematics of the system. A closed circuit distributes the water at a certain temperature (67 °F in the winter, 60 °F in the summer) throughout the WFG and radiant floor. The closed circuit can include a plate heat exchanger to transfer the excess of energy captured by the windows to a buffer tank. The control system decides whether to dissipate the heat by means of geothermal wells or by the ground source heat pump. The design flow per square meter is determined through the maximum increase in temperature between the windows’ supply and return water. The coefficients \(h_i\) and \(h_e\) are taken from the European Standard [25], being \(h_i = 8 \text{ W/m}^2\text{K} (1.41 \text{ Btu/h ft}^2\text{ F})\) and \(h_e = 23 \text{ W/m}^2\text{K} (4.05 \text{ Btu/h ft}^2\text{ F})\) for common vertical glazing. A typical value for the heat transfer coefficient of the water chamber, \(h_w\), is 100 W/m²K (17.61 Btu/h ft² F). According to the European Standard for vertical glazing, \(h_c = 1.16 \text{ W/m}^2\text{K} (0.20 \text{ Btu/h ft}^2\text{ F})\) being argon the gas in the air chamber.
Figure 10. Details of WFG radiant system, a) schematics of the hydronic system: 1. WFG, 2. Air handling unit, 3. Radiant floor, 4. Heat exchangers, 5. Buffer tank, 6. Ground source heat pump, 7. Geothermal wells; b) triple WFG with an air chamber facing indoors and a water chamber facing outdoors.

The results of the simulation in figure 11 show the evolution of indoor temperature on February 5 and on July 20. WFG allows changing the solar heat gain coefficient by changing the flow of water. The results show that indoor comfort conditions are possible by setting the water temperature at 67 °F, and the g value at 0.7, on the coldest days of the winter, due to the solar radiation and internal heat gains. Indoor comfort conditions are possible by setting the g value at 0.2 and the water temperature at 60 °F in summer.

Figure 11. Analysis of indoor temperature with WFG, radiant floor, and ground source heat pump in winter (a) and summer (b).

The absorbed heat in the water chamber is transported later by the flow rate. If the flow rate is high enough, the net energy power gained by the glazing per unit of area, $P$, is given by equation 3.
\[ P = \left( \frac{m \cdot c}{m \cdot c + U_e + U_i} \right) \left[ A_v \cdot i_0 + U_i (\theta_i - \theta_{IN}) + U_e (\theta_e - \theta_{IN}) \right] \] (3)

Where \( m \) is the mass flow rate per unit of area, \( c \) is the specific heat of water, \( A_v \) is the net absorptance of the water chamber, \( i_0 \) is the direct sun radiation, \( \theta_{IN} \) is the temperature of the inlet water, \( U_i \) is the interior thermal transmittance and \( U_e \) is the exterior thermal transmittance. These last two thermal transmittances \( U_i \) and \( U_e \) measure the heat transfer between the water chamber and indoors and outdoors respectively. Typical values for \( A_v \) are given in previous articles [24] depending on the sum of the absorptances of each layer, which makes up the glass pane. A range of values from 0.429 to 0.524 has been considered in this case study. The flow rate should be high enough to transport the energy which is absorbed. If \( m \) is higher than \( U_i + U_e \), the absorbed energy that is transferred indoors and outdoors is minimized. This allows choosing the design flow rate of the water flow glazing. When the water chamber is facing indoors and the gas chamber is facing outdoors, \( U_i \) is much higher than \( U_e \). Its values are given in equations (4) and (5).

\[ \frac{1}{U_e} = \left( \frac{1}{h_e} + \frac{1}{h_c} + \frac{1}{h_w} \right) \] (4)

\[ \frac{1}{U_i} = \left( \frac{1}{h_i} + \frac{1}{h_w} \right) \] (5)

Some test cases are run in summer conditions. Firstly, equation (3) is used to calculate the cooling power on July 20. A mass flow rate of 1 liter per minute and per square meter has been considered to maximize the solar absorption of WFG without increasing the temperature. Secondly, the cooling power has been compared with Design Builder results. Figure 12 illustrates the daily cooling loads, taking into account the following parameters: solar heat gains, equipment, lighting, occupancy, infiltration, and ventilation. The cooling power required with the WFG connected to a ground-source heat pump is lower than that with the air-to-air heat pump simulated with Design Builder in figure 8. Comparing the cooling power required in figure 9, when an overhang provides the glass with shade, the performance of the hydronic system is better over the day, except when the solar radiation reaches its peak and the water flow has to absorb the maximum amount of heat.

The energy required by the WFG and radiant floor for this simulation is 422.2 kBtu (123.8 kWh) per day. If we consider the coefficient of performance (COP) of the ground source heat pump to be 4 (based
on the specifications in the machine used in real conditions), the electric energy consumption is 123.8/4 = 30.9 kWh per day. The daily energy with an air-to-air heat pump is 512.0 kBtu/h (150.1 kWh). If the HVAC system has a COP of 2.5, the electric energy is 150.1/2.5 = 60.0 kBtu/h per day. Energy Efficiency Ratio (EER) is the common performance metric in the US. EER has a linear relationship with COP: EER = (COP) X (3.412). These performance metrics are dependent on the outside temperatures, which is why ground source heat pumps are a great solution also in winter, for it is also easier to extract heat from the ground. Very substantial savings, up to 51%, can be achieved with the WFG/ground source heat pump combination.

5. Conclusions
BIM is a tool for decreasing costs and time during the building-design stage, providing an integrated file which contains architectural and energy information. The goal of this work is to develop and verify a new methodology for overcoming the gap between BIM and energy models and facilitating the use of BIM within the ZEB construction process. The results confirm the applicability of the proposed methodological approach. This article shows the workflow to analyze the potential energy-saving rate in severe cold regions.

The key to achieve the sustainability in the building stock is to reduce the energy demands in buildings to the point where building energy needs can be met entirely through renewable and non-greenhouse-gas emitting energy sources. The use of heat recovery ventilation and high thermal insulation commonly yield more significant energy savings for the building. Improving the airtightness can be the most cost-effective measure in cold climates. Natural night ventilation has a cooling effect in the summer, whenever the outdoor air temperature is below the indoor air temperature.

The infiltration rate of the building was dropped from 0.7 to 0.25 to improve the performance in winter. By doing this, the heating loads reduced from 89 kBtu/h to 51 kBtu/h. In summer, the strategies of natural night ventilation, and projection louvers help reduce the cooling loads from 56 kBtu/h to 42 kBtu/h.

Finally, the results of traditional HVAC systems composed of air-to-air heat pumps and split units are compared with a hydronic system that integrates water flow glazing and a ground source heat pump to evaluate its behavior in the summer conditions. A water flow glazing allows controlling the incoming solar energy into a building through its flow rate. A primary system should be designed for the building to dissipate the excess of heat with an optimum coefficient of performance. The energy savings can be more than 50% in summer with the WFG/ground source heat pump combination.

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