

# Thermal Simulation of a Zero Energy Glazed Pavilion in Sofia, Bulgaria. New Strategies for Energy Management by Means of Water Flow Glazing

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**Abstract.** The building sector is primarily responsible for a major part of total energy consumption. The European Energy Performance of Buildings Directives (EPBD) emphasized the need to reduce the energy consumption in buildings, and put forward the rationale for developing Near to Zero Energy Buildings (NZEB). Passive and active strategies help architects to minimize the use of active HVAC systems, taking advantage of the available natural resources such as solar radiation, thermal variability and daylight. The building envelope plays a decisive role in passive and active design strategies. The ideal transparent façade would be one with optical properties, such as Solar Heat Gain Coefficient (SHGC) and Visible Transmittance (VT), that could readily adapt in response to changing climatic conditions or occupant preferences. The aim of this article consists of describing the system to maintain a small glazed pavilion located in Sofia (Bulgaria) at the desired interior temperature over a whole year. The system comprises i) the use of Water Flow Glazing facades (WFG) and Radiant Interior Walls (RIW), ii) the use of free cooling devices along with traditional heat pump connected to photo-voltaic panels and iii) the use of a new Energy Management System that collects data and acts accordingly by controlling all components. The effect of these strategies and the use of active systems, like Water Flow Glazing, are analysed by means of simulating the prototype over one year. Summer and Winter energy management strategies are discussed in order to change the SHGC value of the Water Flow Glazing and thus, reduce the required energy to maintain comfort conditions.

## 1. Introduction

Energy consumption in buildings has grown over the last decades due to the expansion of cities, the economic prosperity of countries, and the increase in living standards. In 2002, the Energy Performance of Buildings Directive (EPBD) [1] was approved. This directive emphasizes the need to reduce energy consumption and improve energy efficiency in buildings. The EPBD Recast [2] was approved in 2010, introducing objectives concerning the Near to Zero Energy Building (ZEB) for both existing and new construction. Despite the lack of definition in the Directive 2010/31/EU [2], it emphasizes fundamental features of the ZEB. The performance of central heating, ventilation and air-conditioning (HVAC) systems is particularly important to achieve energy efficiency in buildings [3]. The HVAC system is the



largest energy end used in buildings [4] where inefficient operation and maintenance of the HVAC system can cause energy wastage, customer complaints, poor indoor air quality and even environmental damage [5]. The thermal transmittance (U value) generally constitutes the most significant parameter for the selection of both opaque and translucent surfaces. The absorptance, thermal lag and thermal energy storage capacity are also parameters that affect the performance of the opaque surfaces. Meanwhile, for transparent surfaces, in addition to their U value, it is necessary to take into account their visible transmittance and solar heat gain. Sun irradiation represents a major concern over hot months of the year. Evaluating how it affects the different regions inside a building is not simple, as many factors have to be taken into account: visual properties of the glazing, internal reflections and different types of radiation [7]. In the United States, the most common coefficient to measure the solar energy transmittance of glass panes is the Solar Heat Gain Coefficient (SHGC). In Europe, the most common coefficient is the g-value. It ranges from 0 to 1: 0 indicates 0% of radiation passing through the glazing and 1 indicates 100% of radiation passing through a glazing. The difference between both is that, apparently, the g-value usually refers to a glass pane and the SHGC refers to a whole window including frame material, screens and some other features [8].

The glass and window properties are selected with respect to several, often contradictory, considerations. Generally, a window is supposed to let in as much daylight as possible, give comfortable luminance conditions, transmit a minimum of heat from the interior to the exterior. Various solutions are available to control the solar heat gains or losses through windows. The ability of coated windows to block the heat transmission while allowing visible light to pass through has been studied in several articles [9-12]. Water-Flow Glazing (WFG) technology shows promising results in regard to its ability to change thermal properties depending on weather conditions [13]. The Water Flow Glazing system consists of a controlled flow of water at the cavity between two panes of glass. Water has the ability of absorbing infrared radiation. In winter time, it is usually necessary to allow the highest quantity of radiation to enter the building. Lowering the g value is the optimum solution. Nevertheless, having a lot of glazing surface area can increase the energy losses through the glazing. On the other hand, over summer season the g value should be reduced as much as possible as radiation is important and temperatures are usually higher. The optimum solution in Summer is to block radiation. Due to these two opposed situations, it is difficult to select a glazing with optimum properties for both seasons. Water flow glazing is a feasible solution to avoid this problem because the g value can be controlled by changing the flow of water.

The room heat gain can be reduced considerably and, at the same time, the window can serve as a water pre-heating device because flowing water can transport and transfer heat to buffer tanks [14]. In physical terms, the procedure towards NZEBs consists in designing the building envelope for achieving thermal comfort, so that, if a next step including mechanical cooling is required, efficient HVAC systems shall only deliver a limited amount of energy to provide the required thermal comfort conditions. At the same time, efficient lighting and electrical appliances have to be selected to reduce the electricity demand of the building. Then, the overall energy required by the building has to be covered by renewable energy preferably produced on-site.

Industrial Development of Water Flow Glazing Systems (Indewag) is a research proposal submitted under the Horizon 2020 program. Indewag project tackles the cost reduction goal and ZEB performance by using Water Flow Glazing facades (WFG) and Radiant Interior Walls (RIW), while minimizing the size of HVAC and PV-installations. Indewag team will carry out the construction of several prototypes in order to test the behaviour of Water Flow Glazing. One of those prototypes will be a pavilion place in Sofia, Bulgaria.

The aim of this article consists of describing the system to maintain the pavilion at the desired interior temperature over a whole year and simulate its energy consumption. The building prototype consists of a pavilion with a square plan measuring 7 meters by 7 meters. Its envelope is comprised of four façades with WFG panels of 3 meters' height and 1.3 meters' width. WFG panels provide natural light and an enjoyable interior space. The walls are oriented to cardinal points. It includes interior partitions also made up of WFG. The ceiling and floor are well insulated. On the roof, there are photovoltaic panels

working as electrical source system. The city of Sofia has cold and warm seasons; therefore, it is necessary to use appropriate strategies for these two completely different climatic conditions. Detailed energy simulations can help predict the energy performance of the house, and the annual energy production and consumption.

In a context where the objective is managing efficiently the energy consumption, this project aims also to simulate environmental conditions inside a building or a house. Effective energy management systems are considered a promising energy saving technique with significant commercial potential [15-17]. A Smart Energy Management System has been developed by the research group at the Aerospace School of Madrid. The system comprises mesh network transmitter nodes connected to all WFG façade modules. A central controller interacts with a user interface found on a device separate from the central controller. In order to provide the central controller with data the nodes monitor inlet and an outlet temperature of water. Decisions will be made to optimize the behaviour of the system when it comes to water flow.

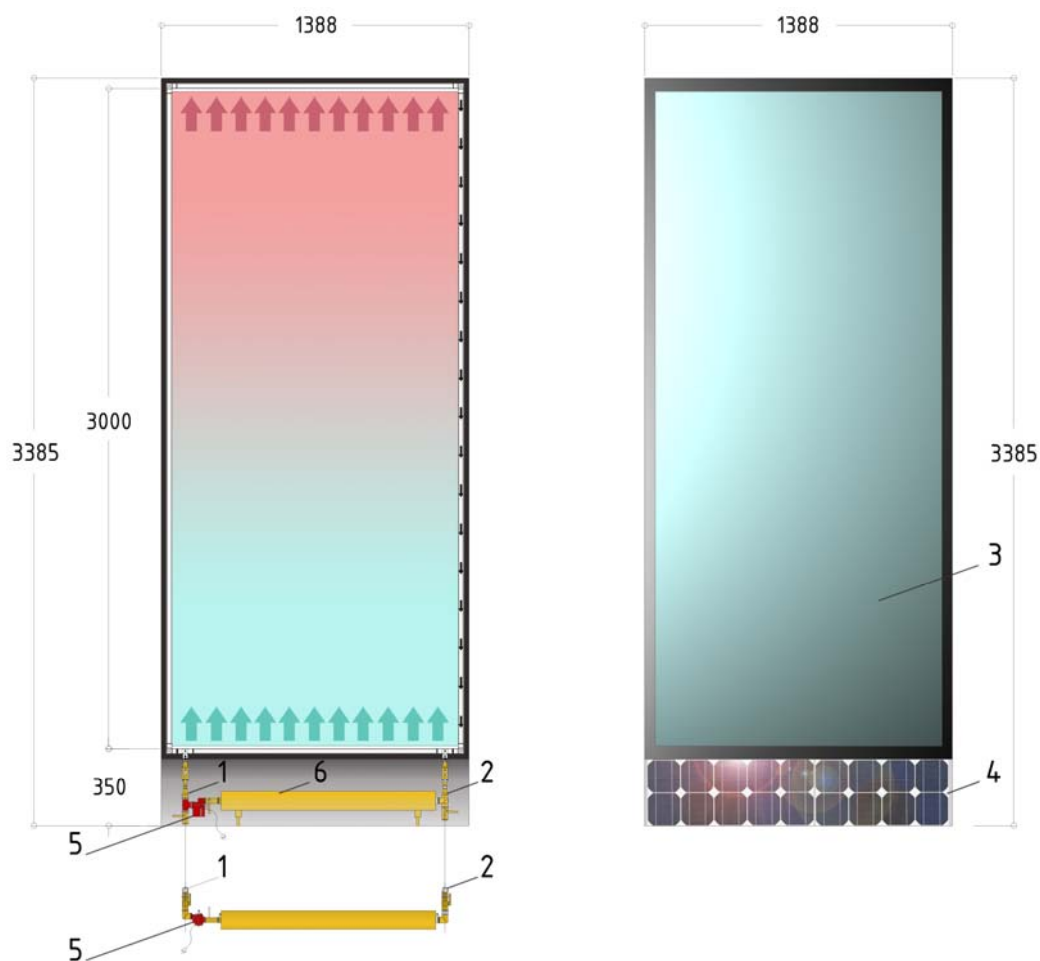


Figure 1: Description of WFG module. 1. Supply pipe; 2. Return pipe; 3. Glass; 4. Photo-voltaic cells; 5. Solar water pump; 6. Heat Exchanger.

## 2. Description of the WFG module.

One of the goals of Indewag project consists of development of standardized industrial production of both WFG-façade elements and RIW partitions. The modular façade units are composed of a Water Flow Glazing panel, a water pump with a heat exchanger, a photovoltaic panel along with the electronic

monitoring system for water temperature in different points of the panel. Figure 1 shows sections and elevations of the module and describes its components.

### 3. Description of the prototype.

The prototype is made up of three elements: i) the pavilion itself, ii) the devices that will allow to keep inside temperature at a comfort range and iii) the monitoring system. Figure 2 shows an external view of the pavilion.

#### 3.1. Pavilion

The pavilion has been designed as a glass box with a square plan measuring 7 meters by 7 meters. The wall glass envelope is made of the above mentioned WFG module. The roof and floor are well insulated and losses through them are not taken into account. The interior partitions are also made up of WFG. On the roof, there are photovoltaic panels working as electrical source system.



Figure 2: External view of the pavilion.

#### 3.2. Description of passive and active heating and cooling system

In order to obtain the desired results, the prototype heating and cooling system is comprised of two circuits: a) **pool-envelope** circuit and b) **heat pump-interior partitions** circuit. It must be noted that these systems and strategies could not be suitable for every place. These strategies have been developed for Sofia (Bulgaria), taking into account both weather conditions and sun radiation.

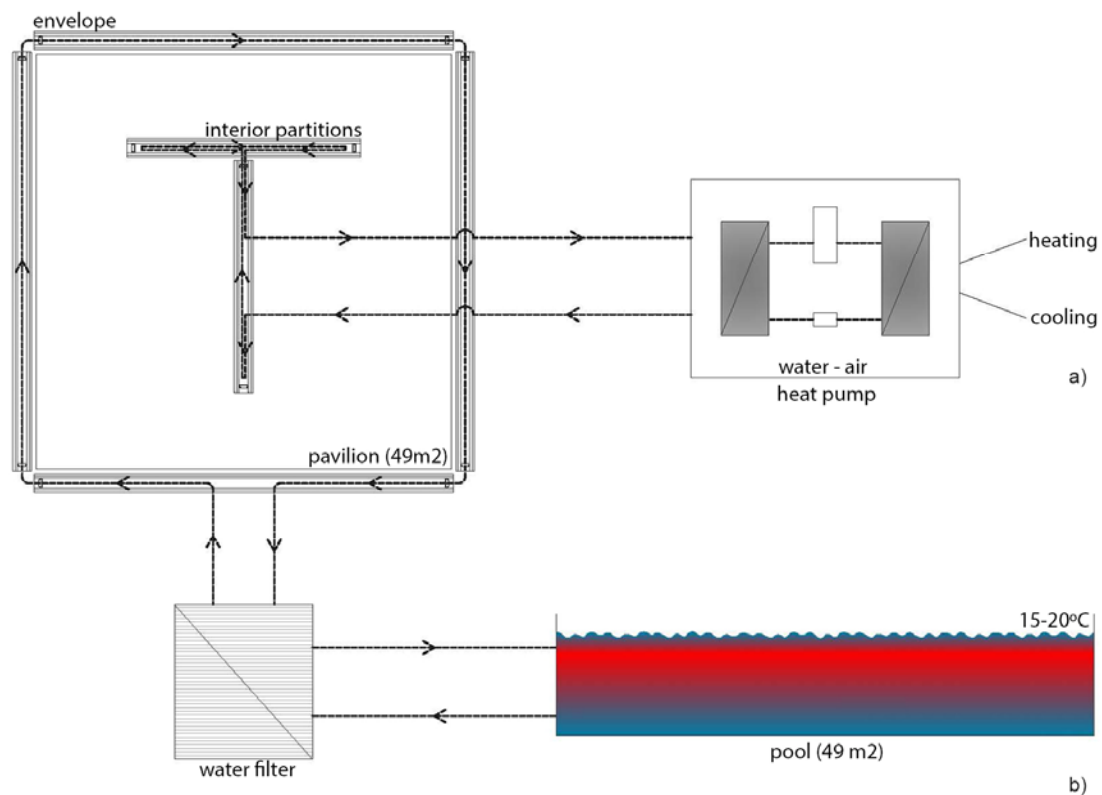


Figure 3: Description of energy management system,  
a) heat pump-interior partitions circuit; b) pool-envelope circuit.

The **pool-envelope** circuit links the envelope WFG by means of heat exchangers to a pool. This system is intended to provide the prototype with free cooling. Evaporative cooling in the pool allows to dissipate the heat. The high daily thermal swing enables the use of the pool thermal mass to balance out the interior temperature and reduce the need for mechanical air conditioning in Summer.

The **heat pump-interior partitions** circuit manages a primary circuit that links a heat pump to the interior WFG partitions by means of heat exchangers. It is intended to heat up or cool down the interior partitions of WFG. This is a heating and cooling backup system.

### 3.3. Monitoring system

A Smart Energy Management System has been developed by the research group at the Aerospace School of Madrid. Nowadays, there is a technology gap in wireless sensors for reliable self-powering mechanisms. The proposed device addresses the gap by developing wireless technology and system-level integration to enable solar powered wireless sensors with significant range to reduce networking infrastructure requirements. The system comprises mesh network transmitter nodes connected to all WFG façade modules. Each node controls temperature of water in different parts of the WFG modular unit. It is important to monitor this condition in the inlet and outlet point of the Water Flow Glazing. Also, monitoring temperature in the inlet and outlet of the heat exchanger is relevant. Some temperature and humidity sensors are placed in different points of the glass to monitor the energy exchange between the room and the outside. Figure 4 shows the schematic view of transmitter nodes included in the WFG module. The components of each node are:

- MCU: the device is operated by a microcontroller, it is used the AVR ATmega328P configured for working at 8MHz, with 3.3V.



- Ultra-Capacitor allows the sensor to keep on sending data in the event of the lack of sun light.
- SHT21 Sensirion temperature and relative humidity sensor inside the node.
- Wire Channels are used to take temperature measures in the different parts, they will be controlled by software.
- RFM 22B Radio is in charge of controlling the wake up of the MCU when it is in Power Down mode.
- Photovoltaic panel will feed the device with 12V or less, and there will be necessary to control this voltage with a Zener diode, some parts in the device cannot exceed 3.6V.
- MOSFET is necessary for controlling the power that is supplied to the internal pump of the modular unit.
- Zener diode controls the input voltage of the ultra-capacitor, it will depend on the nominal voltage of capacitor and the MCU.
- Diode controls the direction of the current, the photovoltaic panel should feed the capacitor and not discharge it when there is not environmental light.

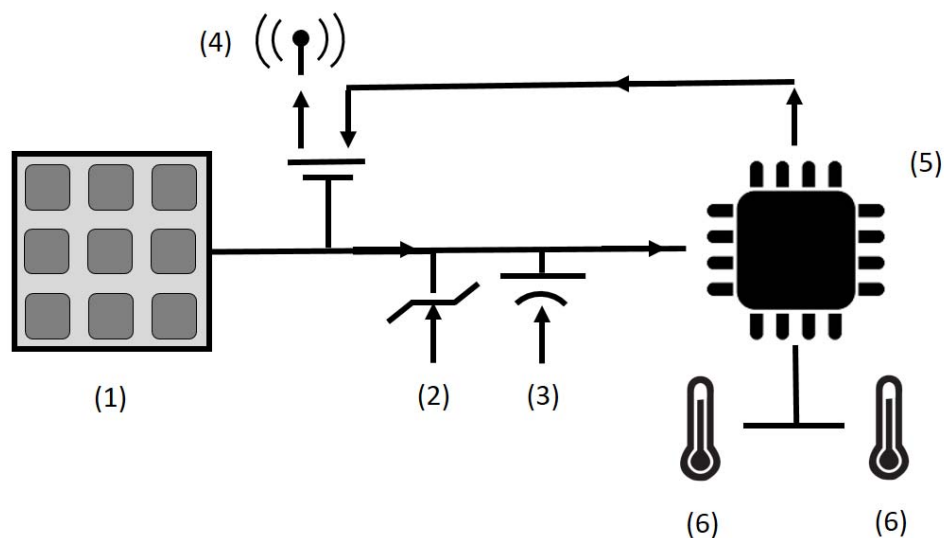


Figure 4. Simplified model of the node circuit. (1) PV microcell; (2) Zener; (3) Ultra Capacitor; (4) Radio frequency transmitter; (5) Microcontroller; (6) Temperature Sensor.

Each node includes a microcontroller and a radio frequency device capable of sending information. Once the node monitors the temperature, the data are sent to a Hub Controller. This Hub is responsible for controlling the flow of water through the window and makes decisions according to the purposes of the glazing (Reject energy, harvest energy, etc.). His ability to control the behaviour of the window lies in the regulation of the voltage that feeds the hydrodynamic pump. Figure 5 shows the elements involved in the system. So, to sum up, the process starts with the measurement of temperature in different parts of the modular unit, this information is sent to the Hub where decisions are made in regard to turning on or off a heat pump. Meanwhile, each node is powered with the photovoltaic panel of the modular unit and its voltage is controlled by a Zener diode, this current charges an ultra-capacitor that will feed the device in the night or in the low light conditions. An embedded software allows the node to control the voltage of the hydrodynamic pump and it will control the water flow through the glass.

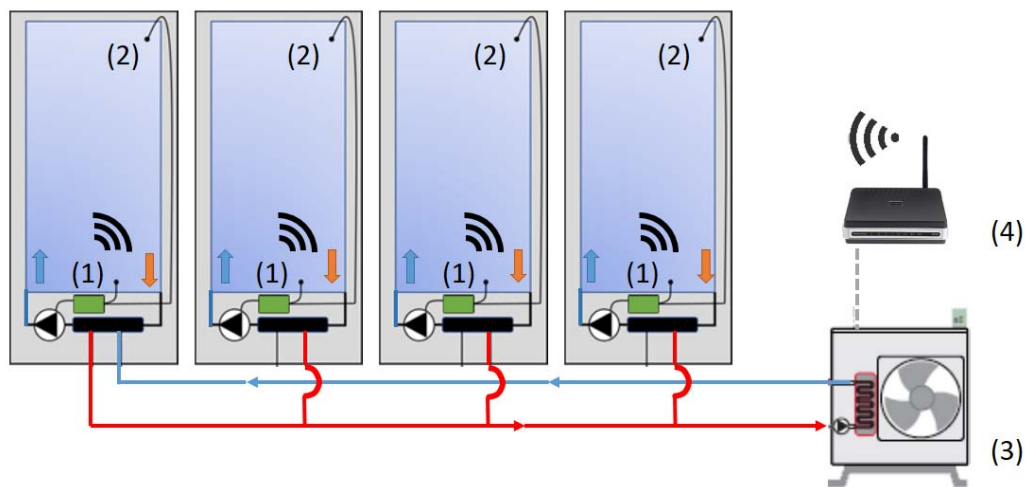


Figure 5. General distribution of the monitoring system. (1) data transmitter node; (2) water temperature sensor; (3); heat pump; (4) hub;

#### 4. Heating and cooling strategies.

The cooling and heating systems proved to be a critical factor in the energy expense [18]. Improper sizing or choice could lead to failing in achieving comfort conditions. The studied pavilion needed a solution that would keep it comfortable, with a steady temperature and low humidity levels, while not using a lot of energy. To solve this problem, two strategies are considered:

During the coldest period of the year, the outside air temperature and solar radiation in Sofia are not enough to maintain the interior space at the desired temperature. In this case, the water flow of the envelope WFGs is off so its g-factor is approximately 0.6 and the peak of exterior radiation reaches the interior and contributes to raise its temperature. However, this radiation could be less than it would be required over most of the day. Hence, the heat pump would be turned on so it would heat the interior structure of WFGs and raise the interior temperature to the desired level.

There is an excess of thermal energy over the Summer. The exterior solar radiation in Sofia could be high enough to heat the interior and increase its temperature above the desired level. Hence, the pool system would be turned on and the g-factor of the envelope WFGs would be reduced to its minimum value of 0.2 because the solar radiation absorbed by the water flow would be quickly removed. Moreover, some of the excessive interior heat would also be absorbed by this water flow. This hot water would return to the pool where it would evaporate due to a low exterior temperature of around 15 – 20°C. If the inside air temperature was still higher than the desired level, the heat pump would be turned on so it would cool the interior structure of WFGs and lower the interior temperature to the desired level.

#### 5. Energy balance

In order to simulate the abovementioned strategies, the authors have developed an energy balance model. It shows the pavilion behaviour under the outdoor conditions and the system working strategy.

The energy demand required to keep the indoor air temperature at 21°C over the year is defined by equations 1 and 2. It is related to the transmittance of each envelope and internal heat gains due to occupancy and equipment. The U value of the roof is set at 0.12W/m<sup>2</sup>K. The U value of the floor is set at 0.27W/m<sup>2</sup>K. In the north façade U=0.17 W/m<sup>2</sup>K, whereas per the WFG U=1.12 W/m<sup>2</sup>K. To carry out the simulation internal heat gains of 10w/m<sup>2</sup> have been taken into account.

$$\text{Heating demand } (t) = \text{positive}(\sum_j U_j(T_i - T_e)S_j - Q_i) \quad (1)$$

$$\text{Cooling demand } (t) = \text{positive}(\sum_j U_j(T_e - T_i)S_j + Q_i) \quad (2)$$

where

$j$  stands for each outside surface

$U_j$  is the transmittance of each envelope

$T_i$  stands for indoor temperature

$T_e$  stands for outdoor temperature

$S_j$  stands for the area of each envelope

$Q_i$  stands for internal heat gains

Solar gains through the glass envelope depend on the g value and are defined by equation 3.

$$\text{Solar Gains } (t) = \sum_j g_j(I_{bj} + I_{dj})S_j \quad (3)$$

where

$j$  stands for each WFG envelope

$g$  is the g factor of WFG envelope

$I_{bj}$  stands for the solar beam radiation projected on the surface  $j$

$I_{dj}$  stands for the outdoor diffuse radiation on the surface  $j$

$S_j$  stands for the area of each envelope

Finding the integral of the above functions with respect to time helps understand the right value for g.

$$\text{Energy of Heating} = \int_0^t \text{Heating demand } (t)dt \quad (4)$$

$$\text{Energy of Cooling} = \int_0^t \text{Cooling demand } (t)dt \quad (5)$$

$$\text{Energy of Solar Gains} = \int_0^t \text{Solar Gains } (t)dt \quad (6)$$

## 6. Results and discussions

Three different kinds of glass in terms of g value have been tested. If  $g=0.6$  the solar gains through the transparent envelope make up for the needed heating demand over the first 80 days of the year. After January and February, heating demand starts falling off. To achieve energy savings the g value of the glass should be changed by increasing the flow of water. Setting  $g=0.2$  solar gains compensate heating demand over March and April. Solar gains peak in summer months, so the desired g value will be set in 0.1 over the warmest months. Figure 6 shows the heating and cooling demand and the solar gains over the year.

**Cooling demand.** May, June, July and August are the warmest months of the year, so the extra heating will be dissipated by the free cooling pool system previously described. The g factor will be set at 0.1 by increasing the flow of water within the WFG. The inside could be cooled by the interior partitions activating the heat pump in cool mode if needed.

**Balanced.** March, April, September and October are average temperature months. In this period of time, the system will be able to manage the outdoor conditions. The WFG strategy with envelope WFG off ( $g = 0.2$ ) could lead to the comfort condition.

**Heating demand.** January, February, November and December are the coolest months. In this case, the system will not be able to manage the heat transfer between the inside and outside, because of the low temperatures and the lack of sun radiation. It will be necessary to connect the heating system. The



g factor will be set at 0.6 by stopping the flow of water within the WFG. When the heat pump is activated, the energy will be provided by means of photovoltaic panels. Building internal mass including floors, partitions, crawl space in ceiling, internal walls, and furniture can affect the thermal behaviour of the building. It absorbs radiant heat through the windows and that from occupants, lighting and equipment and then releases the heat gradually to the air space.

Figure 7 plots the required heating and cooling energy and the solar gains in a year time as per equations 4, 5 and 6. If the g value were very low it would be impossible for the solar gains to make up for the heating demand. On the other hand, if the g value were high there would be an excess of heat gains. WFG can adapt the g value of transparent walls to different weather conditions without affecting the transparency and light transmission.

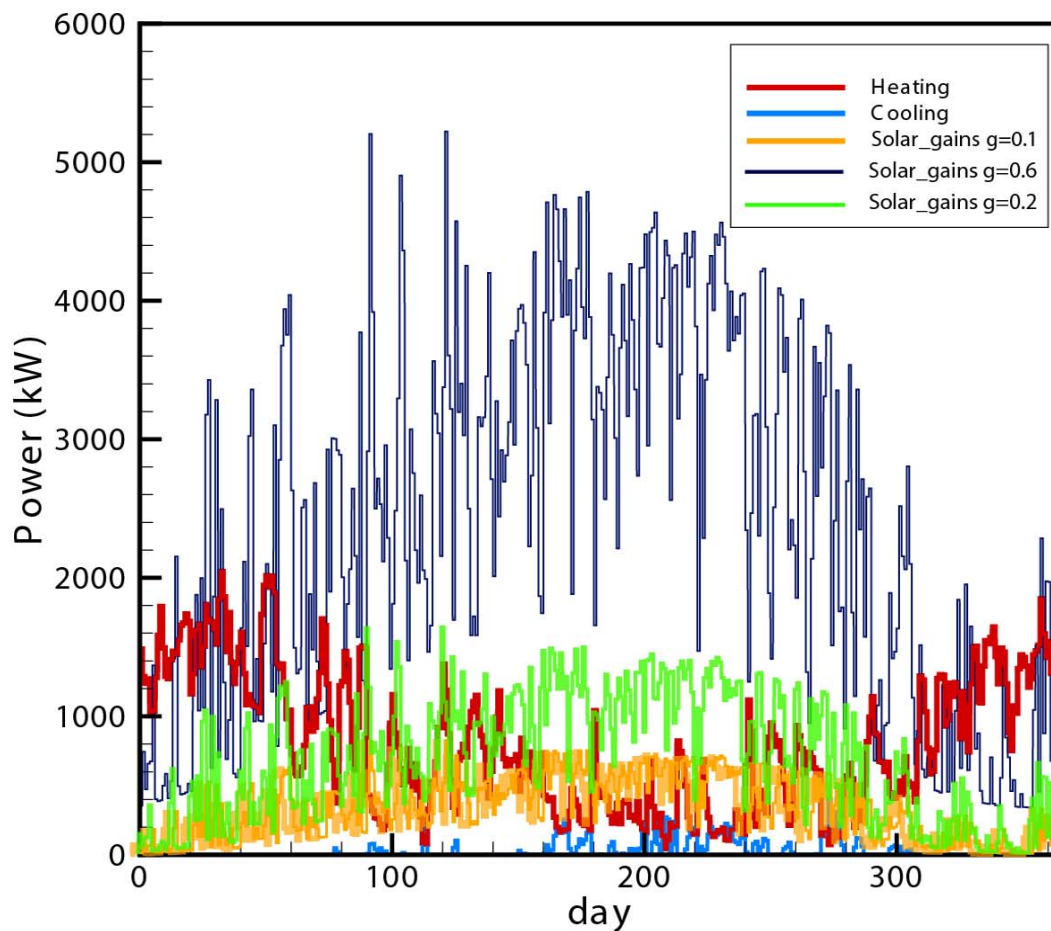


Figure 6. Heating and cooling demand in the prototype. Solar gains with different g values.

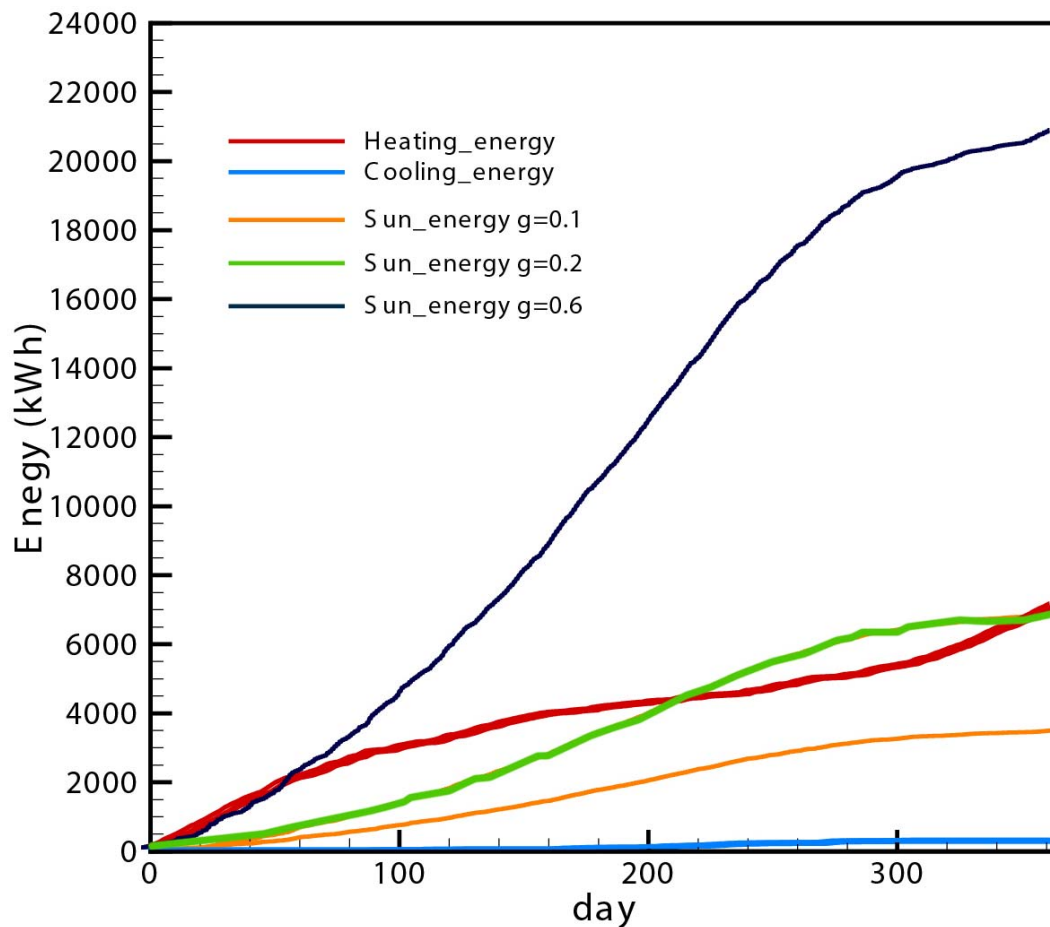


Figure 7 Energy balance inside the prototype over a year time with three different  $g$  values.

The yearly energy analysis of the pavilion shows how to solve the thermal problem. The strategy is different depending on the demand of heating or cooling. Table 1 shows the corresponding monthly demand of thermal energy and the  $g$  factor strategy for the WFG external wall.

**Table 1.** Monthly energy demand.

<u>Jan</u>	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat demand			Average		Cool demand			Average		Heat demand	
g = 0.7			g = 0.2		g = 0.1			g = 0.2		g = 0.7	

### 6.2. Summer strategy

In Summer, sun radiation is high and the outdoor conditions are warmer, so the target is to eliminate the extra incoming radiant energy from outside, and cool down the indoor temperature.

Firstly, most of all outdoor inlet radiation is absorbed by the WFG envelope. WFG in the envelope is on and the fluid circulates. The g factor is low ( $g = 0.1$ ) because water flows and absorbs most of sun infrared radiation. This flow transfers heat energy absorbed from the radiation to the cool pool water. This strategy allows the WFG fluid to reduce its temperature below the outdoor level and it removes most of the internal heat load by means of convection and conduction. Meanwhile the interior partition and the heat pump system are off. If it is necessary the heat pump system would be on in cool mode. Thereby the interior partitions would remove heat energy from indoors.

## 7. Conclusions

The building sector is primarily responsible for a major part of total energy consumption. The European Energy Performance of Buildings Directives (EPBD) emphasized the need to reduce the energy consumption in buildings, and put forward the rationale for developing Near to Zero Energy Buildings (NZEB). This study proposed that a thorough and detailed simulation is required to get a better understanding of the effect of various factors and their complex interaction with the energy requirement of the building. The relationship between the energy demand profile and glass envelope behaviour has been studied. In order to accomplish a NZEB new systems and energy management strategies are required to adapt the building envelope to different weather conditions. The effect of these strategies and the use of active systems, like Water Flow Glazing, were analysed by simulating a prototype that will be placed in the city of Sofia, Bulgaria.

A pilot study was undertaken to analyse the relationship between the heating and cooling energy demand profiles and solar heat gains due to the transparent envelope. To gain insight into how the building is used on a yearly basis, a simulation was carried out. The analysis of yearly thermal behaviour of the building indicated that changing the g value to adapt the building to different weather conditions is key to achieve energy savings in heating and cooling.

WFG has a direct impact on interior comfort conditions of buildings. WFG can change the g value of transparent walls to adapt it to weather conditions without affecting the transparency and light transmission.

## Acknowledgment(s)

The work presented in this paper was supported by Industrial Development of Water Flow Glazing Systems (InDeWaG) under grant number 680441 (H2020-EE-2015-1-PPP). This article has also been sponsored by the American University of Ras Al Khaimah.

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