Analytical Modelling of Achieving Energy Efficiency with Green Walls

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Abstract. *In the last years, energy efficiency has become an important issue for the European Union (EU) and Slovenia, who both strive for more sustainable use of energy in buildings. As an innovative approach to such matter, green walls are vertical structures that can serve both as a façade or an insulation layer as well as an aesthetic design for building applications.*

This paper is an overview of author's master's thesis [1] and, therefore, contains calculated annual heat (transmission) losses through different wall assemblies with and without a constructed green wall in front of them. This paper presents a comparison of values of heat losses between those wall assemblies and the explanation of such results, which can determine if green walls present a viable energy-efficient structure for buildings.

1 Introduction

Population growth and an ever-increasing demand for energy are redirecting people to start using energy more wisely, and efficiently. To reduce greenhouse gas emissions, people have become aware that not only is it essential to reduce the usage of fossil fuels and switch to renewable energy sources but also to change the way how people use energy. Changing our homes to energy-efficient habitat's that immensely reduce the usage of energy, thus becoming energy efficient, has attracted the EU's attention which now greatly invests in such sector. Slovenia is also bounded to increase the percentage of energy-efficient buildings in the upcoming future.

This paper will focus on green walls as an element, a structure that could serve as a potential energy-efficient layer in front of a regular (main) wall assembly that could possibly reduce heat losses through such walls. In this respect, this paper contains the results of analytical models of the green wall, placed in front of three different main wall assemblies and analytical models of main wall assemblies, without the green wall. All simulations (models) were developed in MATLAB by MathWorks.

The goal was to determine the difference of heat (transmission) losses between wall assemblies that contain the green wall structure in front of them and wall assemblies that do not contain such structure. Losses are accounted for and compared by/with each model on an annual basis for the year 2018. This paper will also elaborate on potential energy savings and CO_2 emissions reduction and the results that were given based on the input data.

2 Green walls

Green walls are described as vertical structures (gardens) that have different types of plants or other greenery attached to them. Plants are planted in a growth medium that consists of stone, water, and soil. A built-in irrigation system is featured in a green wall for sustaining living greenery [2].

Figure 1. Green wall system – Kyoto railway station, Japan [3]

Green walls can improve the energy efficiency of buildings in cities, where it is vital to reduce energy consumption so they account for being a sustainable technology that acts as a natural insulation system. They also improve the urban climate (reducing buildings' surface temperature, urban air temperature, regulating CO_2 concentration), and improving air and water quality. Besides good thermal and acoustic performances, they also serve as a great aesthetic structure, that helps to diversify the city landscape. There are also disadvantages such as intensive maintenance due to the vegetation, and a need for a durable supporting construction [4]. While green walls are almost nonexistent in Slovenia, there are already significant strives in countries with big urban areas, such as Japan and Singapore, especially because of large heat island phenomena and high humidity.

Green wall systems include pre-cultivated panels (that provide support) with greenery, vertical modules (planter boxes, filled with a substrate - soil) which are vertically fixed to a support structure or on the wall and an irrigation system to sustain plant life [5]. Plants are appropriately suited to specific climate conditions. During their growth, plants become rooted and a system acts similar to a garden foam [6]. Plants on a wall absorb a large amount of solar radiation for their growth and their biological functions (photosynthesis, evaporation, transpiration, and respiration), and act also as a solar barrier that reduces the absorption of solar energy by reflecting the incident solar radiation. In return, the greenery needs to be carefully maintained with an irrigation system that provides water and nutrient supplements. The structure also restricts the wind effect around the building, traps fine dust, and manages the humidity of the building's environment. Thus, these walls regulate the temperature of the building, and with that, they are reducing energy consumption [5].

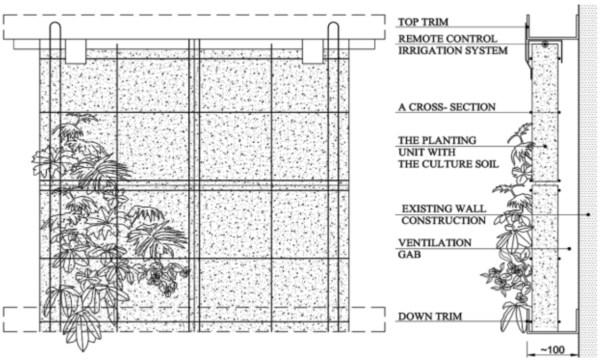

Figure 2. A design example of a green wall system [6]

3 Modeling of the proposed model

The proposed model (building wall) was a theoretical approach with the same dimensions (surface area of 25 m^2) in each cardinal direction (north, south, east, and west) and was not based on a structure, taken from a real, present-time case. The location of the "structure" was set in Maribor, Slovenia (the location is important for assessing values such as solar radiation and external air temperature). Different types of main wall assemblies were set as examples: an energy-efficient wall (highly energy-efficient masonry with thermal insulation – Type A), a highly energy-inefficient wall (old masonry with no thermal insulation – Type B) and an energy-inefficient wall (concrete with some thermal insulation – Type C). The whole process of determining thermal resistivities in our model is explained in [1] and based on those, the density and thickness of the green wall have different impact on heat losses.

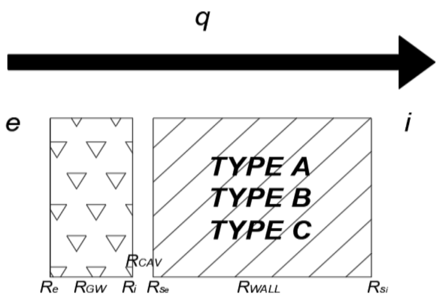

Figure 3. Thermal resistivities for the whole structure [1]

Before we began simulations on the proposed model, we observed a theoretical approach to general building physics, from general terms to thermal resistances for a wall assembly (Figure 3), green wall parameters, normal wall parameters [1], and equations that explain the entire heat flow through a wall: a building structure-green wall [7] and later: a complete structure. Boundary conditions were also applied afterward and a mathematical model was created for each wall assembly respectively. First, by establishing energy balance, plants can perform their functions (photosynthesis), therefore their attempt to maintain an energy balanced leaf temperature attributes to maximizing plants' usefulness. This means that the supplied energy E_{IN} equals the exiled energy E_{OUT} . At equilibrium state:

$$q_{RAD,IN} + q_{SOL,IN} = q_{IR,OUT} + q_{CV} + q_{TR} \quad (1)$$

where $q_{RAD,IN}$ is the heat flow density of absorbed long-wave radiation, $q_{SOL,IN}$ is the heat flow density of absorbed solar radiation, $q_{IR,OUT}$ is the heat flow density of irradiated long-wave radiation, q_{CV} is the heat flow density of convection and q_{TR} is the heat flow density of transpiration. If leaves are not at equilibrium state with its environment, the temperature of the leaves (on its surface) will naturally increase or decrease until such equilibrium is achieved [7]. As the amount of solar radiation depends not only on the power contained in the sunlight but also on the angle between the wall's surface and the Sun (which is continually changing throughout the year), we needed to add some moderations to some equations of the model, when calculating solar radiation given our proposed wall:

$$q_{MODULE} = q_{SOL,DIR} \cdot \cos(180 - \theta_I) \ \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \quad (2)$$

where q_{MODULE} is the solar radiation given the wall, $q_{SOL,DIR}$ is the solar radiation from the Sun, and θ_I is the solar incidence angle, comprised of the declination angle, latitude angle, solar azimuth angle, and declination angle [1]. Equation 2 is the final form for calculations from vernal to the autumnal equinox, while:

$$q_{MODULE} = q_{SOL,DIR} \cdot \left(-\cos(180 - \theta_I)\right) \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \quad (3)$$

is a final form equation, regarding the period from autumnal to the vernal equinox, Equations 2 and 3 are for north and south cardinal directions while Equation 4 is for east and west cardinal directions [1]:

$$q_{MODULE} = q_{SOL,DIR} \cdot \left(-\cos(\theta_I)\right) \ \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \quad (4)$$

4 Results of the simulation

Transmission losses through walls $Q_{T,l}$ were assessed with:

$$Q_{T,l} = \Phi_{T,l} \cdot t_M \cdot 10^{-3} \ [\mathrm{kWh}] \quad (5)$$

where $\Phi_{T,l}$ are transmission losses and t_M is time in hours based on a certain month (for example: January lasts 744 hours) [1]. Wall assemblies (A, B, and C) were compared with the green wall and without it. The results (comparisons) are seen in Figures 4, 5, and 6.

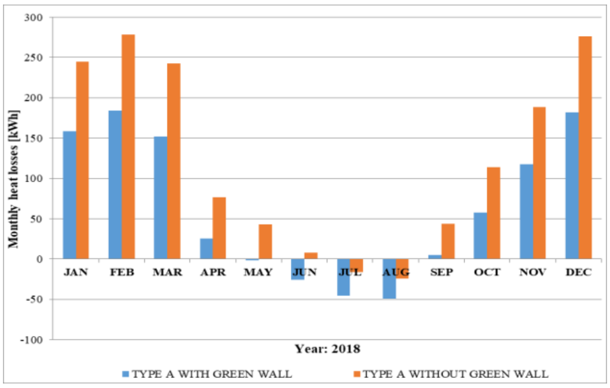

Figure 4. Comparison of monthly heat losses between Type A wall structure with the green wall and without it

If a Type A wall would have a green wall installed, annual heating energy needs (heat losses) would reduce for 41,75 %, yet, annual cooling energy needs would increase. Combined, there would be 550,8 kWh of annual energy savings with Type A wall that would have a green wall installed in front of it (Figure 4).

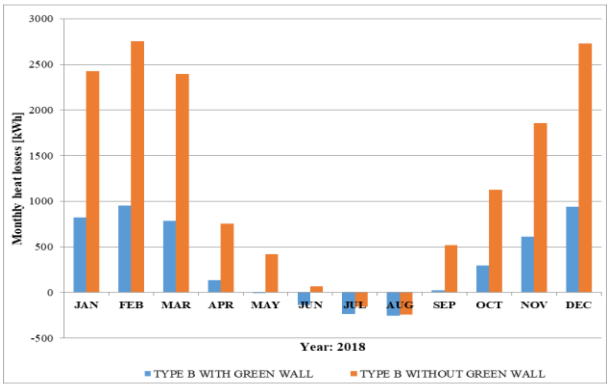

Figure 5. Comparison of monthly heat losses between Type B wall structure with the green wall and without it

If a Type B wall would have a green wall installed, the annual heating energy need (heat losses) would reduce for staggering 69,7 % (from 15.055,5 kWh to 4572,1 kWh) in total respectively. Annual cooling energy need would increase for a bit, however, combined, there would be 10.253,5 kWh of annual energy savings with Type B wall that would have a green wall installed in front of it (Figure 5).

With regards to the third type: if a Type C wall would have a green wall installed, the annual heating energy need (heat losses) would reduce for 59,2 %, annual cooling energy need would increase only from 148,9 kWh to 319,2 kWh, however, combined, there would be 3.193,9 kWh of annual energy savings with Type C wall that would have a green wall installed in front of it (Figure 6).

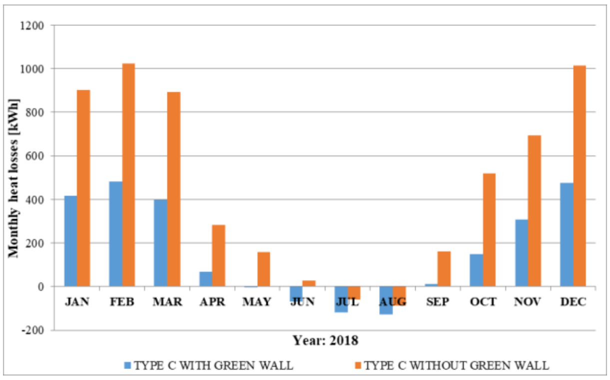

Figure 6. Comparison of monthly heat losses between Type C wall structure with the green wall and without it

For the calculation of CO_2 emissions reduction, we calculated how many CO_2 emissions are produced »in our pilot building« before and after the installment of a green wall. The more energy that a building requires to achieve thermal comfort, the more CO_2 emissions are produced. Not only that green walls make the structure more energy-efficient (also reducing greenhouse gases) but also, due to having greenery as part of the structure, green walls filter particulate matter from the air and convert CO_2 into oxygen. This essentially means an »extra production« of purified air, and the reduction of CO_2 emissions, while serving other essential functions as a wall assembly. According to [8], 1 m^2 of living green wall extracts 2,3 kg of CO_2 from the air per year while roughly producing 1,7 kg of oxygen at the same time. Our pilot building (with an area of 100 m^2) can, therefore, produce 170 kg of oxygen and extract 230 kg of CO_2. With that, we could assess the benchmark if the (possible) reduction of greenhouse gas emissions could contribute to a decision of installing a living green wall as a structure, even if they do not perform well as an insulative layer Yearly produced CO_2 emissions GHG_{kgCO2} are for each energy source, calculated [9]:

$$GHG_{(\text{kg CO2})} = Q_{T,l} \cdot EF \text{ [kg]} \tag{6}$$

where *EF* (Table 1) represents the emission factor (in kg/kWh). An emission factor essentially tells us, how many kilograms of CO_2 emissions will be produced with one kWh of input energy, respectively, later transformed to energy value E_{VALUE} (Table 1) for assessing the amount/supply of each energy source, needed for heating (in their assigned units).

Table 1. *EF* and E_{VALUE} values, used for heating [10]

ENERGY SOURCE	UNIT	E_{VALUE} [KWH/UNIT]	*EF* [KG/KWH]
Heating oil	[litre]	10,31	0,267
Natural gas	[Sm^3]	9,44	0,199
Liquefied natural gas	[kg]	12,78	0,227
Biomass	[kg]	4,17	0,000
District heating	[kWh]	1,00	0,356
Electricity	[kWh]	1,00	0,509

Equation 6 is presented for walls without the installed green wall. With the installed green wall, we need to retract 230 kg from the equation.

Table 2. Annual CO_2 emissions reduction (in kg) for each energy source for each wall type assembly

TYPE A	**Type A without green wall**	**Type A with green wall**
Energy source	GHG_{kgCO2} [kg]	GHG_{kgCO2_GW} [kg]
Heating oil	415,2	38,1
Natural gas	309,4	**-30,2**
Liquefied natural gas	353,0	**-3,0**
Biomass	0,0	**-230,0**
District heating	553,6	127,5
Electricity	791,5	281,1
TYPE B	**Type B without green wall**	**Type B with green wall**
Heating oil	4.126,8	1.159,1
Natural gas	3.075,7	805,3
Liquefied natural gas	3.508,5	951,0
Biomass	0,0	**-230,0**
District heating	5.502,3	1.622,1
Electricity	7.867,1	2.218,1
TYPE C	**Type C without green wall**	**Type C with green wall**
Heating oil	1.554,9	472,1
Natural gas	1.158,9	293,3
Liquefied natural gas	1.322,0	366,9
Biomass	0,0	**-230,0**
District heating	2.073,2	706,2
Electricity	2.964,2	1.108,5

The potential installment of a green wall in front of the main Type A wall assembly would drastically reduce CO_2 emissions, also where the presented values are negative, this means that the reduction of CO_2 emissions goes so beyond, that it is an indication that with the green wall, more CO_2 emissions are extracted from the air than produced (the structure becomes carbon negative). Green walls would then effectively contribute to the reduction of fuel consumption, needed for heating the pilot case building. Naturally, energy savings are the biggest in the case of Type B wall assembly, regarding their quantity. Quite opposite is with Type A wall assembly (the most energy-efficient wall assembly in our research) where consumption of energy sources, regarding their quantity, would be the smallest.

5 Conclusion

Simulation models should be treated only as a simple interpretation of calculating heat losses through such wall assemblies, more complex calculations would require computations for a real-time practical case. The calculation of CO_2 emissions reduction was connected with the mentioned annual heat losses. The assessment of models was based on mathematical, predetermined terms only, nonetheless, these models serve as good analytical research for exploring such matter in an area of innovative approach in energy efficiency.

With simulations, we concluded that, indeed, heat losses for each wall type respectively, would decrease on an annual level, if each type would have a green wall installed in front of the main wall. We can also assume due to results that, the more energy-inefficient the wall is, the better is to install a vertical green wall in front of it. However, the green wall cannot be a »layer« that could single-handedly solve the problem of energy inefficiency of the main wall. Regarding CO_2 emissions: such emissions would decrease drastically.

The values of a real-time »pilot building« would most likely differ to some extent, which would present us with a more explicit way of seeing such matters with a better understanding of its process of functioning. Regardless of results, the development and demand of such innovative structures are rising so there will sure be more research-based, complex models of calculating heat losses through wall assemblies with living green walls and even assessments of CO_2 emissions reduction as well. This paper serves as a good analytical tool with an explored background of such matter, yet surely requires further research in the upcoming future.

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