The Effect of The Residential Building's Wall Thickness and Material on The Heating and Cooling Loads with Special Reference to Using The Green Facades

Tamer Refaat *

Department of Architecture, Faculty of Engineering, Canadian International College (CIC), Cairo, Egypt

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Abstract
The residential buildings consume almost 50% of the total energy, producing about 30% of the world's CO2 emissions. As the building envelope is the one that is responsible for the whole thermal performance of the building, the thickness and characteristics of its material play an important role in improving the thermal performance and minimizing the cooling and heating loads to achieve thermal comfort inside the spaces. The main aim of this research is to study the effect of the wall's thickness and material on the energy consumption in a residential unit located in Janna Residential Project, New Cairo. The methodology of this research starts with reviewing the literature and the methods related to the effect of the building envelope on energy consumption. Then, the practical study uses the Design-Builder Plug-in in the Revit Program to study the effect of the wall thickness and material on the heating and cooling loads. The results show that using the indirect green façade without an air gap and with an air gap in the west and south orientation with WWR 30% reduced the energy consumption by 8.9% in case of no air gap and the wall's R-value increased from 0.6 to 0.88m^2K/W. In the case of a 60 cm air-gap the energy consumption reduced by 14.48%, and the R-value increased to be 0.91m^2 K/W, which means that the thickness and material of the wall as a part of the building envelope have a significant effect on the total energy consumption of the building.

1. Introduction

The residential building consumes almost 50% of the total energy consumption, and about 35% is used for heating and cooling loads. According to the change in the climate due to global warming, this percentage is predicted to increase by 10% in the following years. [1] According to that, the building's wall thickness plays an important role in achieving the energy efficiency of the buildings if it is designed and treated considering the climate conditions and users' requirements, as the walls and windows are responsible for almost 45% of the building's total heat loss. [2] Also, many factors besides the building envelope affect the thermal performance of the building, such as orientation, form, window-to-wall ratio (WWR%) … etc. Therefore, the research is trying to address the effect of the wall thickness and material by comparing the results between the initial building case (wall thickness and material) and after changing the thickness of the wall and adding an insulation layer by using both direct green façade with no air gap and indirect green façade with 60cm air gap.

*email: Tamer_refaa@cic-cairo.com

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1.1. Research Problem

The research problem is the increase in energy consumption in residential buildings due to using heating and cooling systems to achieve thermal comfort inside the spaces.

1.2. Research Aim

The research aimed to improve the building's thermal performance to enhance energy saving by using the green façade as an insulation layer, increasing the wall thickness and R-value, and ensuring the user's satisfaction.

1.3. Research Methodology

The research depends on addressing the importance of building envelope and how it could enhance the thermal performance through reviewing;

1- The building envelope and its effect on the building's thermal performance

2- The requirement of the residential building design code in Arab countries is related to the building envelope.

Then, a practical study using a simulation program was conducted to measure the effect of the wall thickness and material on the energy consumption of the residential unit, describing all the required data that needed to be added in Revit to ensure the accuracy of the results.

2. Methods and tools

This section of the research is designed to include two significant parts. First, the data related to the effect of building envelopes on thermal performance and the requirements of residential building design codes in Arab countries have been reviewed to address the main parameters that affect building energy consumption. Second, the research used Revit's Design-builder plug-in to simulate and measure the effect of adding the green façade with and without an air gap as an insulation layer on the heating and cooling loads.

3. Building Envelope

The building envelope is defined as the line separating the indoor spaces and the outer circumstances, such as wind, noise, rain, temperature, pollution… etc. [3] and consists of walls, ceilings, openings, and floors. [3] This research will focus only on the effect of walls as a part of the building envelope. According to the residential building design code for Arab countries, there are three ways to achieve the requirements of the building envelope:

1- Building Form: The sum of the values of the insulating materials installed in the wall, the cavities and the insulating covers (when/if used) must meet or exceed the minimum required "wall R-value" for the appropriate climate – according to the Arab residential building code are the thermal resistance of ceilings is 1.76 m2/º MW, while walls are 1.00 m2 /ºMW, while the requirements of the Egyptian Energy Code in residential buildings are thermal resistance of ceilings is 2.2 m2/ºMW, while walls are 1.4 m2/ºMW. [4]
2- The overall performance of the building: The proposed design must be compatible with the annual energy costs (8760 hours), which in turn must be compatible with the standard design.

The proposed and standard designs must also be specified using the same approved energy analysis simulation tool, such as VDOE, Energy+, or Design Builder [5].

3- Compatibility of the building envelope with the OTTV: The calculated Overall Thermal Transfer Value (OTTV), W/m2) requirements for air-conditioned buildings could be used in mandatory requirements. To calculate OTTV, solar factors (Solar Factor - SF) and orientation factors (Orientation Factor - OF) must also be calculated from hourly, monthly, and yearly averages of direct and diffuse solar radiation. Solar data were calculated for the eight directions [4].

Finally, the Egyptian Code for Energy Efficiency in residential buildings has determined the amount of thermal resistance for each of the materials used in construction to ensure thermal comfort within the spaces, which in turn leads to achieving energy consumption efficiency because of reducing the needed cooling and heating loads in the spaces. In addition, it has been determined that a window-to-wall ratio of 15% to 20% reduces the total annual electricity consumption of buildings [4]. Also, the solar (Solar Factor - SF) and window orientation factors (Orientation Factor - OF) were also calculated for the eight directions of the wall (north - south - east - west - northeast - northwest - southeast - southwest), as mentioned before. The OTTV, which refers to the amount of heat transferred inside the building through the building facades, roof, openings, and floor that make up the outer envelope, was calculated for each direction for the different variables, e.g., The WWR%, the type of glass, the shading, the color of the wall and the middle and upper floor. The results showed that the mass and types of building materials, and the type of glass and curtains, guidance, Wall thickness (25 cm), wall solar absorption ($\alpha = 0.3$), which increase the thermal performance rate of the building's outer envelope, which in turn leads to reducing the required cooling load by 60% [5].

4. Green facades

Green facades are a type of green wall that uses climbers or plants to cover the building facades. According to the building and climate context, these plants could be evergreen or deciduous [6]. It's divided into two main types first is the direct green facades, in which the plants climb directly on the wall without any support system, and second is the indirect green façade, in which the plants hang on a support system that could be fixed directly to the façade or fixed with an air gap distance (Fig. 1) [7].

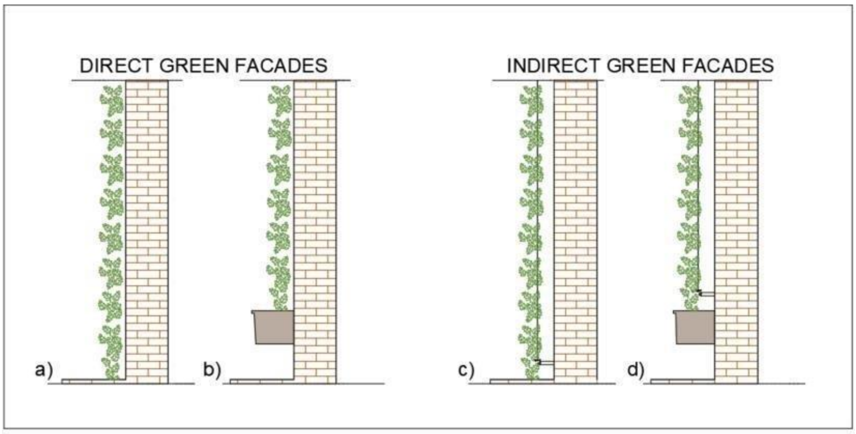

Figure 1: The direct and indirect green facades installation [9]

4.1. Thermal performance of green facades

Using green facades could improve the building's thermal insulation as, according to its shading effect, it could reduce the building's required heating and cooling loads, reduce the urban heat island effect, improve the thermal comfort inside the spaces... etc. [10]. Wong, et al., 2010 studied the green façade with east and west orientations reduced the building's yearly energy saving as a green façade with a thick, continuous substrate layer and plants with leaf area index (LAI) of less than 3.00 could minimize the required cooling loads according to the plant's evaporation [11]. Green facades could maximize the building's energy savings by creating a comfortable condition and reducing required cooling loads used for air conditioning systems due to their shading, insulation, cooling, and wind barrier effects [12]. Sheweka & Magdy, 2011 studied the thermal performance of green facades, and they concluded that green facades act like a barrier against outer circumstances such as wind, solar radiation… etc., and according to that, it protects the building facades from cold weather in winter and the excessive heat in summer [13]. In Baran & Gültekin, 2017 study, they compared the energy consumption before and after installing a green façade, and they found that after adding the green façade layer, the energy consumption for both heating and cooling loads decreased, which led to a financial benefit, which means both user and owner are satisfied. [14] Also, Jeffrey W. Price's 2010 study shows that the ambient air temperature and exterior surface have been reduced, and the indoor air temperature and heat flux, after adding the green wall system, maximizes the user's thermal comfort inside the spaces [15].

Finally, as the sun and its solar radiation affect the outside and inside of the building, using the vegetation layer could block the direct radiation and save the building facades from heat gain, which reduces the temperature of the indoor and outdoor walls, and that's led to decreasing the cooling loads which reducing the total energy consumption of the building [16].

4.2. Maintenance of green facades

Green facade systems (GFS) necessitate regular maintenance owing to their dynamic nature. The maintenance regimen, determined by the customer, serves as the primary determinant that influences the selection of plant species and construction methodology. Deciduous flora (plants) or those bearing fruits/flowers typically demand heightened maintenance. Moreover, the irrigation infrastructure and soil composition necessitate periodic maintenance to ensure the optimal efficiency of green facade systems [19].

4.2.2. Maintenance task of green facades

Per the Australian Growing Green Guide, maintenance tasks are categorized into main five distinct levels: [20]

1- Establishment Maintenance: This phase spans the initial two years following the application of Green Facade Systems (GFS). Its primary aim is to foster robust plant growth through diligent care. Activities encompassed within this category include the upkeep of irrigation systems and the maintenance of plantation health, involving tasks such as weed management and pruning.

2- Routine Maintenance: This category pertains to the regular upkeep of the facade to uphold prescribed standards of functionality, aesthetics, and safety. Its primary objective is to ensure that the facade maintains its intended performance, appearance, and safety levels through routine inspections and maintenance activities.

3- Cyclic Maintenance: This type of maintenance is focused on the structural elements of the building and the various components of the Green Facade Systems (GFS), including the hanging system, plantation, soil, irrigation infrastructure, and other related elements. Cyclic maintenance involves periodic inspection and maintenance tasks aimed at preserving the integrity and functionality of these components over time.

4- Reactive and Prevention Maintenance: This category addresses sudden damages and replacing faulty components within the Green Facade Systems (GFS). Reactive maintenance involves responding to unexpected failures promptly to minimize disruptions, while preventative maintenance focuses on pre-emptive actions to identify and rectify potential issues before they escalate, thereby enhancing the reliability and longevity of the GFS.

5- Renovation Maintenance: This type of maintenance is concerned with modifying the design intent of the GFS in response to changes in ownership or alterations in building usage. Renovation Maintenance involves updating or redesigning aspects of the GFS to align with new requirements or preferences, ensuring continued functionality and relevance in evolving contexts.

As the Green Facade Systems (GFS) consist of both static and living components, effectively conveying the importance of maintenance to clients/owners is crucial for ensuring the long-term success of the system, so that there are many considerations should be taken into account as the following [19, 20].

- Drafting a comprehensive GFS maintenance plan tailored to the specific requirements of the chosen plants, installation techniques, and insulation systems is essential for managing the system's long-term functionality and ensuring enduring installations.
- Maintenance assumes heightened significance in GFS installations where the height exceeds 2.50 to 3.00 meters, emphasizing the need for diligent upkeep to preserve performance and safety standards.
- Implementing a periodic maintenance regimen is imperative for GFS installations with airgap spaces measuring less than 15 to 20 cm, as regular inspection and maintenance activities are necessary to uphold the integrity and effectiveness of the system within confined spaces.
- Similarly, a periodic maintenance plan is indispensable for GFS installations employing drip irrigation systems to guarantee the consistent and adequate delivery of water, thereby sustaining the health and vitality of the living components within the system.

5. Case study description

The chosen case study is a residential Unit in Janna New Cairo residential project with an area of 130 m2 and WWR 30% (Fig. 2). The unit is located on the first floor to neglect the effect of ground and ceiling on the heat gain and loss.

The case study has been chosen as this prototype has been replicated by the government in modern housing projects such as Janna and Sakn Masr in several governments such as Cairo, Giza, Alexandria, Assiut, Mansura… etc.

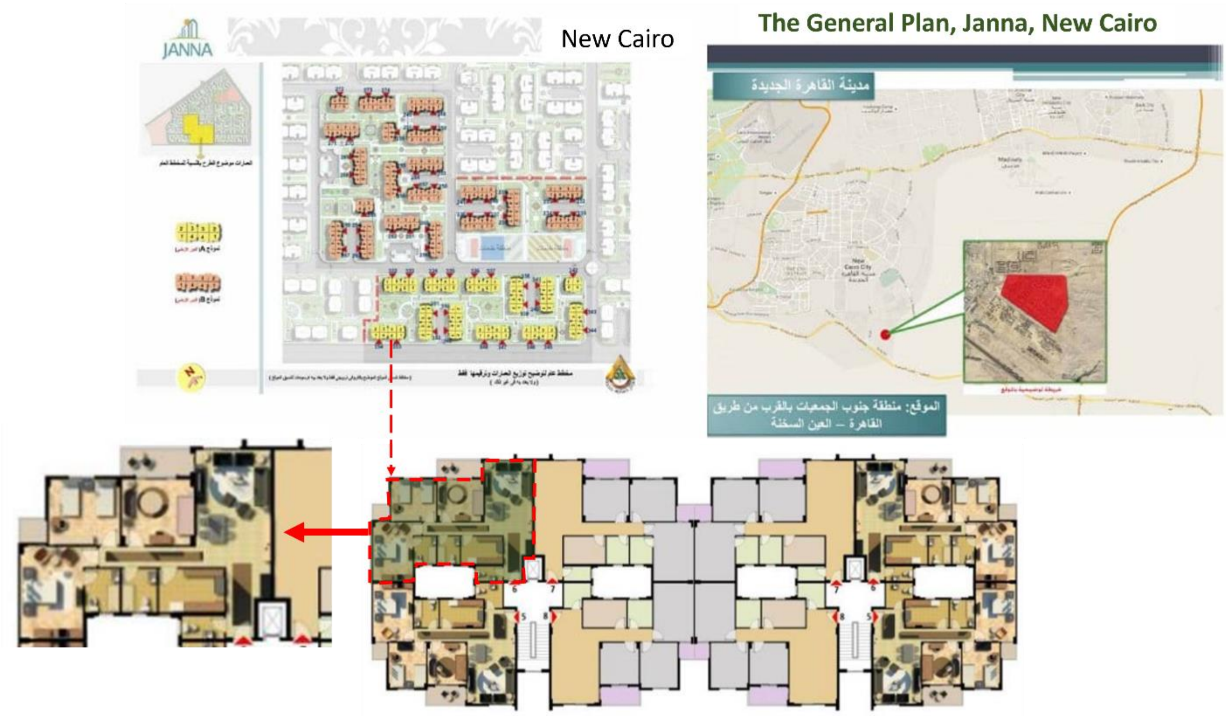

Figure 2: The Residential Building Case Study

The input data in the Revit program for the simulation is divided into four main parts as the following;
First, Climate Data: The climate classification is hot-arid with 30.1° and 31.8° latitude and longitude, respectively, and a height of 232m elevation above sea. The Daily direct normal irradiation is 6 kWh/m2, the max. average outside dry bulb temperature is 29 °C in August, and the minimum is 13 °C in January, the max. The outside dew point temperature is 20 °C in August, which is the minimum. is 6 °C in February, and finally, the max. wind speed is 4.5 m/s and 4.1m/s in April and May, respectively, and the min. is 2.7 m/s in January.

Second, Installation Orientation: The installation will be on an apartment with a 130m2 area, and the green facades will be installed in two locations (West and south) with 100% coverage of opaque parts and WWR% is 30%.

Third, The Simulation Program: the researchers used Revit's Design-builder Plug-in program as it could simulate the vegetation layer in the green façade systems as a kind of wall insulation material by adjusting the height, LAI, specific heat, density, conductivity… etc. The chosen plants will be a Boston IVY (Parthenocissus Tricuspidata 'Veitchii') deciduous climber with an average LAI of 2.96 [17]. All its thermal properties have been defined in the Revit program, as shown in (Fig. 3)

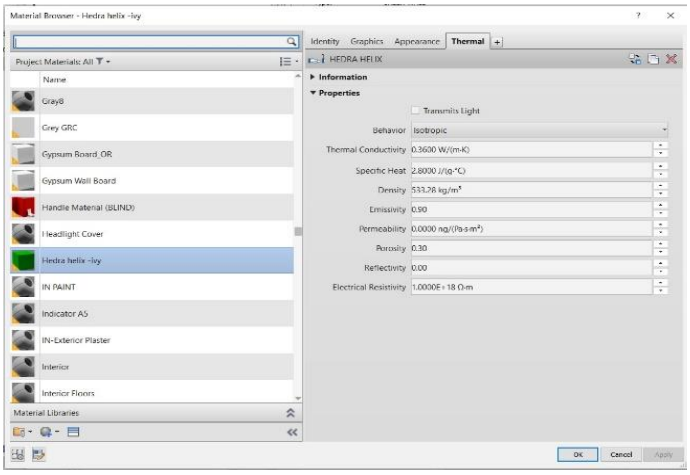

Figure 3: The Thermal Properties of Hedra Helix - ivy in Revit

Fourth, Building input data: the simulation will be done in three cases: the initial case, the case after installing the green façade without an air gap, and finally, the case after installing green facades with a 60 cm air gap system layers as shown in (Table 1, Fig. 4) and the input data will be as the following;

- The indirect installation: a free-standing stainless-steel structure with an air gap of 60 cm and without an air gap
- WWR = 30%, and the glass type is clear single glazing 6mm
- The coverage ratio is 100% of the opaque surfaces
- The irrigation method will be a simple self-irrigation system

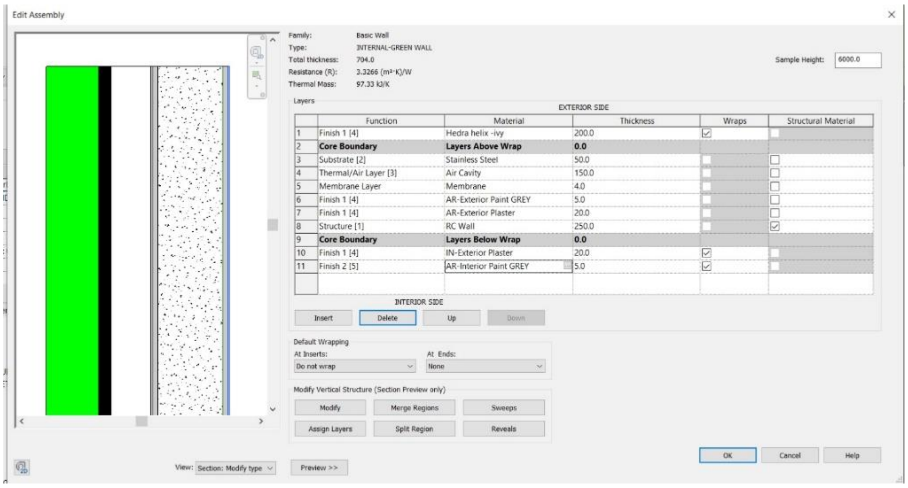

Figure 4: The wall Details after adding a green facade in the Revit program

Table 1: The thermal properties of the Initial Case and green facade installation

Wall layers [18]		Initial Case				Green facade Installation (without an air gap or with an air gap of 60 cm)			
		Sp. H J/kg.K	Den. kg/m^3	Cond. W/m.K	Thickness m	Sp. H J/kg.K	Den. kg/m^3	Cond. W/m.K	Thickness m
Green Facades Model Components	Water vapor	---	---	---	---	1966	0.60	5.56	0.002
	Vegetation	---	---	---	---	2.8	533	0.4	0.20
	Air gap (if it exists)	---	---	---	---	1004	1.3	5.56	0.60
	Stainless-steel	---	---	---	---	460	7900	17	0.05
	Softwood	---	---	---	---	1880	110	0.14	0.015
Case Study Model Components	Plaster	1000	600	0.16	0.005	1000	600	0.16	0.005
	Mortar	896	1570	1.00	0.02	896	1570	1.00	0.02
	Concrete Blocks	840	1950	0.97	0.25	840	1950	0.97	0.25
	Mortar	896	1570	1.00	0.02	896	1570	1.00	0.02
	Plaster	1000	600	0.16	0.005	1000	600	0.16	0.005

6. Results

The table below (Table 2) shows the amount of energy consumption before and after green facade installation, and it also shows the effect of the existence of air gaps and how they affect energy saving.

Table 2: The simulation results

	Total Wall Thickness m	R-value m^{2}k/w	Cooling Loads (annually) KW/hr	Heating Loads (annually) KW/hr	Total energy consumption (annually) KW/hr	Energy saving ratio %
Initial Case	0.3	0.60	2388.96	846.51	3235.47	
Indirect green façade without air gap	0.567	0.88	2259.55	687.68	2947.23	8.9
Indirect green façade with 60 cm air gap	1.167	0.91	2217.64	549.13	2766.77	14.48

By comparing the three cases (initial case, indirect green façade without air gap, indirect green façade with 60cm air gap), the results show that in case of the base case, the total energy consumption was 3235.47 kW/hr, in the case of installing green façade without air gap the energy consumption decreased to be 2947.23 kW/hr and finally in case of green façade installation with 60cm air gap the energy consumption has been decreased to be 2766.77 (Fig. 5) which mean that the indirect green façade has a higher energy saving by almost 14.5% than the one without air gap almost 9% also, the indirect green façade with air gap ensure a low maintenance risk as the system not attached directly to the building which reduce the harmful of plants roots growth and that's led to a low maintenance cost.

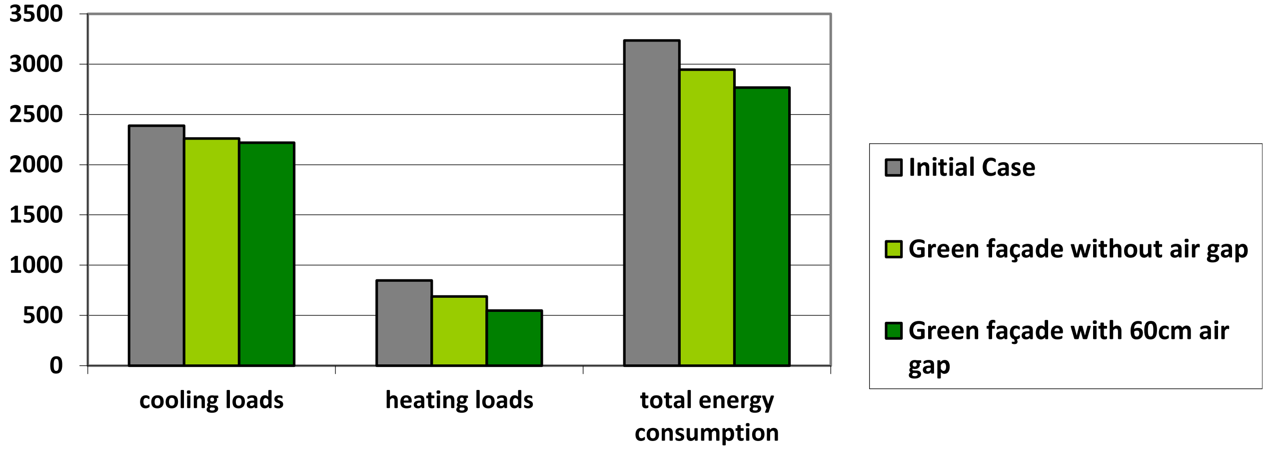

Figure 5: The amount of energy consumption reduction before and after applying a green facade

7. Discussion/Conclusion

Through reviewing the literature, the building envelope plays a major role in improving the thermal performance of the building. Also, it could enhance the negative impact of the built environment on the natural environment if it is designed and treated well, as it could reduce the CO_2 emission UHI effect, which is reflected in reducing the impact of global warming.

The construction industry is considered the most energy-consuming, as it consumes 60% of the total energy consumed, and residential building construction consumes about 50% of this consumption. Therefore, by considering the thickness of the external wall and insulation layer that could be used, such as a green facade, in addition to the WWR% related to the local regulations and codes, it is possible to reduce energy consumption and maintain thermal comfort, because of reducing the amount of the heat gain resulting from the building's envelope, especially walls. Therefore, the Egyptian Code for Energy Efficiency in Residential Buildings and the Energy Efficient Residential Building Code in the Arab Countries for the year 2010 decided to determine the necessary thermal resistance of the elements of the envelope of residential buildings according to each climatic region to ensure reducing thermal loads on buildings and achieving thermal comfort for their users.

The experimental case study shows that it could achieve the energy consumption efficiency of the residential building by adding extra layers in the wall thickness, such as a green façade to block the direct solar radiation and reduce the indoor and outdoor temperature due to its shading effect. The simulation shows that when we use the indirect green façade in both west and south directions in case without air gap, the wall thickness increased from 0.3m to 0.567m and the R-Value from 0.6 m^2k/w to 0.88 m^2k/w the energy consumption reduced by 8.9% and in case of 60cm air gap when the thickness increased to be 1.167m, and the R-value increased to be 0.91 the energy saving increased to be 14.48%

Finally, as the Egyptian energy code for residential buildings mentioned that the WWR% should be 20% to decrease the heat gain through the window, a simulation has been run to show how the

WWR% affects the energy consumption without any modification in the other elements of the building envelope as it reduced the consumption by 5.86% (Table 3) and that's why the architects, designers, and constructor should consider the regulation and design code in their designs with also using the environmental material and treatments to treat the whole envelope to ensure the energy saving of the building with achieving the thermal comfort inside the spaces for the users.

Table 3: The effect of WWR% on the energy consumption of the building

	Total Wall Thickness m	**Cooling Loads (annually) KW/hr**	**Heating Loads (annually) KW/hr**	**Total energy consumption (annually) KW/hr**	**Energy saving ratio %**
Initial Case (WWR 30%)	0.3	2388.96	846.51	3235.47	
With (WWR 20%)	0.3	2289.78	755.94	3045.72	5.86

The primary limitation of the proposed research is mainly related to the accuracy of data collected for environmental analysis using Revit's Design-Builder Plugin, which is paramount, as the entire process hinges upon the quality and reliability of this data. Inaccurate data can compromise the validity of forecasting and predicting future events related to the built environment. Therefore, ensuring the accuracy and integrity of collected data is essential to maintain the efficacy and reliability of environmental analysis outcomes. Indeed, the forecasting process in environmental analysis relies on distinct assumptions, some of which may or may not align with reality. A fundamental assumption in forecasting is the presence of patterns in events. However, it's crucial to recognize that this assumption may not always hold across all scenarios. Environmental systems can exhibit complex and unpredictable behavior, and certain events may not follow discernible patterns. Therefore, while forecasting is a valuable tool, it's essential to acknowledge its limitations and the possibility that assumptions about event patterns may not universally apply.

References

[1] Energy Efficiency Residential Building Draft Code (2010), Final Draft the Arab Countries by the Ministry of Housing, HBRC, Egypt.

[2] H. Sozer, "Improving energy efficiency through the design of the building envelope", Building and Environment. 45. 2581-2593. 10.1016/j.buildenv.2010.05.004, 2010.

[3] Cleveland, Cutler J., and Christopher G. Morris, 2009, Building envelopergy. Expanded Edition. Burlington: Elsevier.

[4] Energy Efficiency Residential Building Code, 2003, Ministry of Housing, HBRC, Egypt.

[5] George B. HANNA, 2010, Energy Efficient Residential Building Code for Arab Countries, 10th International Conference for Enhanced Building Operations, Kuwait.

[6] Dover, J. W. (2015). Green infrastructure: incorporating plants and enhancing biodiversity in buildings and urban environments. Routledge.

[7] Ebtesam M. Elgizawy, (2016), The Effect of Green Facades in Landscape Ecology, Procedia Environmental Sciences, Volume 34, Pages 119-130, ISSN 1878-0296, https://doi.org/10.1016/j.proenv.2016.04.012.

[8] Talhinhas, Pedro, João Cunha Ferreira, Vera Ferreira, Ana Luísa Soares, Dalila Espírito-Santo, and Teresa

Afonso do Paço. (2023), "In the Search for Sustainable Vertical Green Systems: An Innovative Low-Cost Indirect Green Façade Structure Using Portuguese Native Ivies and Cork" Sustainability 15, no. 6: 5446. https://doi.org/10.3390/su15065446

[9] Adel Samy El Menshawy, Abdelaziz Farouk Mohamed, Nayera Mahmoud Fathy, (2022), A comparative study on green wall construction systems, case study: South valley campus of AASTMT, Case Studies in Construction Materials, Volume 16, ISSN 2214-5095, https://doi.org/10.1016/j.cscm.2021.e00808

[10] Kontoleon, K. J., & Eumorfopoulou, E. A. (2010). The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. Building and Environment, 45(5), 1287-1303. doi: 10.1016/j.buildenv.2009.11.013

[11] Wong, N. H., Tan, A. Y. K., Tan, P. Y., & Wong, N. C. (2009). Energy simulation of vertical greenery systems. Energy and Buildings, 41(12), 1401-1408.

[12] Pérez, G.; Rincón, L.; Vila, A.; González, J.M.; Cabeza, L.F. Green Vertical Systems for Buildings as Passive Systems for Energy Savings. Appl. Energy 2011, 88, 4854–4859.

[13] Sheweka, S., & Magdy, N. (2011). The Living walls as an Approach for a Healthy Urban Environment. Energy Procedia 6 (pp. 592–599). Cairo: Elsevier Ltd. doi: 10.1016/j.egypro.2011.05.068

[14] Baran, Y., & Gültekin, A. B. (2017, March). Green Wall Systems: A Literature Review. International Sustainable Buildings Symposium, pp. 82-96.

[15] Hien WN, Istiadji AD. Effects of external shading devices on daylighting and natural ventilation. 2003.

[16] Price J. Green facade energetics [1489133]. United States -- Maryland:University of Maryland, College Park; 2010

[17] Gabriel Pérez, Julià Coma, Marta Chàfer, Luisa F. Cabeza, “Seasonal influence of leaf area index (LAI) on the energy performance of a green façade”, Building and Environment, Volume 207, Part B, ISSN 0360-1323, 2022 - https://doi.org/10.1016/j.buildenv.2021.108497.

[18] Yoshimi, Juri & Altan, Haşim, “Thermal simulations on the effects of vegetated walls on indoor building environments”, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, 2011.

[19] Green Roof Organization, (2008). http://greenplantsforgreenbuildings.org/about.htm. Access on: November, 2018

[20] Sidonie Carpenter, Growing Green Guide, A guide to green roofs, walls and facades, National Library of Australia Cataloguing-in-Publication data, (2014). ISPN: 978-1-74326-715-8,