A co-simulation workflow to evaluate the building level performance of Vertical Greenery Wall Systems in climate change scenario for office buildings in temperate climate

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Abstract

The impacts of climate change, excessive greenhouse gas emissions, and the current energy crisis have motivated the European Union to adopt mitigation and adaptation strategies. In the deep renovation of buildings, whether public or private, the adoption of resilient technologies is considered crucial to achieve significant improvements in energy efficiency and environmental sustainability. Among these, non-traditional solutions are gaining ground, such as Vertical Greenery Systems (VGS). These include green façades, characterised by a vegetative layer self-developing on the vertical surface or on a support media, and living walls, integrating vegetation into the façade construction with plants and substrate placed on the vertical surface of the exterior wall. Provided the lack of thermo-physical details and integration of existing VGS models in literature, in previous work the authors developed two Python-based mathematical models describing the hygrothermal behaviour of VGS (both green facades and living walls), based on literature.

The present paper aims at evaluating the potential building performance of VGSs in terms of impact on thermal energy needs (heating and cooling), overheating discomfort and thermal resilience indicators, in the context of climate change, and compared VGS to more traditional opaque building envelope solutions (i.e. ETICS system). This is achieved by developing a co-simulation framework based on EnergyPlus and integrated in parametric SW (Grasshopper for Rhino), to integrate VGS models with building-scale dynamic energy simulations. The application was performed on existing and new typical office building in the context of northern Italian climate, one of areas in EU affected by climate change in terms of heat waves and average temperature rise. The results show that adopting green solutions for the building envelope can contribute to achieve building energy efficiency and thermal resiliency goals in a climate change scenario, and that the modelling of these technologies can be easily integrated into building-scale model for dynamic energy simulation.

Key Innovations

- Vertical Greenery Systems (VGSs) building-level performance evaluation in a climate change scenario.
- VGS models integration in building-level energy modeling by co-simulation within VPL (Visual Programming Language) parametric software.

Practical Implications

This study demonstrates the potential in integrating VGS in office buildings in a temperate climate to reduce building energy use and improve occupant thermal comfort in near future climate change scenario through co-simulation in a parametric software.

1. Introduction

Policy actions introduced by the European Union, as the “Renovation Wave” (European Commission, 2020), are aimed to increase the yearly amount of buildings to be deeply renovated, in both residential and non-residential sectors. The attainment of this objective has been further remarked by the recently amended Energy Performance of Buildings Directive (EPBD) recast (European Parliament, 2024), which also introduced the Zero Emission Building (ZEB) concept. Urgent actions needed on the existing building stock are also addressed to reduce CO_2 emissions in the future. Thus, the building sector plays a crucial role in mitigating climate change impacts and achieving sustainability goals. Cities are among the greatest greenhouse gas producers (Gurney *et al.*, 2022); they are causing not only global warming, but urbanization also determines local overheating phenomena. When natural materials are substituted with artificial ones limiting evaporation and trapping heat, urban areas become warmer than their rural counterparts (Li *et al.*, 2019), causing the so called urban heat island (UHI) phenomenon.

In the literature, it has proven that nature-based solutions are effective in reducing overheating both indoors and outdoors. A study carried out in Addis Ababa showed that parks can decrease air temperature up to about 7 °C, and the thermal benefit can be perceived even more than 200 m further the park extension (Legese *et al.*, 2014). Researches performed in densely urbanized areas, whereas parks are limited, demonstrated that buildings can contribute in reducing UHI through installation of integrated vegetation technologies, such as green roofs and walls. In a study of Susca (2019), it was shown that these technologies are also effective in reducing building energy use for cooling – and consequently the CO_2 emissions – up to about 70%, when installed on non-insulated rooftops, and up to 30%, when installed on insulated rooftops. Compared to green roofs, walls – also recognised as Vertical Greenery Systems (VGSs) – can cover a remarkable percentage of urban surfaces double

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the footprint area occupied by buildings (Köhler, 2008). Despite representing a traditional technology, nowadays VGS is evolving into innovative configurations.

According to literature, VGSs are usually divided into two main categories, *green façades* and *living walls*. Green façades are characterised by a vegetative layer, which self-develops on the vertical surface, due to either self-climbing or with the help of support systems (Safikhani *et al.*, 2014; Perini *et al.*, 2011). Based on the type of supporting structure employed, the green façade can be further classified into *modular trellis system* (i.e., three-dimensional rigid grid structure supporting plants growing vertically), *cable wire system* (i.e., cables used to support faster growing climbing plants with denser foliage), *grid system* (i.e., rigid two-dimensional grid commonly used), and *mesh system* (i.e., wire mesh, not rigid as in the previous types, but flexible) (GRHC, 2008). Living walls fully integrate both vegetation and substrate on the vertical surface of the exterior façade. Most used types of living walls are the *continuous living wall*, and the *modular living wall*. The former is a wall type without interruptions, in which the substrate is replaced by layers of geotextile into the plants; their roots can anchor and subsequently develop. The latter is characterised by several modules that are repeated to form the living wall. Plants are placed in the modules, having different configurations, and grow directly in containers filled with soil, inorganic growing medium or natural fibre; to ensure the continuity of the system, each module normally includes an interlocking system on the sides to connect to each other (Manso and Castro-Gomes, 2015; Susorova and Bahrami, 2013).

Whereas the mathematical models of green roofs are quite developed, VGSs models existing in literature are often not very detailed or partially complete due to the limited knowledge of such systems. The available researches focus on the different physical phenomena that contribute to the cooling effects, such as solar shading due to the presence of the vegetation layer, and evapotranspiration from both vegetation and substrate. For instance, Stec *et al.* (2005) proposed a simplified approach for calculating latent heat to reduce the complexity of heat and moisture transfer models associated with green walls. Nevertheless, adopting such a simplified method might lead to inaccurate results. Susorova *et al.* (2013) developed a mathematical model of an exterior wall covered with climbing vegetation, considering equal the convective heat transfer coefficients of the bare wall and of the vegetation covered wall, and highlighting that this assumption could be addressed in future research.

Only few studies in the literature suggest improvements in the main thermo-physical phenomena previously investigated, such as Hartmann *et al.* (2023) and Garcìa *et al.* (2019). In the work of Nesci *et al.* (2024), the authors developed two Python-based mathematical models describing the hygrothermal behaviour of VGSs – both green façades and living walls – based on literature. The mathematical models implemented aimed to fill gaps identified in previous models, making them among the most detailed models available for the study of VGSs.

While most literature address VGS application mainly on opaque building envelope compnents, some studies investigated green façade application on glazed surfaces, as a solar control strategy to reduce surfaces and indoor temperatures, such as Moghaddam *et al.* (2021).

The present paper builds up on the mentioned work by Nesci *et al.* (2024) with particular emphasis on VGS applications on opaque parts of the building envelope.

The aim of this paper is to evaluate the potential of VGSs (for Green Façade, GF, and for Living Wall, LW) integration on opaque building envelope parts in mitigating climate change effects at building scale. This is achieved by developing a co-simulation framework integrating integrating state-of-the-art VGS models in whole building-level energy simulation, and by evaluating the effect of these technologies on energy use and overheating risk in current and near future climate in a temperate location. In Section 2 the methodology of the work is described, presenting: (i) details of the VGS models; (ii) integration for co-simulation within a BIM (Building Information Modelling) to BEM (Building Energy Simulation) workflow; (iii) the case study on which their impact is tested; (iv) the building performance Key Performance Indicators evaluated and (v) the climate conditions considered for the current and near future scenario. The results are presented and discussed for different variants of the same building, according to the level of performance of the building envelope and to the strategies to control indoor temperatures during summer. Finally, the limitation of the study and of the models are discussed, together with possible future extension of the methods and models adopted.

2. Methodology & Case Study

Vertical Greenery System models

In this study, two mathematical models were selected to represent green façades and living walls, due to their distinct morphological characteristics. These models address gaps found in previous research, making them among the most detailed available for studying Vertical Greenery Systems (VGSs). For an in-depth presentation about the models, refer to Nesci *et al.* (2024). For green façades, the Dynamic Heat Transfer (DHT) model by Zhang *et al.* (2022) was chosen, as it provides the most comprehensive description of the thermophysical processes associated with this typology. Additionally, it outlines the methodological approach used to integrate the algorithms into EnergyPlus. In contrast, no complete model exists in the literature for living walls, as existing studies focus on specific thermophysical phenomena. To address this issue, various scientific contributions were selected and integrated. The heat balance for an external wall surface covered by a VGS is expressed as:

$$q_{\mathrm{s,w}} + q_{\mathrm{r,w}} + q_{\mathrm{c,w}} = q_{\mathrm{d,w}}$$

where the terms, in W/m², represent the net solar radiation flux, net longwave radiation flux, convective heat flux, and conductive heat flux at the VGS-covered wall surface, respectively. The GF model modifies the equation for net longwave radiation flux to account for radiation exchange with the ground, sky, and air. By solving the heat balance

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equation for the vegetation canopy, its bulk temperature can be determined, allowing for the calculation of longwave radiation exchange between the vegetation canopy and the external wall. The vegetation's energy balance is given by:

$$q_{s,v} + q_{r,v} + q_{c,v} - q_{tr,v} = 0$$

where the terms, in W/m², correspond to the net solar radiation flux absorbed by vegetation, net longwave radiation, convective heat flux, and latent heat flux from transpiration, respectively.

Building upon the Green Roof Model (GRM), the LW model introduces key modifications. To account for longwave radiation absorption by leaves and substrate, Hartmann's study (Hartmann *et al.*, 2023) is referenced. The GRM in EnergyPlus considers absorption of longwave radiation from the sky, radiation emitted by leaves, and multiple reflections between the plant layer and substrate. However, for vertical green walls, radiant exchange occurs not only with the substrate and sky but also with the ground. Therefore, view factors for both sky and ground were incorporated into the longwave radiation balance. Convective heat transfer coefficients for both vegetation and substrate also play a crucial role in differentiating green walls from green roofs. The Nusselt number is determined using Stanghellini's equation, which describes convective exchange between air and the leaf layer, and is applicable to vertical green walls (Stanghellini, 1987):

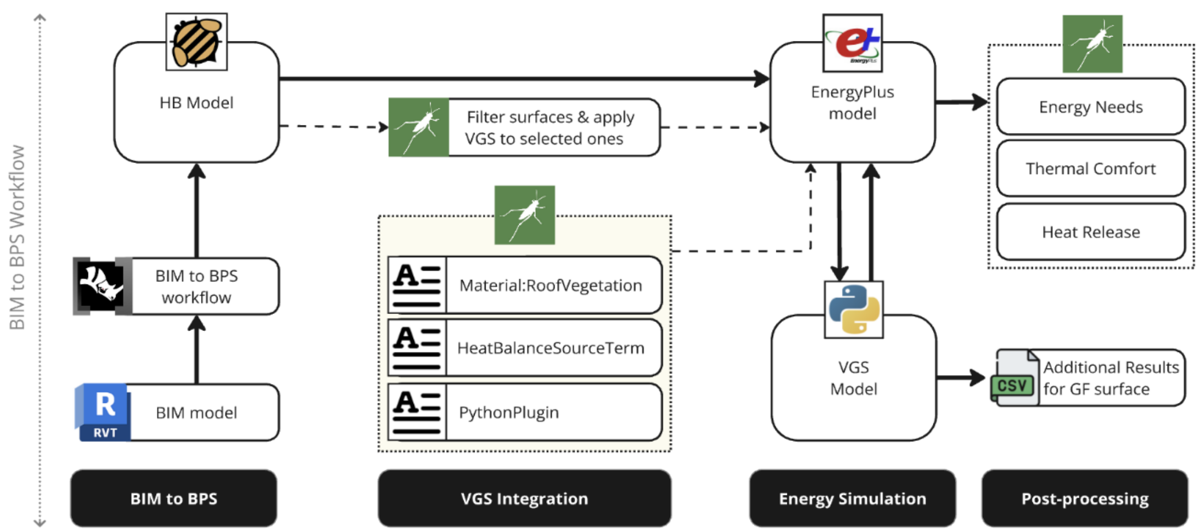
$$Nu = 0.405\,(Pr \cdot Gr + 6.29\,Pr \cdot Re^2)^{0.25}$$

BIM to BEM Workflow integration

The VGS models are integrated in a parametric workflow developed in VPL (Visual Programming Language) in Rhino's Grasshopper software, that ensures interoperability between a Building Information Modelling (BIM) software (REVIT in this study) and Building Performance Simulation (BPS) Tools (HoneyBee – LadyBug Tools). This approach employs the use of EnergyPlus v.24 as a primary engine for dynamic energy simulations under varying environmental conditions. Once the building energy model is produced by importing the BIM model into the VPL environment, VGS Python models' integration is not yet possible due to Honeybee tool limitations, relating to co-simulation with external models. In fact within HoneyBee Tools, it is not possible to co-simulate by means of Python plugin or EMS of Energy Plus, external models of advanced building envelope systems (Zhou *et al.*, 2023), due to simplification of EnergyPlus interface in the VPL tool. For this sake, within the developed BIM-BPS workflow, a VPL interface of the EnergyPlus Python plugin interface was developed, so to include the possibility to perform co-simulation in a different way and at a different scale in a seamless way: (i) data-integration for visual comfort evaluations from Radiance software, (ii) co-simulation with external Python models of building envelopes components (as for the present work), and (iii) building envelope and building systems integrated controllers (i.e. use of Radiance illuminance results to feed automatic dimming of artificial lighting, which is considered as a variation in internal loads in EnergyPlus energy simulation). In all these three types of co-simulation, boundary conditions and data are passed between the different tools to ensure convergence of the outputs and enhanced post-processing and debugging possibility.

In the present work, the second co-simulation feature of the developed BIM-BPS parametric workflow is adopted to integrate the different VGS models, differentially to each opaque vertical envelope external surface available in the model, as outlined in Figure 1. By means of the VPL interface, it is possible to define the VGS features, i.e., type of VGS, material properties of the vegetation layer (e.g., variation of LAI during the season and leaf solar reflection), and of the soil if present (e.g., thickness, thermal properties, water content), as shown in Figure 1 ("VGS integration"). On the other hand the VGS VPL component handles automatically the connection between the VGS models and the surfaces of EnergyPlus (by means of the Python Plugin), passing surface by surface the information related to (i) the boundary conditions of the external surfaces on which the VGS is integrated, (ii) all the heat balance terms of the VGS, that represent the additional heat flow (positive or negative) due to the VGS and (iii) the resulting surface temperatures of the foliage

Figure 1 - VGS Integration in BIM to BPS VPL-based parametric simulation workflow.



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layer and of the wall (see Figure 1, "Additional results for VGS").

Case Study and Simulation Scenarios

The selected case study has been defined as representative of the Italian building stock of existing (built pre 1970) and new (recently built) low-rise medium sized office buildings, based on national office archetype building (ENEA, 2009). The two building variants (existing and new) have equivalent geometrical properties, featuring 4 floors with a total floor area of nearly 2000 m^2. The building is of rectangular form with the main longitudinal façade facing South (shown in Figure 2). The floor plan is similar across the 4 floors of the building, with office rooms situated alongside the periphery of the building, while the central core hosts distribution and services spaces. The openings are mainly concentrated on the Southern and Northern façade and the Window-to-Wall Ratio (WWR) is 18%. The primary difference between existing and new office building types is the construction characteristics of the building envelope, where the existing one is poorly insulated and the new one has *U*-values set according to the Italian national regulations (DM 26/6/2015), as summarised in Table 1. When VGSs are integrated, they are considered to cover all available opaque south façade only in the first case, then all façades exposed to solar radiation (east, south & west) in the second case. Hence, VGS-applied surfaces represent nearly 32% and 67% of the whole vertical façade of the building.

Default programs were considered for each of the rooms (thermal zones) inside the energy model depending on the space use. Internal gains, such as lighting and electric equipment, are predefined as schedules based on the room's occupancy level. Various scenarios of Heating, Ventilation & Air-conditioning (HVAC) systems and ventilation strategies were investigated with VGS applications. The heating period is based on Italian legislation and functions from October 16th till April 15th.

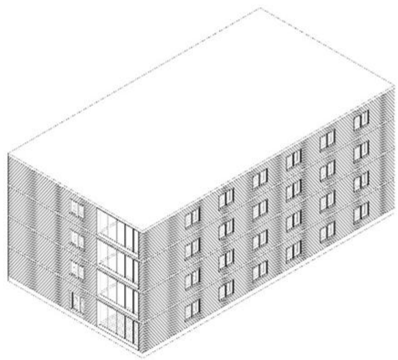

Figure 2 - Building geometry.

Table 1 - Building Surfaces Thermal Properties

Office Building Variant	Component U-value [W/(m^{2}K)]			
	Window	External Wall	Ground Floor	Roof
Existing	5.78	1.47	0.8	1.62
New	1.40	0.26	0.27	0.22

Two building systems scenarios are considered according to the presence or not of a cooling system. The first scenario, named as *No Cooling,* assumes only the use of a heating system to control the indoor temperature during the heating period, while ventilation is assumed to be natural, maintaining anyway the minimum ventilation requirement to ensure a good level of indoor air quality according to category II of EN 16798-1 (CEN, 2018). In the second scenario, named as *With Cooling*, both heating and cooling systems are considered to control the indoor air temperature, with the use of mechanical ventilation throughout the whole year to maintain indoor air quality requirements, integrated with a hear recovery system with nominal efficiency of 75%. Details of building systems and ventilation are reported in Table 2.

Table 2 - Building systems and indoor environment.

Ventilation parameter	**No Cooling**	**With Cooling**
Mechanical ventilation rate (m^3/s per m^2 floor)	0.0014	0.0014
Operable area for natural ventilation (m^2)	1.35 m^2 (per window)	N/A
Setpoint for natural ventilation (°C)	Tin > 23°C Tin > Tout	N/A N/A
HVAC characteristics		
Heating setpoint (°C)	setpoint 20 setback 16	setpoint 20 setback 16
Cooling setpoint (°C)	N/A	setpoint 26
E+ HVAC system	Ideal Air loads	Ideal Air loads

For all the considered cases, simulations were conducted for a temperate climate (with balanced heating and cooling demand), for the location of Turin – Italy (based on experimental data availability). Current (2020) and mid future (2050) Typical Meteorological Years (TMYs) have been produced with a dynamical downscaling methodology (Machard *et al.*, 2024) considering RCP 8.5 scenario, using 10 years of hourly climate observation in the city of Torino (2012-2022) for the bias adjustment (Heiranipour *et al.*, 2024). The Heating Degree Days (HDD) (12 °C heating base temperature) and Cooling Degree Days (CDD) (18 °C cooling base temperature) variations from current climatic scenario to the near-future one are summarized in Figure 3.

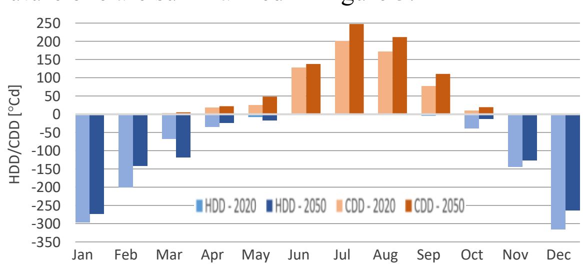

Figure 3 – Monthly HDD and CDD of current and near-future climate scenario of Turin – Italy.

Table 3 summarises the buildings and climate scenario analysed, related VGS technologies (Green Façade and Living Wall system), and orientations to which they were applied to. The building performance of VGS at the building level is always compared to its relative building benchmark, without the VGS, in terms of savings in delivered energy use and reduction of overheating hours.

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Table 3 – Simulation variations.

Climate scenarios	2020	2050
Building Variant	Existing	New
Building System	No cooling	With cooling
VGS type	GF	LW
VGS position	S	ESW

Key Performance Indicators (KPIs)

The following metrics were evaluated through the multi-objective parametric workflow, in order to assess the performance of the building integrated VGS:

- Building area-weighted average delivered energy for heating, lighting and cooling (if present), in kWh/m^{2}y;
- Overheating, in terms of building occupant-weighted average overheating degree hours (OHDH) over the non-heating season, considering operative temperature limits relative to a medium level of expectation of occupants, thermal comfort category II (EN 16798-1, CEN 2018).

In order to account for the total specific delivered energy of the building considering the same electrical energy vector, an Air-Source heat pump system is considered for hot and cold water generation, with yearly average Coefficient of Performance (*COP*) and Seasonal Energy Efficiency Ratio (*SEER*) of 3 and 4.8 respectively, based on the simplified model by Bordignon *et al.* (2024), which is validated for air-to-water systems against both manufacturer specifications and experimental data.

In order to average room level overheating hours at the building level, as to have an overall building level metric, an average based on the density of occupation of the people in each room is performed. The operative temperature thresholds considered are dependent on the outdoor mean running temperature, therefore for a specific day these could be higher considering a mid-future climate scenario, compared to the 2020 one. Nevertheless, the applicability of adaptive comfort model could be reduced when considering climate change scenarios, even though for Europe this variation could be considered a minor one (Bienvenido-Huertas *et al.*, 2020).

3. Results

External Surface Temperature

Figure 4 shows the external surface temperature of the Southern façade in current and near-future climate scenarios, over two representative days of winter and summer season. During the summer period (4a), surface temperatures for all benchmarks and VGSs show an evident increase from 2020 to 2050. Although the surface reaches higher temperatures in the new building type compared to the existing one (peak temperature reaching 55 °C instead of 50 °C in 2050 scenario), the cooling impact of VGS is more pronounced in the existing type in both climate scenarios. Both GF and LW demonstrate significant surface temperature reductions, with GF always outperforming LW. In 2050 climate scenario of the existing building, GF and LW reduced peak surface temperature by 20 °C and 10 °C respectively, while in the new building, LW decreased the surface temperature by 7 °C only, implying a reduced effect on buildings with higher levels of insulation.

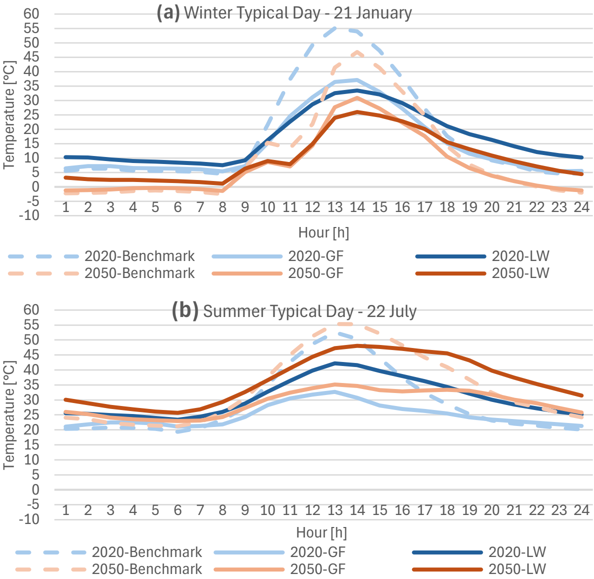

Figure 4 - External surface temperature profile for the insulated building in 2 representative days

In the winter period (4b), in the specific representative day, temperatures decrease from 2020 to 2050, due to reduced presence of solar radiation. LW in this period decreases the surface temperature due to the effect of solar radiation during the day, from 36 °C to 20 °C (14 °C reduction) in the existing building, and from 45 °C to 26 °C (19 °C reduction) in insulated building. This could imply a potential increase in the heating energy need. However, LW increases surface temperatures during the night hours due to its insulation effect, thus reducing temperature fluctuations. GF effect was less prominent than that of LW, mainly due to the lower LAI of the vegetation layer, reducing surface temperature to 24 °C in the existing building (8 °C reduction) and to 31 °C in the new one (14 °C reduction) in 2050 scenario.

Building Energy Demand

Regarding energy demand, VGS impact on whole building delivered energy saving was minimal in all cases. A higher impact was noticeable in non-insulated buildings (existing building) compared to insulated ones (new building), as evident in Figures 5 and 6. Moreover, VGS application on all facades with solar exposure (E-S-W) maximises its effect on the whole building results compared to applying it to southern-facing ones only.

In the first building system scenario (a), where only heating and lighting systems are present, delivered energy mainly increased with VGS application. In existing building, it increased only up to 3.1% in comparison to the benchmark value with GF, in both 2020 and 2050 climate scenarios, whereas LW effect was less visible, with an increase of less than 0.5% when applied to South Façade only (in both climate scenarios). This could be due to VGS blocking of needed solar radiation in winter, increasing heating demand. Notably, LW application on the 3 solar façades (E-S-W) led to a nominal energy

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saving of less than 0.6% in both climate scenarios due to the decrease in heating energy demand. This can be attributed to the insulating effect of the soil layer of LW, increasing the building's thermal mass and reducing thermal losses. In new building, impact of both GF and LW is negligible, increasing total delivered energy in a range less than 0.5% for both climate scenarios. While for LW model on ESW, a negligible energy saving is evident.

When the cooling system is present (b) in the summer period, both VGSs provide an improved, but still minimal effect, on the total delivered energy reduction. For existing building, GF and LW perform similarly, except in 2050 scenario where GF outperforms LW. However, they both show an advantage in reducing cooling energy demand, mostly with their application on the 3 exposed facades (ESW), reducing unwanted solar gains in the summer. GF on ESW in 2050 climate scenario exhibits the highest energy saving potential of all cases, reaching up to 2.2% reduction in whole building delivered energy, a quite limited value. In new building type, a lower impact is visible. Energy savings with GF are still lower than 1%. While no energy savings, a slight increase in demands instead were evident with LW.

Overheating

As visible in Figures 7 and 8, due to increased temperatures, overheating risk inside the building, expressed as overheating degree hours (OHDH), increases from the 2020 climate scenario to 2050 in all case studies, as well as from non-insulated to insulated building. OHDH decrease significantly with GF, particularly when applied to ESW façades in 2050. LW effect is less prominent due to its insulating properties. While on one hand it decreases overheating risk, it is increased on the other due to higher thermal mass, as demonstrated in Figure 4.

GF and LW application on existing building in absence of cooling system (a) contributed to the reduction of overheating risk inside the building, mainly detected during the summer period. In 2020 and 2050 climate scenario, GF impact was the highest, reducing OHDH up to 19 degree hours in absolute terms in 2050 when applied on ESW. LW had a more reduced effect, reducing only about 6 OHDHs in the same scenario. As for the new building, GF has a less pronounced effect in both climate scenarios than that on existing one. LW on the other hand showed an increase in in OHDH compared to the building without a VGS system, which suggests a disadvantage in near-future climate scenario application due to reduction of thermal losses through the envelope and subsequent increase of indoor temperatures.

With a cooling system (b), overheating becomes negligible, specifically in existing building, whereas in the new one, a slightly higher OHDH is documented, mainly during mid-season months. It is important to highlight that the results of reduction of OHDH in this case are not very convenient due to the cooling system.

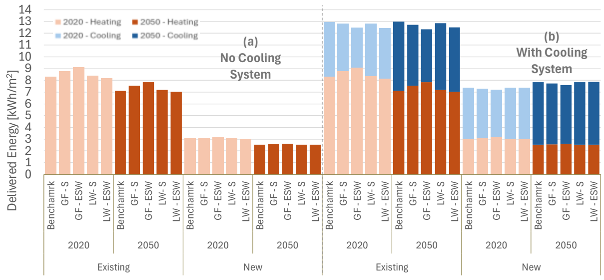

Figure 5 - Building-level area normalized heating and cooling delivered energy [kWh/m²]

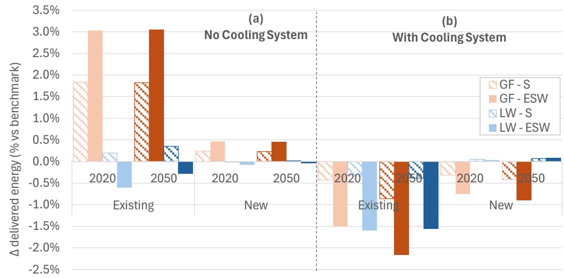

Figure 6 – Relative difference in overall delivered energy with respect to benchmark [%] with VGS

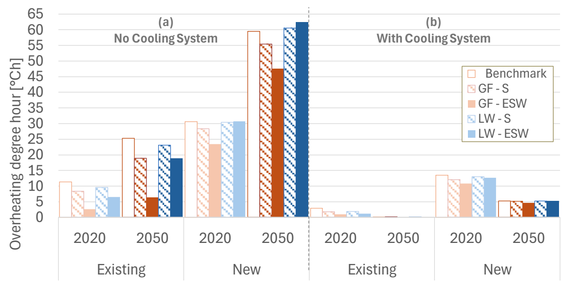

Figure 7 - People-averaged overheating degree hours for whole building.

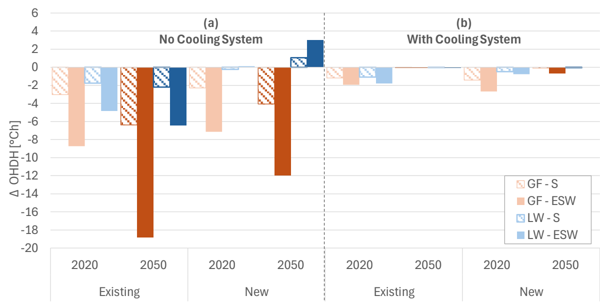

Figure 8 – Difference in OHDH with respect to benchmark with VGS application.

4. Discussion

Figure 9 summarizes the results presented in Section 3 and demonstrates the relative magnitude of impact of VGS on the selected case study variants in different climate scenarios on reducing the building's delivered energy and overheating of indoor spaces. A notable observation is the impact of the building's envelope properties on the effectiveness of VGSs on the building performance. Both energy savings and reduction in overheating are more pronounced in VGS application on the existing building types, more specifically the impact on OHDH reduction when the cooling system is absent,

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even if energy demand slightly increases (due to heating increase). The insulation layer provided by the substrate of the Living Wall minimises the vegetation effect, therefore, it is outperformed by the Green Façade in most of the cases. Moreover, this insulating effect of the LW is a disadvantage in new buildings, leading to a slight increase in overheating, as well as in yearly cooling energy demand, and a consequent decrease in heating energy demand, both of which remain minimal. The obtained results align with previous findings, in fact VGS contributes significantly in reducing external surfaces temperatures, however this effect minimally impacts the buildings' energy demand reduction, up to 2.5% for GF, mainly due to cooling energy saving. On the other hand, it can mitigate the relative overheating risk inside indoor spaces, especially for non-insulted buildings without cooling, in mid-future climate scenario (2050).

The surface temperature reduction by both GF and LW could be an important feature to mitigate climate change in combination with Urban Heat Island effects. Nevertheless, the integration of VGS models into EnergyPlus inputs/outputs still needs to be refined to consider the actual "Heat Release to the Outside" of an opaque wall construction integrating a VGS system. The limitation will be object of future work, besides the validation of the VGS models with experimental data.

It is also worth noting that these buildings (both insulated and non-insulated) have already a good performance in terms of thermal comfort, as the natural ventilation during summer months was optimised already; therefore, the additional improvement in thermal comfort provided by a VGS is only marginal. Nevertheless, the selection of the case study has been fundamental to explore the potentials of VGS, not to overestimate their potential effects. It is also important to consider that the Living Wall system is based on the adaptation of the EcoRoof Model of EnergyPlus, which does not consider thermal inertia. Moreover, evapotranspiration effect of irrigation and rain on LW is not yet developed. Future work will aim to overcome these limitations in LW model to represent its full potential, enhancing its impact on surface temperature reduction during the summer period.

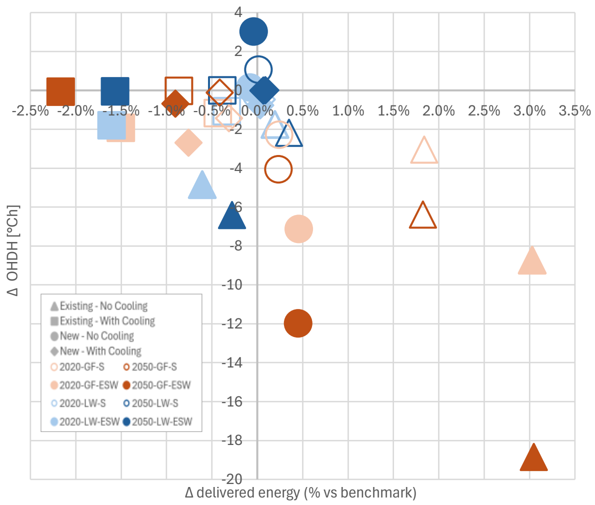

Figure 9 - Multi-objective comparative analysis.

5. Conclusion

This study investigated the potential of Vertical Greenery Systems (VGS) as a passive cooling strategy on the opaque components of the vertical building envelope to mitigate the impact of climate change, by means of a novel co-simulation approach in a BIM to BEM setting. The shielding and evapotranspiration effects of VGS is examined not only for its effect in reducing external surfaces temperatures and surrounding elements, but also taking into account building Key Performance Indicators (KPIs) related to building energy efficiency and reduction of occupant thermal discomfort. Python-based mathematical models of VGS were integrated in a parametric software that enabled co-simulation with building-scale dynamic energy models and multi-criteria evaluation based on current and mid-future climatic conditions for an office building in a temperate climate.

With the VGS covering part or most of the building opaque vertical façade, although a significant effect in reducing surface temperatures (in line with previous findings), it revealed a minor impact at the building level in a temperate climate, in terms of potential energy savings and improved thermal comfort. The reduction of overheating risk is maximised, even though always very low in absolute term, for buildings using natural ventilation as a primary passive cooling strategy and for existing buildings that are poorly insulated, especially in mid future climate projections, representing a possible solution to improve heat resiliency of existing buildings. Green Façade performed slightly better than Living Wall as a passive cooling solution, due to the lower thermal resistance introduced. A deeper consideration should be taken of the optimal effectiveness of the substrate layer thickness and balance with the envelope thermal properties, after introduction of the thermal inertia into the LW model, while understanding the impact of an increased VGS surface. The integration of VGS models within the BIM-BPS simulation workflow presented, allowed to scale up the evaluation of such systems at the building scale, to more accurately evaluate their potential impact supporting design decision making.

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