POLITECNICO DI TORINO

Master Degree course in Building Engineering

Master Degree Thesis

Decarbonizing curtain wall facades: a life cycle approach to embodied and operational carbon

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A chi mi ha donato amore, in ogni sua forma;
A chi sono sicura me lo avrebbe dato con tutto se stesso
ma se ne è andato troppo presto
per vedermi raggiungere questo traguardo;
A chi non mi ha mai fatto sentire casa troppo lontana,
e a coloro che hanno fatto diventare casa posti sconosciuti

Alla mia famiglia, supporto e spalla costante su cui piangere e gioire;
A mia mamma, grazie alla quale sono la donna che sono oggi,
mi hai insegnato cosa vuol dire essere forte, resistere, e farcela nonostante tutto
perchè sei stata capace di proteggermi e quando possibile alleviare i miei dolori;
A mio padre, perchè 18 anni fa l'unica mia paura
era che non saresti stato al mio fianco in momenti come questo,
e non c'è cosa più bella di vederti orgoglioso di me oggi,
la tua forza sarà sempre di esempio per me;

Ai miei nonni, perchè se Bologna era lontano chissà cosa avreste pensato di Torino,
in tanti momenti avrei voluto un vostro abbraccio,
ma prometto che l'amore che mi avete donato basterà per tutta la vita;

A Morena, Roberto e Martina, che non siete famiglia ma è come se lo foste,
grazie per avermi cresciuta e accompagnata in ogni momento della mia vita;

A Francesco, perchè nonostante tu sia entrato nella mia vita da poco,
il tuo supporto costante e incondizionato è stato fondamentale,
ti auguro di avverare ogni tuo sogno
e ci auguro che la vita ci porti a farlo mano nella mano;

Alle mie amiche, perchè grazie a voi casa non è mai stata troppo lontana,
e i chilometri che ci dividevano non sono mai stati una scusa
per non essere presenti una per l'altra,
grazie per avermi fatto commuovere per un sacchetto di dolci
conseganti da un rider in Belgio
e grazie perchè in ogni momento mi avete sempre dimostrato di poter contare su di voi;

Ai liegèoise perchè siete riusciti a far diventare caloroso un posto freddo come Liège,
siamo stati la famiglia uno dell'altro per 5 mesi,
e in voi in quel momento, ho trovato tutto ciò che stavo cercando,
è difficile esprimere a parole il nostro legame,
ma so per certo che l'erasmus mi ha regalato persone preziose
che spero di non perdere mai;

A Chiara e Serena, perchè prima di voi mai avrei pensato di vivere con qualcuno,
grazie perchè siete state le mie confidenti, mi avete ascoltata
e con voi so che anche il più piccolo silenzio non rimane inascoltato,
in quelle mura rimarrà per sempre un pezzo del mio cuore;

A chi ha condiviso con me gioie e dolori di questo percorso,
vi auguro di essere felici, di trovare la vostra strada,
e di costruire la vostra vita nel posto per voi migliore.

Abstract

The building sector is responsible for one third of global energy-related CO_2 emissions, deriving both from operational energy use and from embodied carbon associated with extraction, manufacture, and assembly of materials. As energy efficiency and renewable technologies can reduce operational emissions, embodied carbon has become a main contributor to the environmental footprint of buildings. Within this context, the thesis explores the challenge of decarbonizing curtain wall facades through an integrated Life Cycle Assessment (LCA) approach that considers both embodied and operational carbon impacts. Glazing facades are one of the most carbon-intensive facade systems due to their reliance on energy-demanding materials such as glass and aluminium, both characterized by high emission factors and relatively short service lives.

This research adopts the ISO 14040 and ISO 14044 standards for LCA and quantifies the carbon performance of different curtain wall facade configurations through the stages of production (A1-A3), replacement (B4) and use. Embodied carbon is calculated starting from the emission factors derived from the ICE database, while operational carbon is estimated through COMFEN5 simulations that account for energy demand. The study systematically varies parameters such as window to wall ratio (WWR), bay dimensions, wind load magnitudes and material alternatives for frame, glass, and opaque components to identify configurations that minimize total life-cycle emissions.

The results highlight that glass and aluminium dominate embodied carbon, contributing together to more than 70% of facade-related emissions. Substituting virgin aluminium with recycled aluminium, GFRP, or laminated timber, embodied carbon can be reduced up to 50%, while the use of low-carbon glass achieves reductions of about 25%. Opaque materials such as natural stone panels show lower emissions compared to GRC panels and aluminium sheets, offering additional pathways for mitigation.

The analysis of replacement scenarios reveals that insulated glass units require substitution after approximately 25 years, contributing significantly to life-cycle emissions. Extending IGU service life or improving durability therefore becomes a crucial decarbonization strategy.

Operational simulations show that facade configurations with lower WWR can decrease energy-related emissions by 20-30% compared to fully glazed facades due to improved thermal performance and reduced cooling loads. However, this reduction must be balanced with daylighting needs and architectural requirements, demonstrating the inherent trade-off between embodied and operational carbon. Moreover, operational carbon plays a key role in the emissions of a building especially when built due to today's CO_2 factors, but through the decarbonization of the grid, its impact can decrease over the building service life.

By combining all life-cycle phases, the study identifies that adopting low-carbon materials, optimized facade geometry and durable components can cut total facade-related emissions by 30-45% without compromising comfort, aesthetic or structural integrity. The findings underline the importance of integrating life-cycle thinking into facade design from the earliest design stages and provide quantitative guidelines to decrease emissions.

Finally, the thesis demonstrates that the decarbonization of curtain wall facades is achievable through comprehensive LCA based framework that merges material efficiency with operational energy optimization.

Contents

Chapter 1

Introduction

Buildings are an essential part of everyone's everyday life, but they also represent one of the largest sources of greenhouse gas emissions in the world. In fact, building sector alone is responsible for more than one third of global energy related CO_2 emissions.
These emissions come from two main sources: those generated during the operation of buildings due to heating, cooling, lighting and ventilation; and those produced during their construction, called embodied carbon. In recent years, as operational emissions have gradually decreased thanks to more efficient technologies and renewable energy, embodied emissions have become increasingly significant.
Hence, considering the impact of buildings during their construction and service life, this thesis addresses the challenge of finding solutions and design strategies to decarbonize facades. Especially, it focuses on curtain wall facades that despite they give visual identity and allow natural light to enter, they also have one of the highest carbon impacts among facade systems. Producing and maintaining large glass surfaces requires energy-intensive materials such as glass and aluminium, whose manufacturing processes release large quantities of CO_2. Furthermore, these components typically have shorter service lives than structural elements, meaning they must be replaced at least once during a building's service life. Therefore, reducing the environmental impact of facades, especially the glazing ones, is essential for achieving the global decarbonization goals set by Paris Agreement.
From a technical perspective, curtain wall systems combine materials with very different thermal and mechanical properties, which makes them complex to optimize. From an environmental point of view, they represent around 30% of the embodied carbon of the entire building. This means that even moderate improvements in facade design can lead to significant global reduction in emissions. Therefore, the research is highly relevant to develop low-carbon construction strategies without compromising aesthetics, comfort or performances.

This work is based on the development of a comprehensive Life Cycle Assessment (LCA) of glazing facade systems, combining both embodied and operational carbon. The study quantifies the emissions associated with the production, maintenance, and use of different curtain wall facade configurations, and explore strategies to minimize their total carbon footprint. In particular, the research investigates how design variables such as the window to wall ratio (WWR), bay dimensions, wind loads and choice of materials for glass, frames and opaque parts as well as the decarbonization of the electrical grid, influence the life cycle emissions of the facade. By systematically comparing alternative design options and future scenarios, the study identifies practical solutions that can reduce emissions without affecting structural or thermal performances.

The methodology used in this thesis follows the international standards ISO 14040 and ISO 14044 for Life Cycle Assessment. The analysis begins with an overview of the embodied carbon of buildings and facades, based on current literature and environmental databases such as *One Click LCA* and *The Global Building Data Initiative*. Then, a detailed LCA model is developed to quantify the emissions of different glazing facade typologies through the stages of production (modules A1-A3), replacement (B4) and use. The embodied carbon is estimated using emission factors from the ICE database, while the operational carbon is simulated with the software *COMFEN5* under different situations, which calculates energy demand for heating, cooling, and lighting under varying conditions. The two results are then combined to assess the overall environmental impact and to highlight the trade-offs between material efficiency and energy performance.
Hence, this thesis aims to demonstrate that the decarbonization of curtain wall facades can be effectively achieved through an integrated life cycle approach, considering both material choices and operational energy performance. The findings contribute to the current debate on sustainable construction, provide designers with data-driven guidelines for the selection of low-carbon materials and facade configurations.

For developing a complete analysis the thesis starts presenting the context of embodied and operational carbon emissions in the building sector, with a particular focus on facade systems and their impact on the total carbon footprint of buildings. Then the adopted methodology for the whole study, the Life Cycle Assessment framework and the parameters considered are explained. After that, the analysis starts focusing on strategies and design options to decarbonize curtain wall facades. Firstly existing facade projects and datasets from industry partners are analyzed to identify the main contributors to carbon emissions of buildings and establish benchmarks for comparison. Then, the two considered stages of LCA, production (A1-A3) and replacement (B4), are examined. The first one focuses on the released embodied carbon from the production of each component: glass, frame and opaque panels. While the replacement stage accounts for the environmental cost of substituting glazing units during the service life of the building. After having evaluated embodied carbon, also the operational carbon is assessed by simulating energy consumption with different window to wall ratio and analyzing how the performance of insulated glass units changes over time. Finally, the results are integrated and embodied and operational carbon are compared for finding the optimal facade configuration that minimize total emissions.
Through this comprehensive analysis, the thesis demonstrates how careful design and material selection can make curtain wall facades not only visually appealing and functional, but also compatible with the urgent need for sustainable, low-carbon construction.

Chapter 2

Embodied carbon emissions of buildings and facades

The building sector is responsible alone of the 34% of the global energy-related CO_2 emissions and over 32% of energy demand [4].

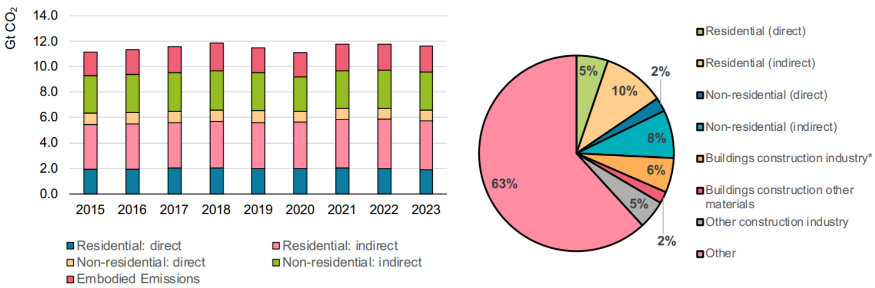

Figure 2.1. Emissions in building sector 2010-2023 (left) and share of buildings in global energy and process emissions in 2023 (right) (IEA 2024a) [4]

By examining this graph is clear how the building sector has not followed a positive trend in reducing its carbon emissions in the past few years, remaining almost constant. This means that for achieving the global decarbonization and respecting the climate goals of the Paris Agreement, this sector needs to decrease its emissions by 50% by 2030 [4]. With the same purpose, also the new EPBD released in April 2024 [7], highlights the importance of reducing the emissions of the building sector focusing on the energy demand and emissions of buildings during their entire life cycle. In fact to meet the goals of Paris Agreement all new buildings should be zero emission by 2030, while existing buildings should be zero emission buildings by 2050. Being zero emission buildings means that the building does not emit carbon emissions by fossil fuels on site, and it has the capacity of adapting its consume, generation and stock of energy based on external signals. With this aim, for each building its energy performance should be calculated as well as its GWP over its entire life cycle. The GWP is calculated for each phase of the building life cycle through its embodied and operational carbon emissions [7].

Furthermore, in Italy, a protocol named ITACA [14] was set to define operational tools to evaluate the sustainability of buildings regarding both their energy performance and environmental impacts. Through this methodology is possible to obtain a final score for each building representative of its level of sustainability.
Hence, considering all these standards and protocols, the calculation of embodied and operational carbon of buildings plays a main role to meet the decarbonization of the sector. The embodied carbon can be defined as the carbon emissions associated with materials and construction processes throughout the whole life cycle of a building, this typically includes construction, maintenance, repair, refurbishment and demolition phases [3]. While the operational carbon refers to the emissions associated with energy used to operate the building including heating, hot water, cooling, ventilation, lighting systems, equipment and lifts [3]. Since embodied emissions sites are expected to account for over the 50% of the total lifetime emissions in the next 10-15 years [1], the reduction in embodied carbon should be prioritized. For this reason, limits in these terms are set for buildings in order to meet the goals cited before.
Different associations have set different limits over the years but the main ones are presented below.
Buro Happold [1] proposed in 2021 the following targets to reach in the next years to meet the decarbonization of the building sector.

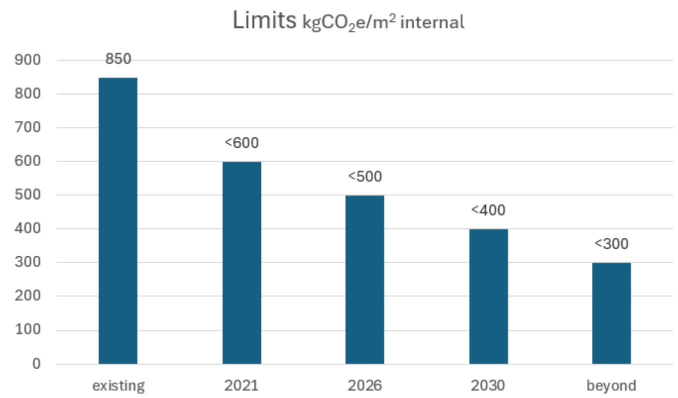

Figure 2.2. Limits set by BURO HAPPOLD in terms of embodied carbon for buildings

Also the software One Click LCA [21] proposed its limits in terms of embodied carbon subdivided in levels from the minimum acceptable to the best one for almost all countries. Below it is reported the specific one for the Western Europe set in 2023.

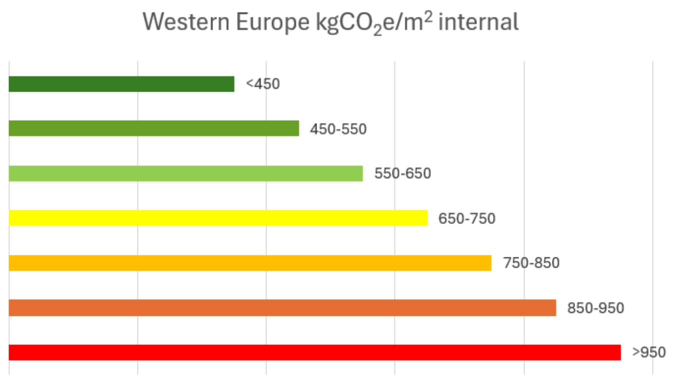

Figure 2.3. Limits set by One Click LCA in terms of embodied carbon for Western European buildings

If these two graphs are compared between them and with parts of the buildings present on the database 'The Global Building Data Initiative' (GBDI) that includes the evaluation in terms of embodied carbon of thousands of buildings all over the world, it is possible to say that the limits set by Buro Happold are quite optimistic since the majority of the analyzed buildings built between 2021 and 2024 do not fulfill them. While the ones set by One Click LCA are representative of the state of the art in the building sector. For this reason, even if both will be presented below as a support for other statements, only the ones by One Click LCA will be used as a threshold for the projects that will be studied and analyzed in the following chapters.

Analyzing buildings on both database One Click LCA and The Global Building Data Initiative, it is clear how facades have a significant impact on the embodied carbon of the whole building. In fact, if the contributions of each part of the building in terms of embodied carbon are considered, could be noticed that facades are the second element accounting for around 30% of the global emissions of the building, before it only the structures that are responsible for the 40-50% [1].

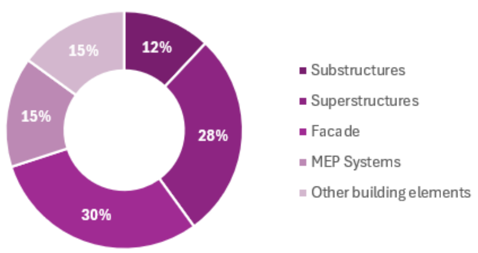

Figure 2.4. Breakdown of typical proportions of the building

This breakdown meets perfectly also the data coming from the tool One Click LCA. In fact analyzing the buildings present on the software and looking for the contribution

of the facades in the whole result of the embodied carbon for all of them, it is possible to conclude that as mean value the facade accounts for the 29.95%. So taking into account the role that facades have in the embodied carbon of buildings, this study will completely focus on them trying to reduce their impact.
Hence, the limits presented above are transformed in terms of facades. For doing it two typologies of buildings are considered: not very compact buildings and very compact buildings. For 'not very compact buildings' it is meant buildings that have a ratio S/V between 0.2 and 0.9 m^2/m^3, this means that 1 m^2 of net floor area corresponds to 0.6-0.9 m^2 of facade. While for 'very compact buildings' it is meant buildings that have a ratio S/V between 0.7 and 1 m^2/m^3, this means that 1 m^2 of net floor area corresponds to 1.2-1.8 m^2 of facade.
The limits seen before from Buro Happold and One Click LCA are transformed considering all these values.

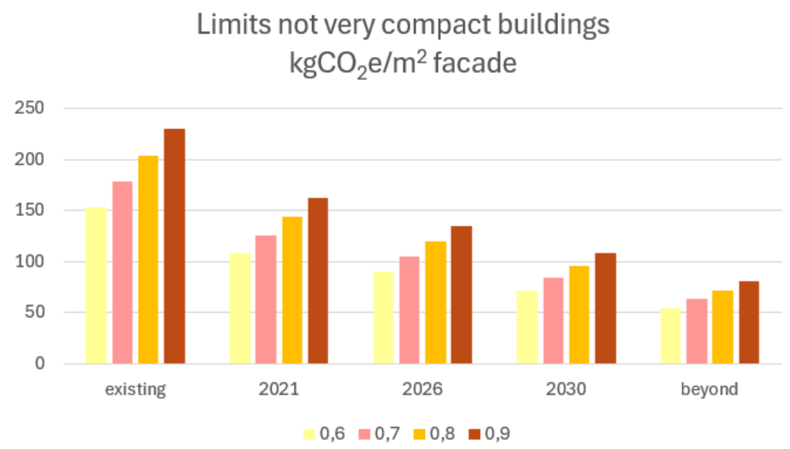

Figure 2.5. Limits set by BURO HAPPOLD in terms of embodied carbon for not very compact buildings

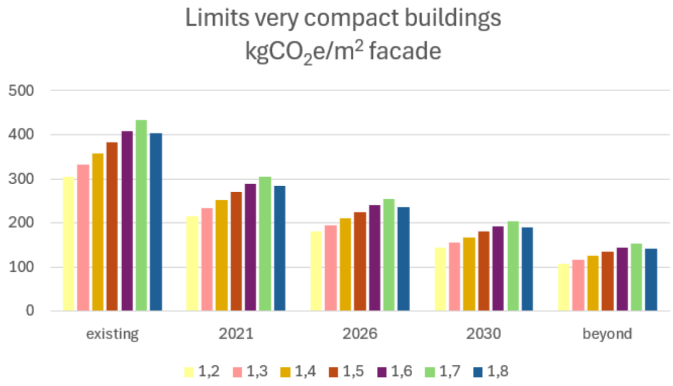

Figure 2.6. Limits set by BURO HAPPOLD in terms of embodied carbon for very compact buildings

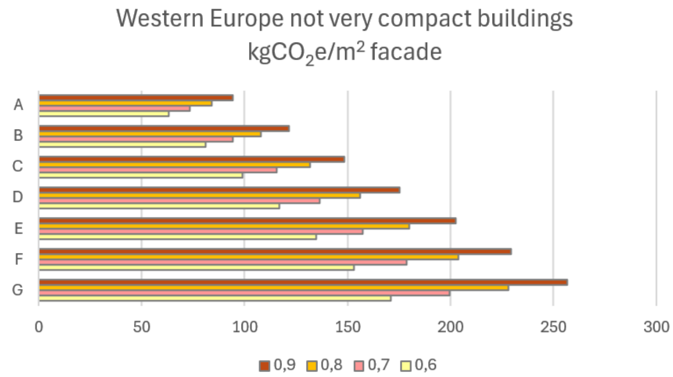

Figure 2.7. Limits set by One Click LCA in terms of embodied carbon for Western European not very compact buildings

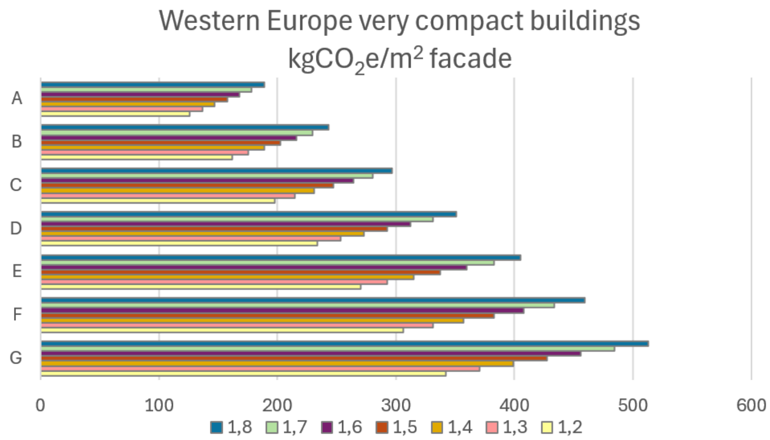

Figure 2.8. Limits set by One Click LCA in terms of embodied carbon for Western European very compact buildings

In order to have a better understanding of the values and limits, the graphs that represent the mean values are also reported below.

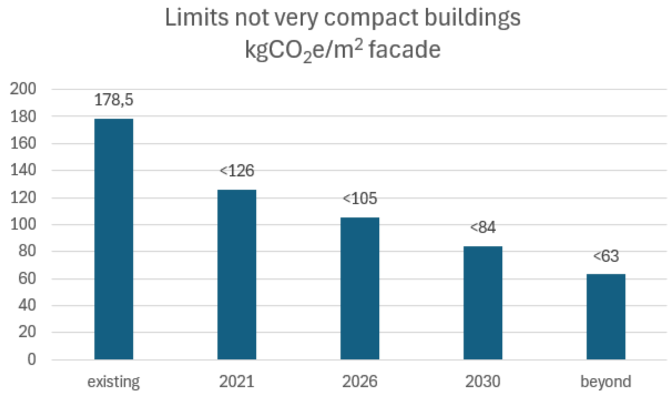

Figure 2.9. Mean limits set by BURO HAPPOLD in terms of embodied carbon for not very compact buildings

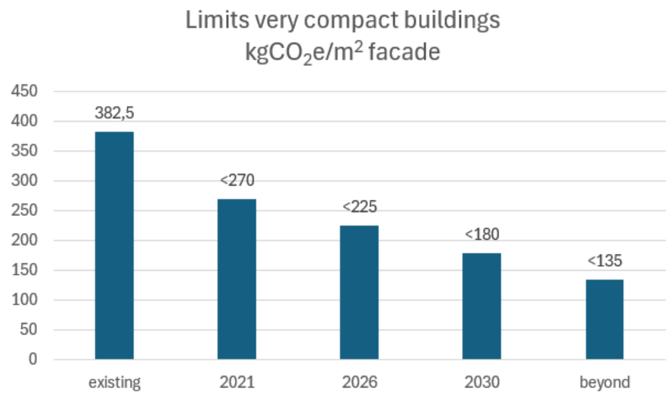

Figure 2.10. Mean limits set by BURO HAPPOLD in terms of embodied carbon for very compact buildings

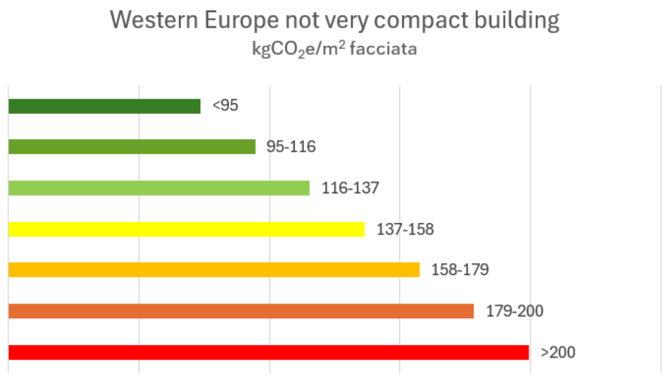

Figure 2.11. Mean limits set by One Click LCA in terms of embodied carbon for Western European not very compact buildings

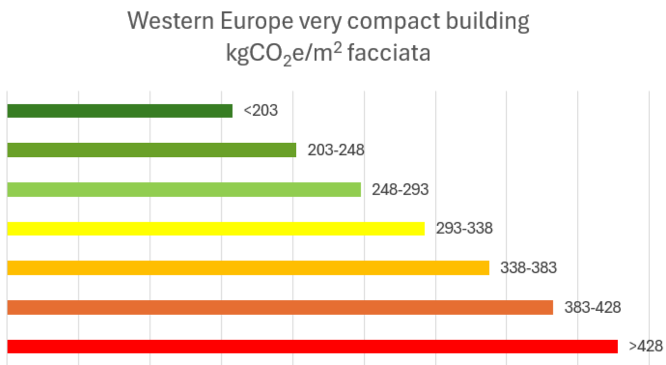

Figure 2.12. Mean limits set by One Click LCA in terms of embodied carbon for Western European very compact buildings

Now that the limits are fixed, different facade typologies are analyzed to understand which are the most emissive ones.
Buro Happold [1] compared eight typical options for residential and industrial buildings and compared their impacts in terms of embodied carbon. The results are expressed per m^2 of facade.

- Pre-cast concrete system: 116 $kgCO_2/m^2$
- Hand set brick on ancon shelves with SFS backing: 223 $kgCO_2/m^2$
- Limestone rainscreen with SFS backing: 255 $kgCO_2/m^2$
- Aluminium rainscreen with SFS backing: 263 $kgCO_2/m^2$
- Ceramic tile rainscreen with SFS backing: 305 $kgCO_2/m^2$

- Granite rainscreen with SFS backing: 350 $kgCO_2/m^2$
- Fully unitised glazed system: 380 $kgCO_2/m^2$
- Brick slips on SFS system: 613 $kgCO_2/m^2$

While if the results are expressed in m^2 of net floor area, these are the outcomes.

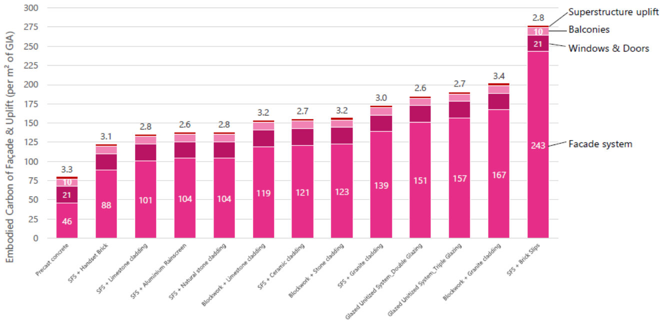

Figure 2.13. Embodied carbon of different types of facades and uplift [1]

Also Taborianski et Prado [24] studied the impact of different types of facades on a building. The following ones were selected for the analysis: structural glazing facade, brick facade with mortar coating, brick facade with aluminium composite panel covering, ACM. A LCA study was performed and the results are presented below.

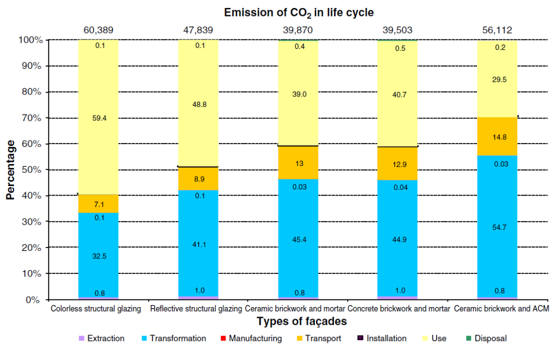

Figure 2.14. Carbon emissions of different types of facades during their lifecycle [24]

In both analysis one of the most emissive facades is the glazing one. This happens because they are characterized by high levels of embodied carbon both in production and use phases. In fact the production of glass is one of the most emissive since high temperature, great quantities of electrical energy and fossil fuel are needed. At this should be added the fact that glazing should be replaced after 20-25 years, so the emissions increase. Moreover, in the use phase the emissions are higher than those of other materials because the thermal insulation ability of transparent components is lower than opaque materials.

For this reason, in this study, glazing facades are explored to find methods to reduce their embodied carbon.

Chapter 3

Methodology

To analyze the embodied and operational carbon of glazing facades and study strategies to reduce it, the following methodology will be used.

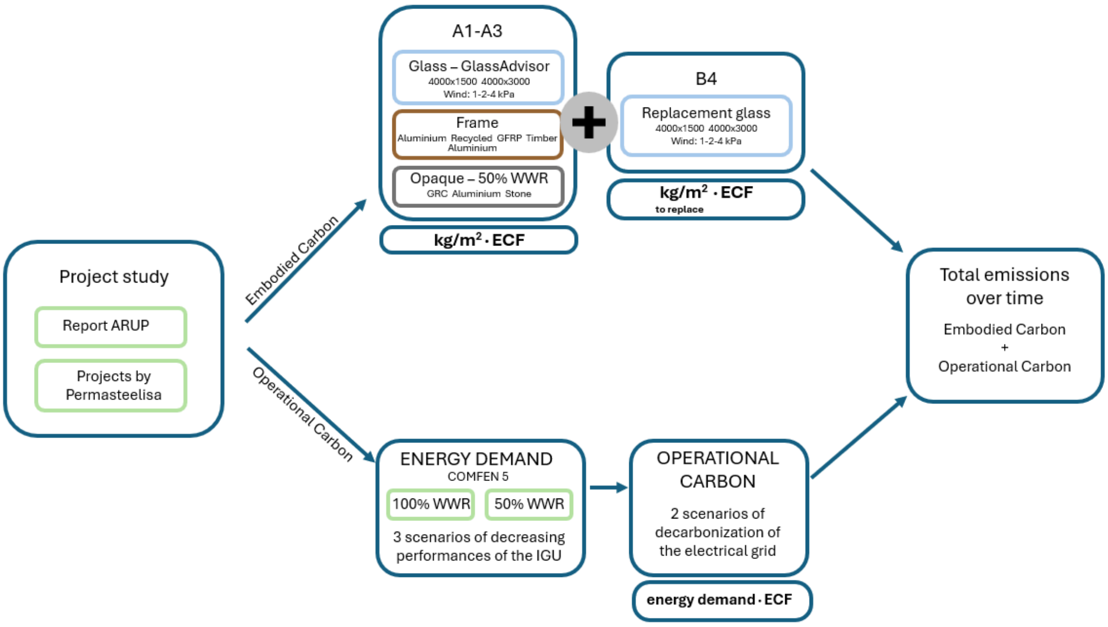

Figure 3.1. Methodology scheme

First, sixteen different types of glazing facades from ARUP and Saint Gobain Glass [5], together with nine facade projects by Permasteelisa [15] are examined throughout the LCA method to understand what this study should focus on to decrease the impact of curtain wall facades. Then, always using the stages of Life Cycle Assessment analysis, both embodied and operational carbon will be estimated for curtain wall facades characterized by different design options.

As regards embodied carbon, the stages of production (A1-A3) will be explored focusing on the emissions of glass, frame, and opaque components. Firstly two different bays are considered, one with dimensions of 4000 mm x 1500 mm, and the other 4000 mm x 3000 mm, with three different configurations of wind: 1 kPa, 2 kPa and 4 kPa. Then, considering two different window to wall ratios (100% and 50%) the frame is calculated comparing four different materials: aluminium, recycled aluminium, GFRP, and timber. As final step, the opaque components are analyzed in the configuration of 50% WWR considering as materials GRC, aluminium and stone.
Together with the production stage, also the replacement stage (B4) is considered in the analysis of the embodied carbon. This stage accounts mainly for the substitution of glass during the service life of the building. For this step the two configurations of window to wall ratio are considered, and the correlated emissions calculated.
These two phases are then summed together to obtain the quote of embodied carbon in all facade configurations.
While to determine the operational carbon, the energy demand is calculated through the software COMFEN5 in three different scenarios of variation over time of energy demand due to the decreasing performances of insulated glass unit. Then the values of energy demand over time are multiplied by the emission factor characterizing the electrical grid over the years of building life expectancy in two different scenarios. This is done considering three different $\frac{facade}{floor}$ ratio, 50%-30%-20%, and the two configurations of facade with 100% WWR and 50% WWR. Finally a comparison is made between triple glazing units and double glazing units to evaluate the advantages in terms of energy need and operational carbon.
As final step the two impacts of embodied and operational carbon are analyzed together to evaluate the distribution of both during the building life expectancy. An example of the distribution of emissions over time is reported below.

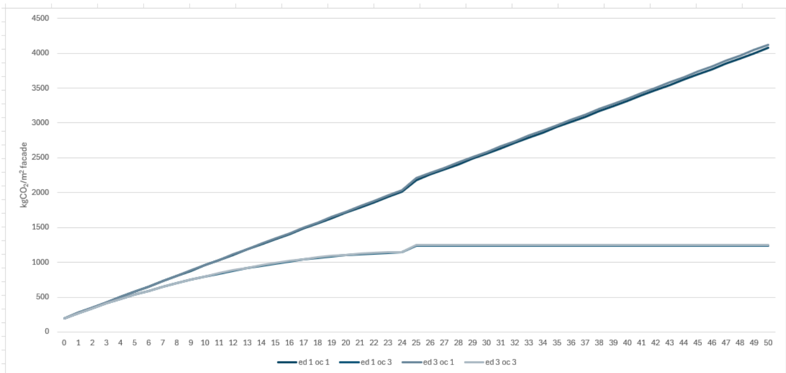

Figure 3.2. Example of emissions over the building life expectancy

The calculated emissions in each step of the analysis are normalized per m^2 of facade to directly understand the impact of the facade itself on the emissions of the whole building. This normalization has an effect on the magnitude of embodied and operational carbon in the results. In fact if the emissions are normalized per m^2 of facade, the energy demand, and as a consequence the operational carbon, will be greater than the embodied carbon. While if the emissions are normalized per m^2 of net floor area, the embodied carbon will have a greater impact. This happens because the net floor area is greater than the facade surface.

The driven methodology of the whole analysis of curtain wall facades emissions is the Life Cycle Assessment (LCA). This methodology is described by the standards ISO14040 [17] and ISO14044 [18] and its main goal is to define the different stages during a material or components life that can contribute to global warming. This includes embodied carbon as a global warming potential indicator used to quantify this impact [2].
To quantify with precision the embodied carbon, each stage of the life cycle is broken down into modules as shown in the following figure to consider each contribution.

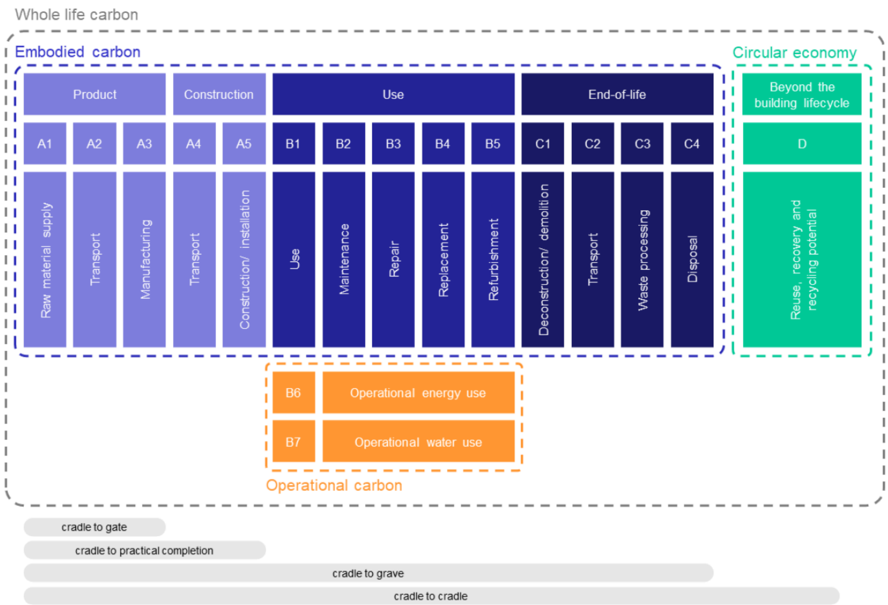

Figure 3.3. LCA stages and modules as defined in BS EN 15978 [2]

The first stage takes into account the production and contains the modules from A1 to A3. These modules include the emissions associated with the raw material extraction, processing, transportation to manufacturer and manufacturing [2]. The construction stage includes the modules A4 and A5 that account for the emissions associated with the transportation to the building site and installation into the building, including emissions from on-site testing [2]. Then, the use stage includes all the modules from B1 to B7 that consider the emissions associated with the use, maintenance, repair, replacement and refurbishment of the asset. In particular, modules from B1 to B5 take into account the embodied carbon emissions within the use stage; while modules B6 and B7 include the operational carbon emissions associated with the operational energy and water use of the asset [2]. Finally the end-of-life stage that comprehends modules from C1 and C4 includes the emissions associated with the de-construction, transport away from site and end-of-life scenarios [2]. Moreover, as a final step, there is the benefits and loads beyond the system boundary stage that includes module D. This is a stage existing outside the life cycle of the asset and considering the emissions and sequestration of carbon associated with recycling, recovery and reuse of materials [2].
In particular, in stages A and B the procedure to calculate the embodied carbon is driven

by the same principle: multiplying the quantity of material needed for its specific embodied carbon factor (ECF). Each ECF represents the global warming potential (GWP) in units of $kgCO_{2e}$ per unit quantity of material or component.
The ECF used in this study were taken from the ICE database by Circular Ecology [6] that provides the embodied carbon factors for the majority of materials used in the building sector. An extract of this database with the values of the most frequent materials is reported below.

MATERIAL	**ECF [$kgCO_2/kg$]**
Glass	1.4-1.8
Aluminium	6.5-6.8
Steel	2.7-2.8
Concrete	0.1
Clay brick	0.213
Laminated timber	0.7-0.4
GRC	0.6
Stone	0.1
Ceramic	0.75
Mineral wool	1.25
Polystyrene	3.69

Table 3.1. ECF from ICE database of the most common materials

These factors are mainly representative of the materials manufacturing processes. In fact, materials that need high temperature processes, great quantities of fossil fuels and electrical energy have greater ECF than materials characterized by a lower emissive manufacturing process and lower distances from the extraction to the production sites. This means for example that aluminium and steel have higher ECF than timber.

Chapter 4

Projects study

Now that the applied methodology was clarified, different glazing facades are analyzed to understand which are the components and materials with the higher contributions in embodied carbon. For doing it a study from ARUP and Saint Gobain Glass [5] regarding sixteen facade typologies representing European and United Kingdom facade design is reported as well as a study on nine facade projects by Permasteelisa all over Europe.

Starting with the analysis of ARUP and Saint Gobain Glass [5], the following ones are the sixteen representative facade typologies selected by them.

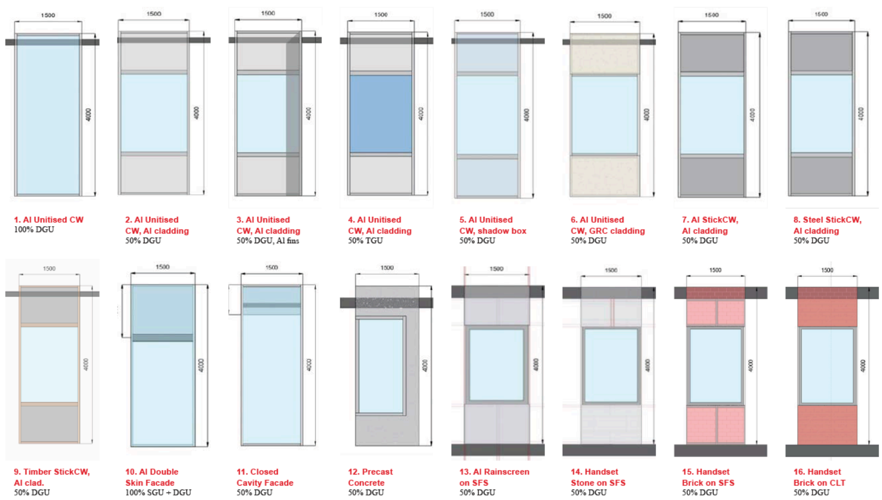

Figure 4.1. 16 facade typologies selected by Arup and Saint Gobain Glass to represent the breath of European and UK facade design [5]

The same dimension of the bay (4000 mm x 1500 mm) is considered with different window to wall ratios at which different materials for the opaque parts are applied.

The embodied carbon over the whole life cycle of these facades were studied and below the results are shown.

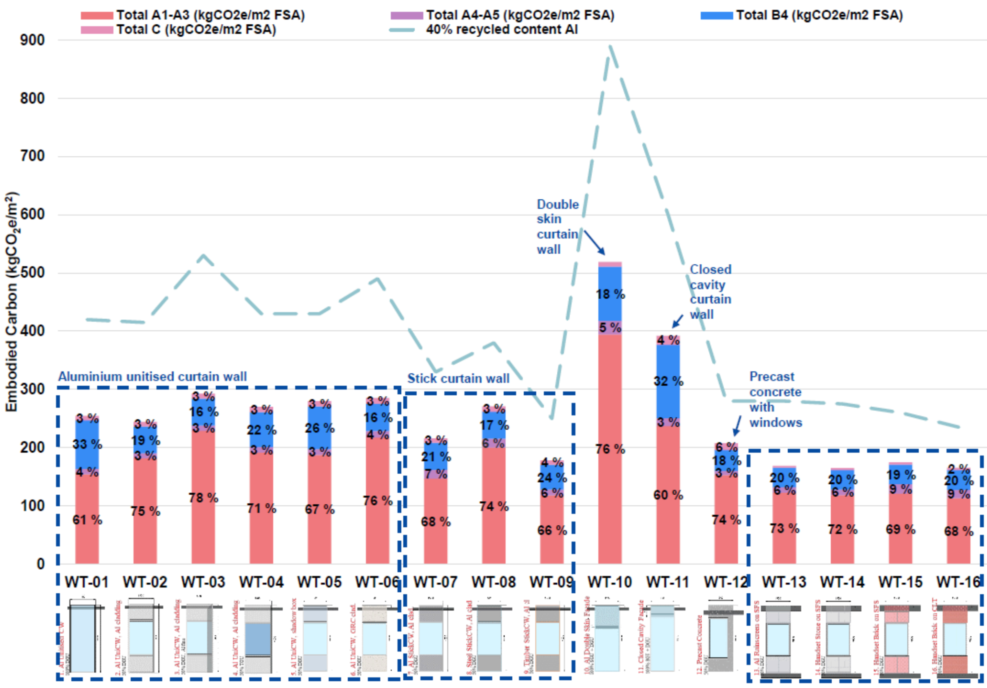

Figure 4.2. Embodied Carbon per stage [5]

From this graph it is clear which are the phases of facades life cycle that have a major impact on their embodied carbon. In fact, stages regarding production (A1-A3) and replacement (B4) are the most emissive ones, while the others have a relative negligible impact. For this reason, this study will focus on the phases of production and replacement to investigate solutions to reduce their emissions.

To go deep in details, after having understand the life cycle phases to analyze, the sixteen facades embodied carbon is now evaluated considering the contribution of each material.

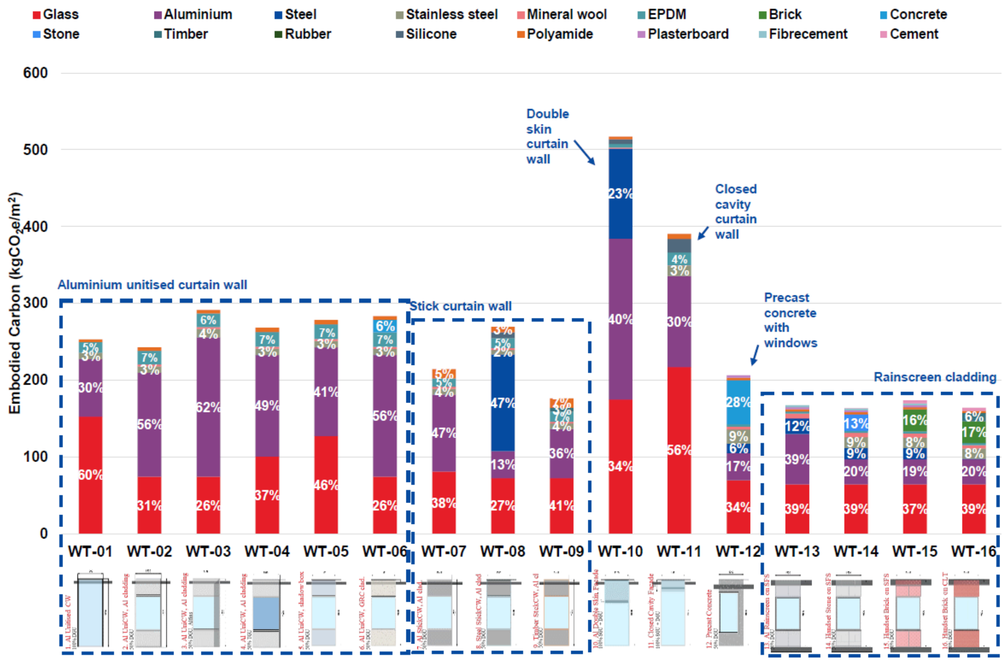

Figure 4.3. Embodied carbon by material [5]

Hence the materials that clearly give the major contributions to embodied carbon are aluminium, steel and glass. If glass is obviously used in the transparent part of the facade, the next graph shows where aluminium and steel are mostly employed.

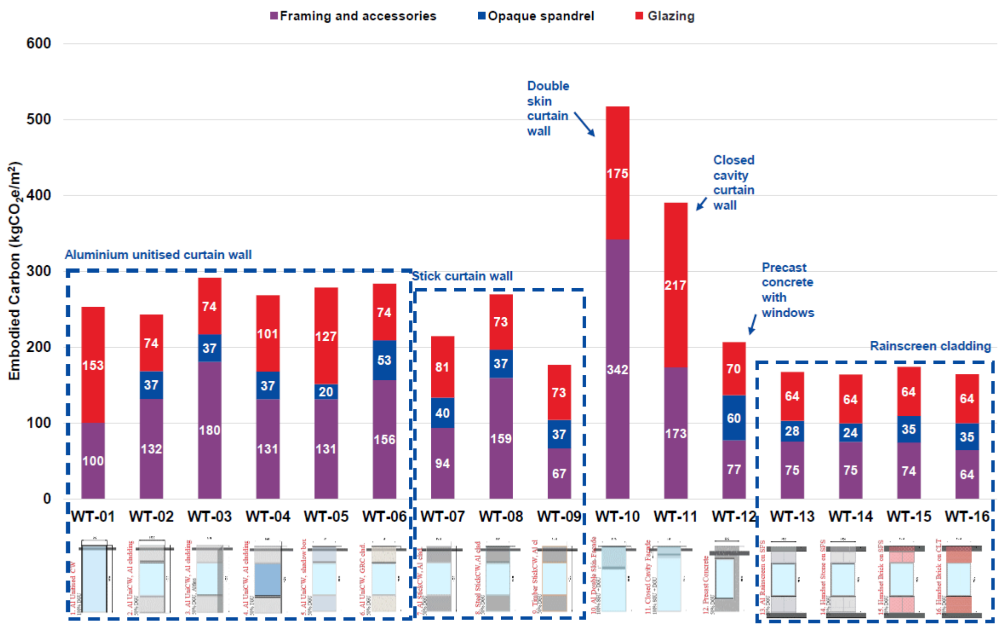

Figure 4.4. Embodied carbon by framing, opaque spandrels and glazing [5]

Analyzing this graph, the framing and its accessories plays a main role in embodied carbon emissions. This means that to reduce significantly the embodied carbon of glazing facade, an intervention should be done trying to replace the aluminium of the frame system with other less emissive materials. For this reason the next chapter will focus on alternative materials for frame and their impact. Moreover, also a focus on materials used in the opaque part of the facade is done.

Very similar results to the ones of ARUP and Saint Gobain Glass are given by the study of the glazing facade projects by Permasteelisa [15].

The following ones are the analyzed projects.

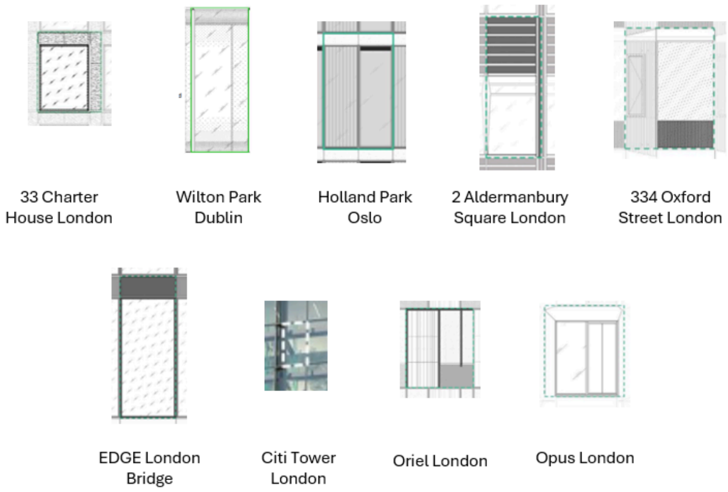

Figure 4.5. Facade of the projects by Permasteelisa considered in the analysis

Even if in this case the considered bays have not the same dimensions and regular window to wall ratio, the following ones are the obtained results after having applied a LCA analysis to these projects.

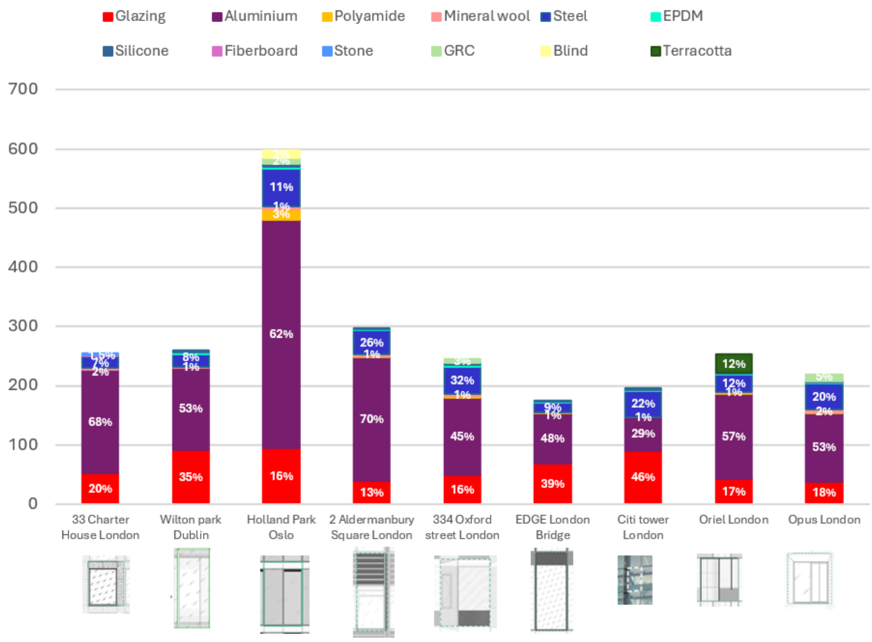

Figure 4.6. Embodied carbon by material

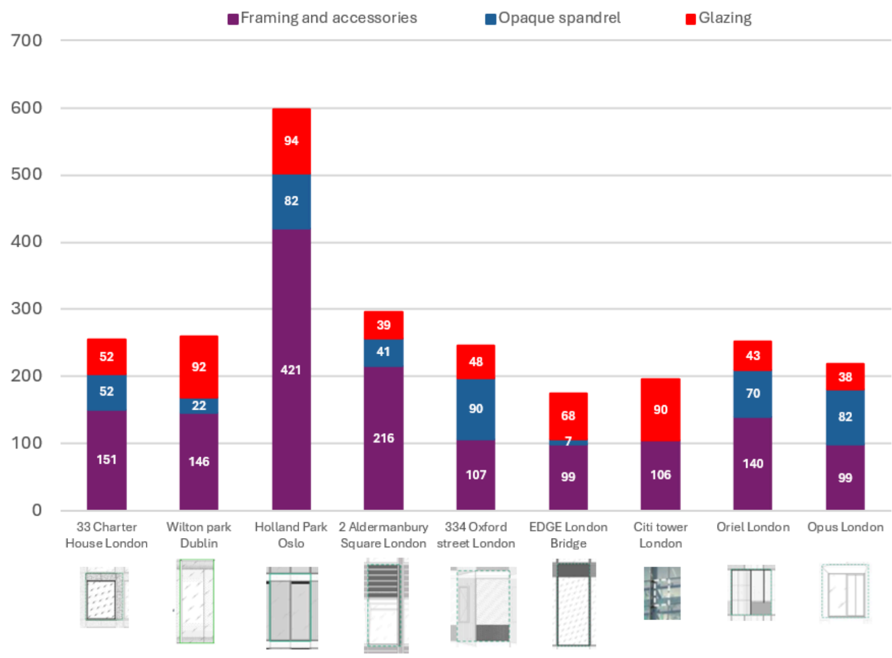

Figure 4.7. Embodied carbon by framing, opaque spandrels and glazing

Again the main contribution to embodied carbon is given by the aluminium that is mainly used for the facade frame. So the analysis of these real projects highlights one more time the importance of acting on the frame to reduce its emissions.

Furthermore, Arup and Saint Gobain Glass [5] investigated also the influence that other different design decisions have on the embodied carbon emissions of facades.
First of all the influence of the window to wall ratio was examined.
In general as the window to wall ratio increases the upfront embodied carbon (A1-A3) decreases. This happens because glazing has a lower embodied carbon with respect to the opaque components. So there is a linear relationship between the decreasing of the opaque area and the reduction in embodied carbon [5]. But if the other stages of LCA are considered, in particular stage B4 regarding the replacement of glass, the embodied carbon increases [5] because glass should be replaced at least once along the service life of a facade.
Moreover, the window to wall ratio should be considered also with respect to the operational carbon. In fact if the window to wall ratio increases, the operational carbon also increases because glazing components have a lower thermal insulation ability compared to opaque components [5]. So both the decreasing of embodied carbon and the increasing of operational carbon should be considered to find the right equilibrium for each facade system.
As another parameter, also the dimension of the bay is considered. Arup and Saint Gobain Glass tried to vary its the dimension, increasing it, to see the variation in trend of

embodied carbon with increasing window to wall ratio.

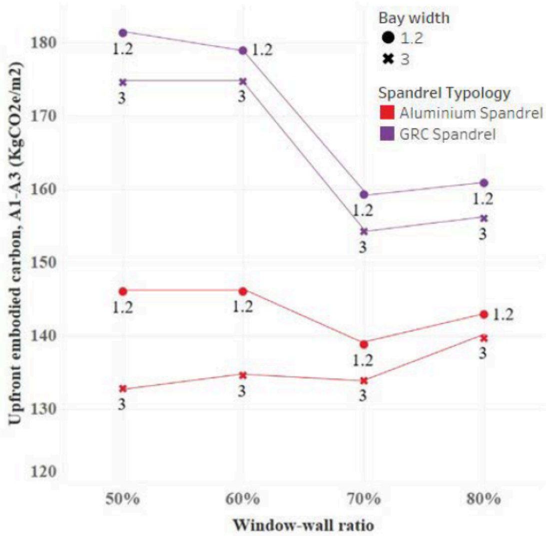

Figure 4.8. Four simulations showing variation in trend of embodied carbon with increasing WWR [5]

So from the graph it is possible to see how for the aluminium spandrel there is no significantly reduction in embodied carbon by varying the window to wall ratio, while for the GRC spandrel there is a great decreasing in embodied carbon while increasing the window to wall ratio.

Hence, as a conclusion of their studies, Arup and Saint Gobain Glass state the importance of design choices from the very beginning of the design process as well as the increasing of the IGU service life to reduce the whole life carbon of facades. Especially this second topic will be explored in the following chapters.

Chapter 5

Production: stage A1-A3

In this chapter the embodied carbon regarding the production stage of a glazing facade is developed. The three modules in LCA concerning this topic includes raw material supply, transport from extraction to production site, and manufacturing. These stages will be analyzed taking into account the three main components of a glazing facade: insulated glass unit, frame and opaque components for those facades having a window to wall ratio less than 100%. Furthermore, the embodied carbon will be calculated considering two different dimensions of the bay: 4000 mm x 1500 mm and 4000 mm x 3000 mm; and three different configurations of wind acting on them: 1 kPa, 2 kPa and 4 kPa. Then for each combination different materials for frame and the transparent and opaque part will be explored. All the calculations about the transparent part of the facade and the frame are performed in compliance with the Eurocode 1 [13] and the standards UNI CEN/TS 19100 [11] and UNI EN 13830 [12].

5.1 Insulated Glass Unit

As regards the insulated glass unit, it is modeled considering 100% WWR, this means a facade completely transparent. The necessary configuration and thickness of the IGU is calculated and verified with the tool glassAdvisor considering the two dimensions of the bay in the three configurations of wind acting on it in both pressure and depression. Together with the wind load, climatic loads are also considered: +600 m of altitude, +20 °C of temperature, and +4 kPa of pressure. In fact for IGUs, loads can be applied from both faces and also internal loads can occur. Furthermore, all loads that are applied to one or the other face, are shared by all panes thanks to the phenomenon called load sharing for which the load is carried by all panes depending on the stiffness. As regards particularly climatic loads, they are internal loads due to changes in weather conditions such as temperature, pressure and altitude. Each one of this change has a specific effect on the IGU as represented by the following image.

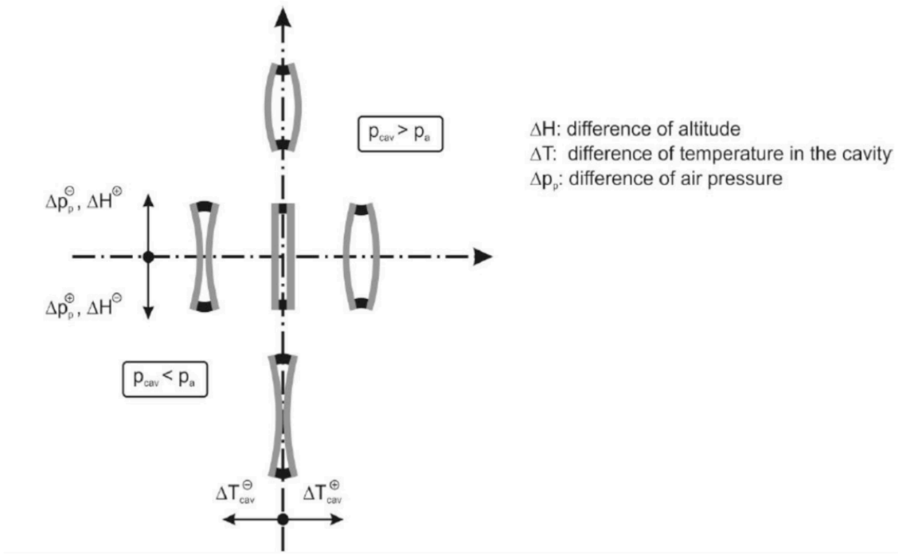

Figure 5.1. Effects of climatic loads on the IGU

Hence, we have two configurations of climatic loads that give the worst effects on the IGU:

- decreasing in temperature + decreasing in altitude + increasing in pressure
- increasing in temperature + increasing in altitude + decreasing in temperature

Therefore, considering all the specified loads, stress and deflection are checked at both ultimate and serviceability limit state by glassAdvisor in compliance with the standard EN16612 [9].
For performing the verifications, the IGU should be designed on glassAdvisor entering in the software all its layers.

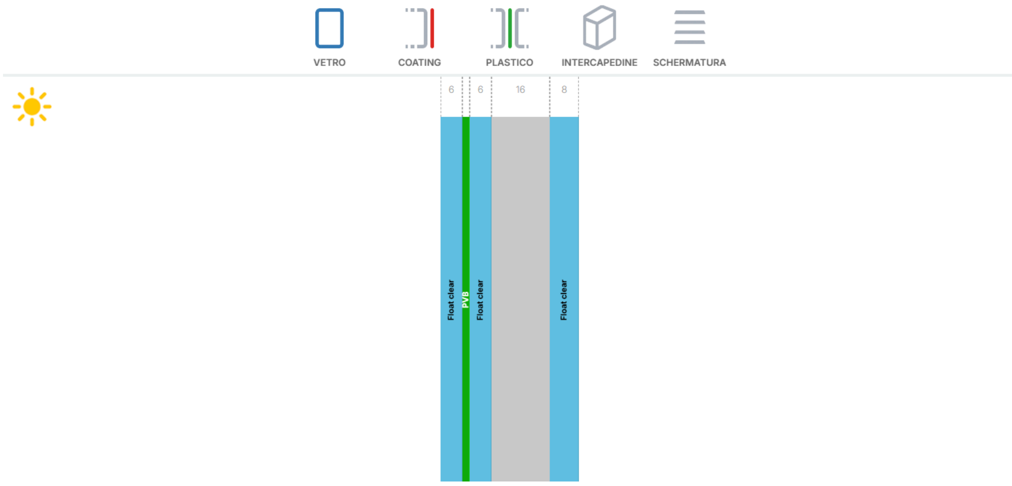

Figure 5.2. IGU design

After having design the IGU, all loads acting on it should be inserted and the verifications are performed.

Figure 5.3. Wind load data to insert

Figure 5.4. Climatic loads data to insert

The following are the obtained dimensions of the double glazing unit considering all the variables explained before.
After knowing the necessary thickness of glass, the kg of material per m^2 of facade are calculated considering the glass density equal to 2400 kg/m^3. Then through that value is possible to calculate the kg of CO_2e per m^2 of facade for which glass is responsible by multiplying the value expressed in kg/m^2 for the ECF of glass (1.62). In this way the embodied carbon associated with glass is obtained.

- For bay dimension 4000 mm x 1500 mm and 1 kPa of wind load:

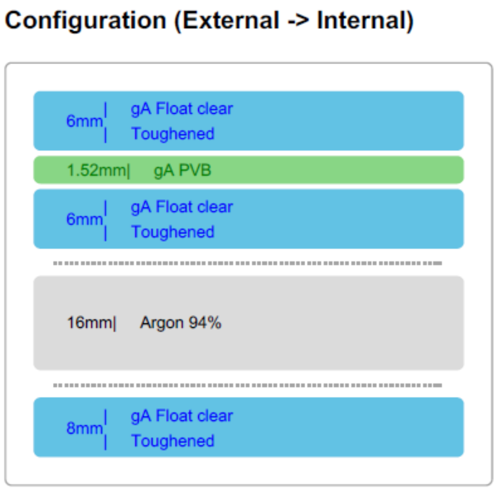

Figure 5.5. Configuration IGU

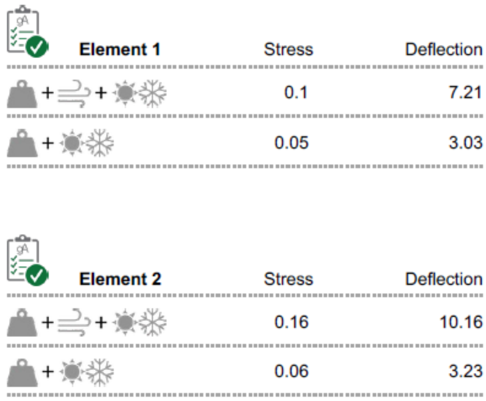

Figure 5.6. Verification for deflection and stress

The total thickness of glass to fulfill both the verification regarding stress and deflection is 20 mm. Considering that thickness 48 kg/m^2 are obtained that corresponds to 77.76 $kgCO_2e/m^2$.

- For bay dimension 4000 mm x 1500 mm and 2 kPa of wind load:

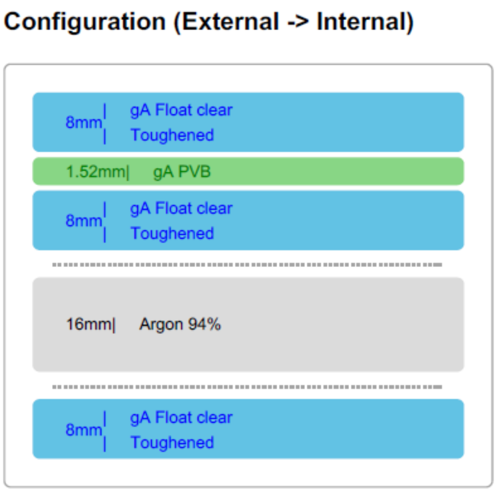

Figure 5.7. Configuration IGU

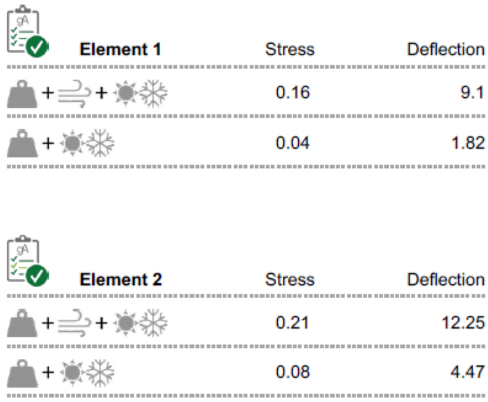

Figure 5.8. Verification for deflection and stress

The total thickness of glass to fulfill both the verification regarding stress and deflection is 24 mm. Considering that thickness 57.6 kg/m^2 are obtained that corresponds to 93.31 $kgCO_2e/m^2$.

- For bay dimension 4000 mm x 1500 mm and 4 kPa of wind load:

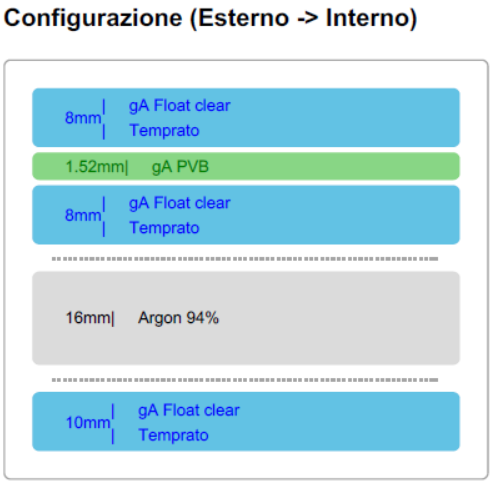

Figure 5.9. Configuration IGU

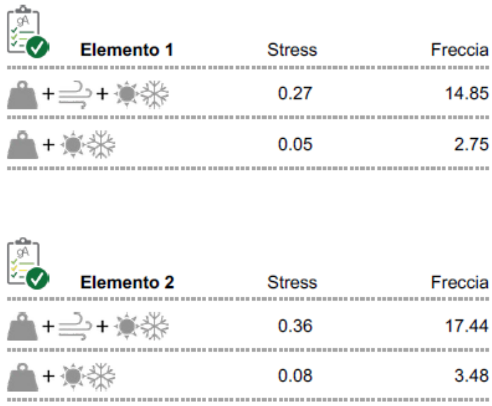

Figure 5.10. Verification for deflection and stress

The total thickness of glass to fulfill both the verification regarding stress and deflection is 26 mm. Considering that thickness 62.4 kg/m^2 are obtained that corresponds to 101.09 $kgCO_2e/m^2$.

- For bay dimension 4000 mm x 3000 mm and 1 kPa of wind load:

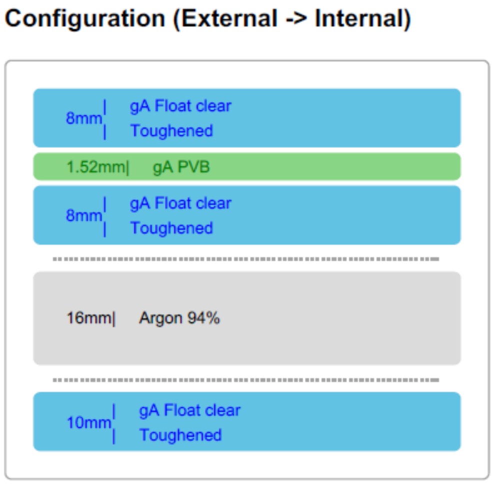

Figure 5.11. Configuration IGU

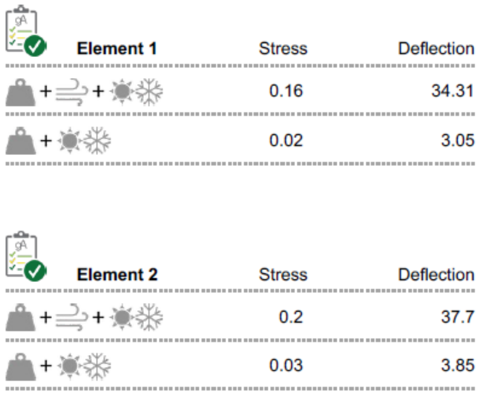

Figure 5.12. Verification for deflection and stress

The total thickness of glass to fulfill both the verification regarding stress and deflection is 26 mm. Considering that thickness 62.4 kg/m^2 are obtained that corresponds to 101.09 $kgCO_2e/m^2$.

- For bay dimension 4000 mm x 3000 mm and 2 kPa of wind load:

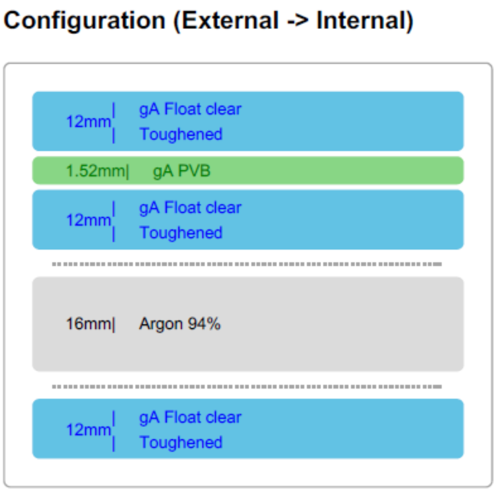

Figure 5.13. Configuration IGU

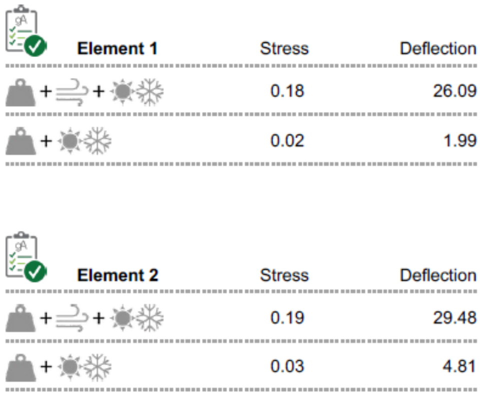

Figure 5.14. Verification for deflection and stress

The total thickness of glass to fulfill both the verification regarding stress and deflection is 36 mm. Considering that thickness 86.4 kg/m^2 are obtained that corresponds to 139.97 kgCO_2e/m^2.

- For bay dimension 4000 mm x 3000 mm and 4 kPa of wind load:

Figure 5.15. Configuration IGU

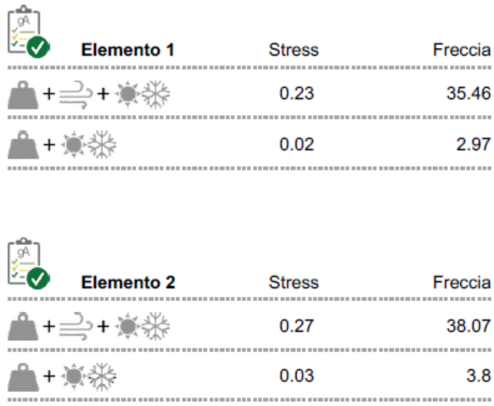

Figure 5.16. Verification for deflection and stress

The total thickness of glass to fulfill both the verification regarding stress and deflection is 60 mm. Considering that thickness 144 kg/m^2 are obtained that corresponds to 233.28 kgCO_2e/m^2.

To resume the obtained results regarding the IGU:

bay dimensions	1 kPa	2 kPa	4 kPa
4000x1500	77.76 kgCO_2e/m^2	93.31 kgCO_2e/m^2	101.91 kgCO_2e/m^2
4000x3000	101.91 kgCO_2e/m^2	139.97 kgCO_2e/m^2	233.28 kgCO_2e/m^2

Table 5.1. Carbon emissions of IGU per square meter of facade

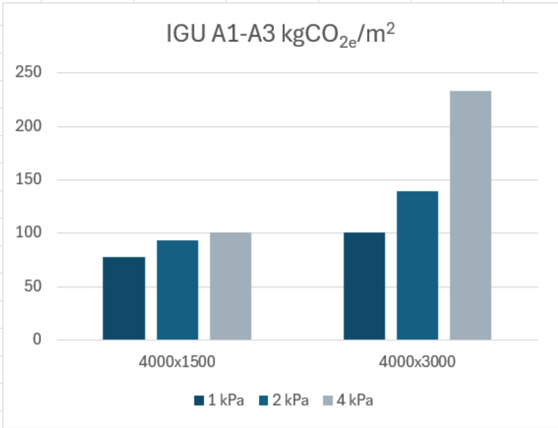

Figure 5.17. Stages A1-A3 for IGU

The embodied carbon increases almost constantly with the intensifying wind load acting on the double glazing unit. This trend is interrupted only for the wind load of 4 kPa on the bay 4000 mm x 3000 mm, where the embodied carbon spreads to much higher values with respect to the previous configuration. In fact to withstand this magnitude of load, considering the greatness of the bay, the thickness of the IGU increases a lot, and with that also its emissions.

Since the obtained results reveal the great impact of glass, to reduce it, the calculations are performed again considering a low-carbon glass, that means a glass with a percentage of recycled glass inside manufactured in plants that implement decarbonization strategies, such as the reduction in the use of fossil fuels to produce energy.
What changes in terms of embodied carbon is the ECF used in the analysis. In fact, glass has an ECF of 1.62; while 1.2 is the one of low-carbon glass obtained from EPDs. So below are shown how the results change if the same procedure as before is used for calculating the embodied carbon related with the IGU.

bay dimensions	1 kPa	2 kPa	4 kPa
4000x1500	57.6 $kgCO_2e/m^2$	69.12 $kgCO_2e/m^2$	74.88 $kgCO_2e/m^2$
4000x3000	74.88 $kgCO_2e/m^2$	103.68 $kgCO_2e/m^2$	172.8 $kgCO_2e/m^2$

Table 5.2. Carbon emissions of IGU with recycled glass per square meter of facade

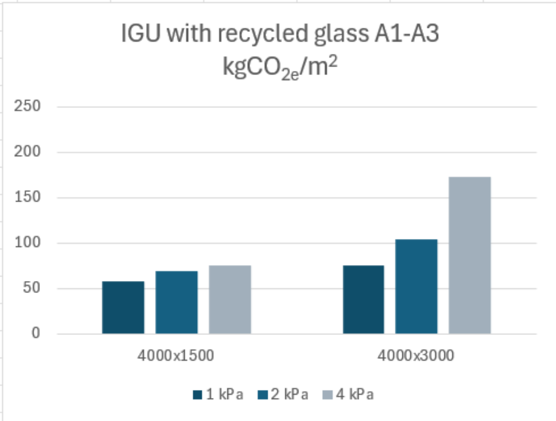

Figure 5.18. Stages A1-A3 for IGU with recycled glass

Using a low-carbon glass the embodied carbon decreases of almost 26% for all configurations. The greatest impact of using a low-carbon glass is for bay 4000 mm x 3000 mm with 4 kPa of wind acting on it. In fact, even if the glass is much thicker than the other cases, the use of this material reduces the emissions a lot, also making this configuration not as emissive as before.

5.2 Frame

The embodied carbon of frame is calculated considering four different materials and the same three configurations of wind considered for the IGU. The tested materials are aluminium, recycled aluminium, GFRP and laminated timber.
All frames are calculated without considering the behavior under fire of the materials themselves for being comparable among them. This means that for aluminium and recycled aluminium in the embodied carbon is not considered the impact of the fire protection coating that is generally applied to those structures to meet fire-resistance ratings. The same approach is used for GFRP frames, where fire-retardant resins or fire protection layers that are usually applied to their surface to protect them against fire, are not considered. While for laminated timber frame the verifications specifically regarding fire resistance are not performed, therefore the considered sections could be smaller than the ones really needed to meet those requirements.
To know the impact of each frame system, firstly structural analysis and verifications should be performed to obtain the sections of mullions and transoms needed in the facade to withstand the loads.
The following properties are considered in the calculation for the selected materials.

Material	Young modulus (E)	R_p,0	γ_m
Aluminium	70000 MPa	190 MPa	1.1
Recycled aluminium	70000 MPa	150 MPa	1.1
GFRP	50000 MPa	800 MPa	1.6
Laminated timber (GL28h)	12600 MPa	19 MPa	1.25

Table 5.3. Material properties

Furthermore, the verifications are also performed for the two dimensions of the bay (4000 mm x 1500 mm and 4000 mm x 3000 mm).

e are the considered sections to calculate: for aluminium, recycled aluminium and GFRP an hollow section is considered, while for laminated timber a solid one is taken into account.

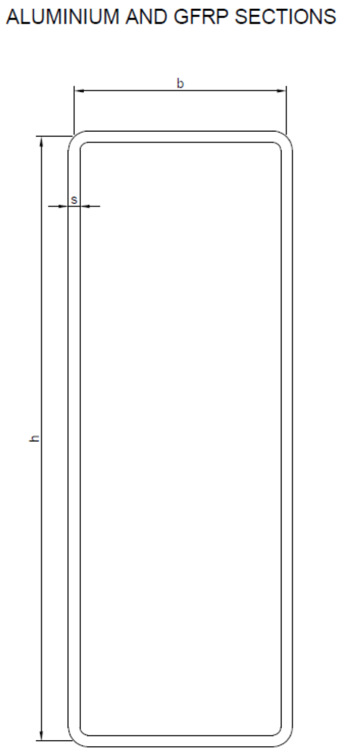

Figure 5.19. Typical section for aluminium, recycled aluminium and GFRP

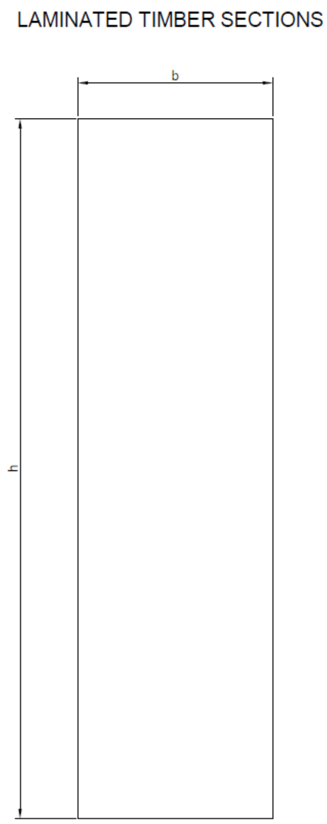

Figure 5.20. Typical section for laminated timber

Firstly, the verification for the mullion is carried out.
For the mullion only the wind load is considered. The wind acts on it with a trapezoidal

shape, but for simplification, a rectangular one is considered. The doubled of the wind magnitude is taken into account in the calculation in order to considered the two mullions of the bay at once.

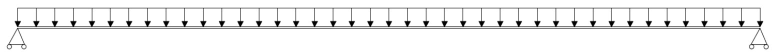

Figure 5.21. Schematization of wind load on the mullion

So the values of wind load used in the calculation are 1.5 N/mm, 3 N/mm and 6 N/mm for a bay of 4000 mm x 1500 mm; while for a bay of 4000 mm x 3000 mm are 3 N/mm, 6 N/mm and 12 N/mm. The section of mullion is verified with two checks regarding deflection and bending moment.
As regards the first check the the maximum deflection due to the load should be lower than the allowed one.
This means:

$$f_{max} = \frac{5}{384}\frac{ql^4}{EI_x} < f_{all} = \left(\frac{H}{300}\right) + 5 \tag{5.1}$$

Where:
f_{max} is the deflection due to load
f_{all} is the maximum allowed deflection
q is the wind load
l is length of the mullion
E is the Young modulus
I_x is the moment of inertia
H is height of the bay

Regarding the second check, the resistant bending moment should be greater than the design bending moment.
This means:

$$M_{Ed} = \frac{ql^2}{8} < M_{Rd} = R_{p,0}\frac{W_x}{\gamma_m} \tag{5.2}$$

Where:
M_{Ed} is the design bending moment
M_{Rd} is the resistant bending moment
q is the wind load
l is the length of the mullion
$R_{p,0}$ is the resistance of the material
W_x is the section modulus
γ_m is the material safety factor

The section of the mullion that satisfies these two verifications is the one used in the facade.

Then the transoms are checked.
For transoms three loads are considered: wind load, glass load and dead load of the section itself. For this verification the wind load is considered as acting on the transoms with a triangular shape where the maximum value is considered for calculation, while the glass load is a punctual load and the dead load a distributed one. As before, wind load is considered doubled to take into account the two transoms of the bay at once.

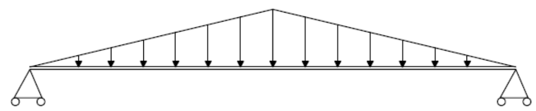

Figure 5.22. Schematization of wind load on the transom

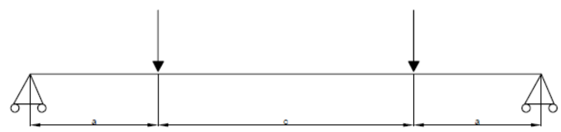

Figure 5.23. Schematization of punctual glass load on the transom

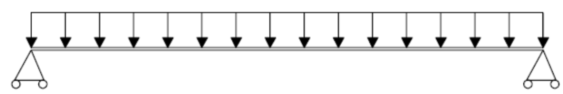

Figure 5.24. Schematization of distributed dead load on the transom

Dead load changes based on the considered section but wind load and glass load are constant for the considered configurations and below are the values.
For bay 4000 mm x 1500 mm:

Wind load	Glass load
0.004 N/mm	1411.2 N
0.008 N/mm	1693.44 N
0.016 N/mm	1834.56 N

Table 5.4. Wind and glass load for bay 4000 mm x 1500 mm

For bay 4000 mm x 3000 mm:

Wind load	Glass load
0.0053 N/mm	3669.12 N
0.011 N/mm	5080.32 N
0.021 N/mm	8467.2 N

Table 5.5. Wind and glass load for bay 4000 mm x 3000 mm

Considering these loads, the deflection and section are checked for both the strong and weak axes to determine the transom section to use in the facade.
As regards the strong axis in the deflection verification, the maximum deflection due to loads should be lower than the allowed one.
This means:

$$f_{max} = \frac{1}{120}\frac{ql^4}{EI_x} < f_{all} = \frac{B}{200} \tag{5.3}$$

Where:
f_{max} is the maximum deflection due to loads
f_{all} is the maximum allowed deflection
q is the wind load
l is the length of the transom
E is the Young modulus of the material
I_x is the modulus of inertia
B is the base of the bay

While as regards the section check, the resistant bending moment should be greater than the design bending moment.
This means:

$$M_{Ed} = 1.5\frac{ql^2}{12} < M_{Rd} = R_{p,0}\frac{W_x}{\gamma_m} \tag{5.4}$$

Where:
M_{Ed} is the design bending moment
M_{Rd} is the resistant bending moment
q is the wind load
l is the length of transom
$R_{p,0}$ is the material resistance
W_x is the section modulus
γ_m is the material safety factor

Deflection and section are checked for the weak axis as well as for the strong axis.
For the deflection verification the maximum deflection due to the summation of the deflections caused by glass load and dead load should be lower than the maximum allowed

deflection.
This means:

$$f_{max} = f_{max,P} + f_{max,DL} < f_{all} \tag{5.5}$$

Where:

$$f_{max} = q_P \cdot a \frac{3 \cdot c^2 - 4 \cdot a^4}{24 \cdot EI_y} + \frac{5}{384} \frac{q_{DL} l^4}{EI_y} < f_{all} = min(\frac{B}{500}; 3) \tag{5.6}$$

Where:
q_P is the glass load
a is the distance between the end of the transom and the punctual load
c is the distance between two consecutive punctual loads
E is the Young modulus of the material
I_y is the modulus of inertia
q_{DL} is the dead load
l is the length of the transom
B is the base of the bay

While as regards the section check, the resistant bending moment should be greater than the design bending moment.
This means:

$$M_{Ed} = 1.35 \cdot q_P \cdot a + 1.35 \cdot \frac{q_{DL} l^2}{8} < M_{Rd} = R_{p,0} \frac{W_y}{\gamma_m} \tag{5.7}$$

Where:
M_{Ed} is the design bending moment
M_{Rd} is the resistant bending moment
q_P is the glass load
a is the distance between the end of the transom and the punctual load
q_{DL} is the dead load
$R_{p,0}$ is the resistance of the material
W_y is the section modulus
γ_m is the material safety factor

Once these four checks are all verified, a biaxial moment check is performed.
This means:

$$\frac{M_{Ed,x}}{M_{Rd,x}} + \frac{M_{Ed,y}}{M_{Rd,y}} < 1 \tag{5.8}$$

Performing all these verifications, the following ones are the obtained dimensions of the mullions and transoms sections.
For the bay 4000 mm x 1500 mm:

	Aluminium									
	mullion					transom				
	b	h	s	kg/m	kg/m^2	b	h	s	kg/m	kg/m^2
1 kPa	58 mm	160 mm	3 mm	3.43	2.29	40 mm	70 mm	3 mm	1.68	0.42
2 kPa	75 mm	200 mm	3 mm	4.36	2.91	40 mm	70 mm	3 mm	1.68	0.42
4 kPa	95 mm	250 mm	3 mm	5.49	3.66	40 mm	70 mm	3 mm	1.68	0.42

Table 5.6. Aluminium sections

	Recycled Aluminium									
	mullion					transom				
	b	h	s	kg/m	kg/m^2	b	h	s	kg/m	kg/m^2
1 kPa	60 mm	160 mm	3 mm	3.47	2.31	40 mm	80 mm	3 mm	1.84	0.46
2 kPa	80 mm	200 mm	3 mm	4.44	2.96	40 mm	80 mm	3 mm	1.84	0.46
4 kPa	100 mm	250 mm	3 mm	5.57	3.72	40 mm	80 mm	3 mm	1.84	0.46

Table 5.7. Recycled aluminium sections

	GFRP									
	mullion					transom				
	b	h	s	kg/m	kg/m^2	b	h	s	kg/m	kg/m^2
1 kPa	80 mm	160 mm	4 mm	3.34	2.23	40 mm	80 mm	4 mm	1.61	0.40
2 kPa	100 mm	200 mm	4 mm	4.20	2.80	40 mm	80 mm	4 mm	1.61	0.40
4 kPa	125 mm	250 mm	4 mm	5.28	3.52	40 mm	80 mm	4 mm	1.61	0.40

Table 5.8. GFRP sections

	Laminated Timber							
	mullion				transom			
	b	h	kg/m	kg/m^2	b	h	kg/m	kg/m^2
1 kPa	50 mm	180 mm	3.46	2.31	50 mm	140 mm	2.70	0.67
2 kPa	60 mm	220 mm	5.08	3.39	50 mm	160 mm	3.08	0.77
4 kPa	80 mm	260 mm	8.01	5.34	60 mm	180 mm	4.16	1.04

Table 5.9. Laminated timber sections

For the bay 4000 mm x 3000 mm:

	Aluminium									
	mullion					transom				
	b	h	s	kg/m	kg/m^2	b	h	s	kg/m	kg/m^2
1 kPa	75 mm	200 mm	3 mm	4.36	1.45	95 mm	190 mm	3 mm	4.52	1.13
2 kPa	95 mm	250 mm	3 mm	5.49	1.83	105 mm	210 mm	3 mm	5.01	1.25
4 kPa	145 mm	300 mm	3 mm	7.11	2.37	120 mm	250 mm	3 mm	5.90	1.47

Table 5.10. Aluminium sections

	Recycled Aluminium									
	mullion					transom				
	b	h	s	kg/m	kg/m^2	b	h	s	kg/m	kg/m^2
1 kPa	80 mm	200 mm	3 mm	4.44	1.48	100 mm	200 mm	3 mm	4.76	1.19
2 kPa	100 mm	250 mm	3 mm	5.57	1.86	110 mm	220 mm	3 mm	5.25	1.31
4 kPa	150 mm	300 mm	3 mm	7.19	2.40	125 mm	250 mm	3 mm	5.98	1.49

Table 5.11. Recycled aluminium sections

	GFRP									
	mullion					transom				
	b	h	s	kg/m	kg/m^2	b	h	s	kg/m	kg/m^2
1 kPa	90 mm	200 mm	4 mm	4.06	1.35	100 mm	200 mm	4 mm	4.20	1.05
2 kPa	120 mm	250 mm	4 mm	5.21	1.74	110 mm	220 mm	4 mm	4.64	1.16
4 kPa	150 mm	310 mm	4 mm	6.51	2.17	130 mm	260 mm	4 mm	5.50	1.38

Table 5.12. GFRP sections

	Laminated Timber							
	mullion				transom			
	b	h	kg/m	kg/m^2	b	h	kg/m	kg/m^2
1 kPa	65 mm	200 mm	5.01	1.67	90 mm	280 mm	9.70	2.43
2 kPa	80 mm	250 mm	7.7	2.57	100 mm	300 mm	11.55	2.89
4 kPa	105 mm	320 mm	12.94	4.31	110 mm	350 mm	14.82	3.71

Table 5.13. Laminated timber sections

The obtained kg/m^2 of each material for each configuration are multiplied for the corresponding ECF, and the embodied carbon is obtained for all cases.

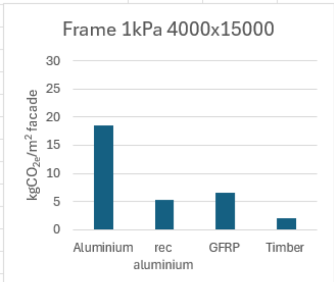

Figure 5.25. Embodied carbon of frame with 1 kPa of wind acting on it

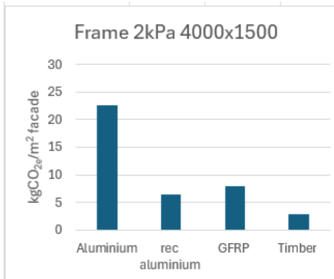

Figure 5.26. Embodied carbon of frame with 2 kPa of wind acting on it

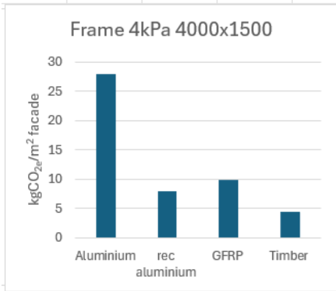

Figure 5.27. Embodied carbon of frame with 4 kPa of wind acting on it

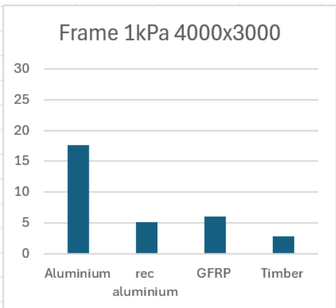

Figure 5.28. Embodied carbon of frame with 1 kPa of wind acting on it

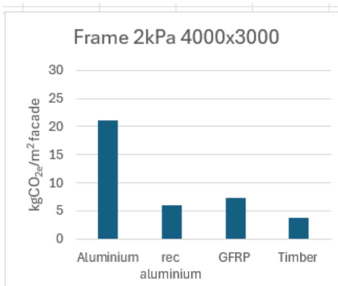

Figure 5.29. Embodied carbon of frame with 2 kPa of wind acting on it

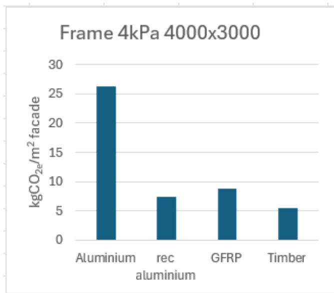

Figure 5.30. Embodied carbon of frame with 4 kPa of wind acting on it

For all bay configurations and dimensions, the aluminium frame is the one with the highest embodied carbon emissions, followed by the GFRP. While recycled aluminium and laminated timber have the lowest emissions. This happens because even if these two last materials have larger sections to withstand loads due to their lower resistances, their ECFs are much lower. This reduces the contribution to embodied carbon.

5.3 Opaque

The embodied carbon contribution of opaque components is evaluated in the 50% WWR configuration. Three different materials are considered for this part of the facade: GRC, aluminium and stone. They are not only the most used materials in this field, but they also represent the ones with the most different impacts among them.
Since for realizing the opaque part of the facade, these materials are used in sheets, the

first step for evaluating their emissions per m^2 of facade is to define their thicknesses and specific weights. All thicknesses and specific weights were assumed by considering EPDs of materials from different manufacturers.

material	thickness	density
GRC	30 mm	2000 kg/m^3
Aluminium	2 mm	2700 kg/m^3
Stone	25 mm	2800 kg/m^3

Table 5.14. Properties of opaque materials

Considering these values, the kg of material per m^2 of facade are defined. This number should be multiplied for the embodied carbon factor of each material and for the percentage of facade that this material occupies (50%) to obtain for each of them their emissions expressed in kg of CO_2e per m^2 of facade.

material	kg/m^2	ECF	emissions
GRC	30 kg/m^2	0.9 $kgCO_2e/kg$	27 $kgCO_2e/m^2$
Aluminium	2,7 kg/m^2	6.58 $kgCO_2e/kg$	17.77 $kgCO_2e/m^2$
Stone	35 kg/m^2	0.08 $kgCO_2e/kg$	2.8 $kgCO_2e/m^2$

Table 5.15. Embodied carbon emissions of opaque components

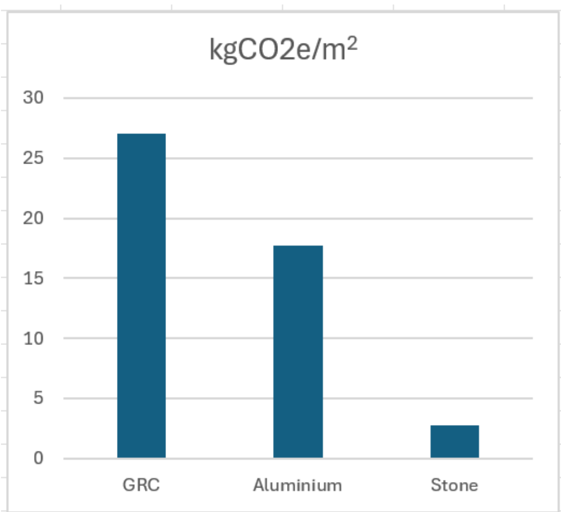

Figure 5.31. Opaque components carbon emissions per m^2 of facade

The obtained results could be surprisingly. In fact aluminium which is the material with the higher embodied carbon factor, is not the material that in the end has the greatest carbon emissions. This happens because even if the ECF of aluminum is much higher than the ECF of GRC, the thickness of aluminum is much lower than that of GRC, which reduces its impact considerably. So, as regards opaque parts of facades, could be useful using aluminium sheets instead of GRC to save embodied carbon emissions. But the best option remains to use materials such as stone with a lower impact thanks to their production process. In fact even if stone sheets have more or less the same thickness of GRC, their ECF is much lower, which brings to approximately 1/10 of emissions.

5.4 Total emissions A1-A3

Since all components of a glazing facade have been discussed for stages A1-A3, now all results are put together to evaluate the total embodied carbon emissions of the facade for this specific module.
Below are shown the results for both facades with 100% window to wall ratio and 50% window to wall ratio.

5.4.1 100% WWR

For the bay 4000 mm x 1500 mm:

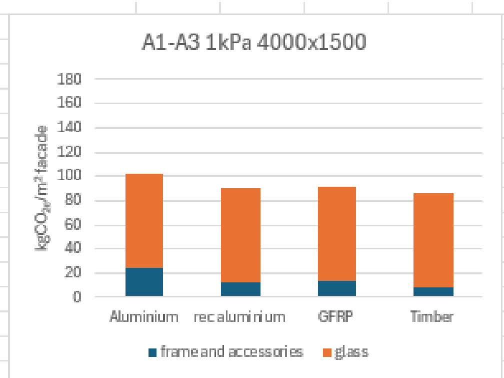

Figure 5.32. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

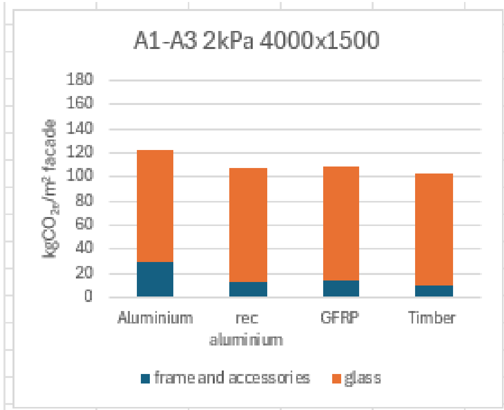

Figure 5.33. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

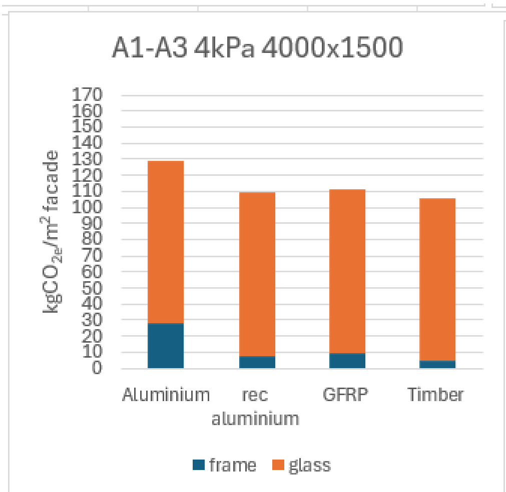

Figure 5.34. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

Also the results considering the low-carbon glass are shown

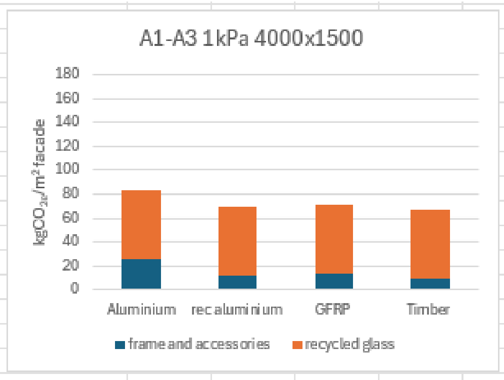

Figure 5.35. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

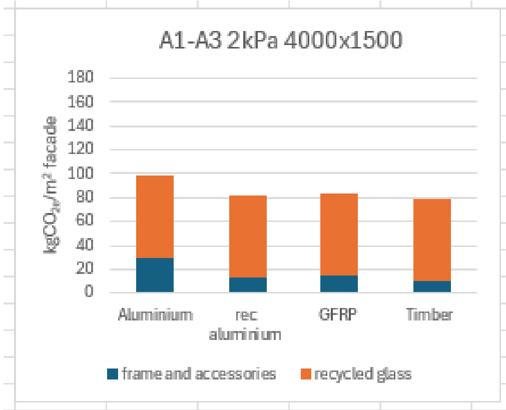

Figure 5.36. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

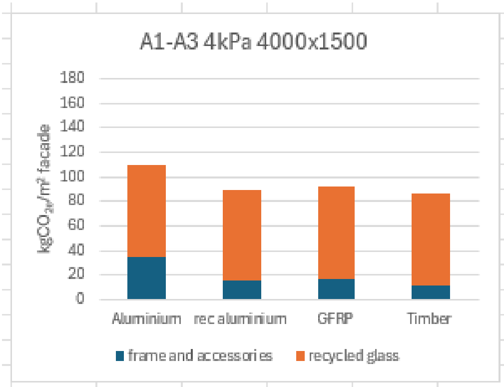

Figure 5.37. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

For the bay 4000 mm x 3000 mm:

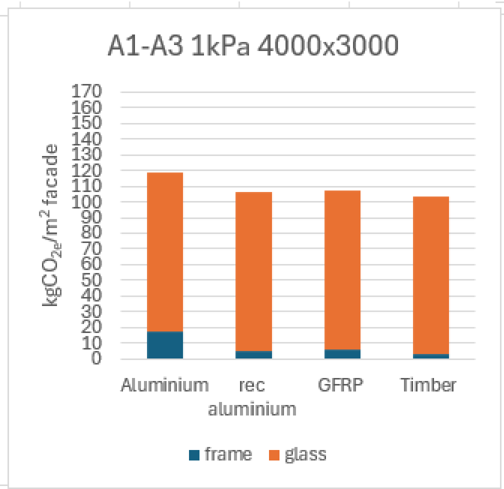

Figure 5.38. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

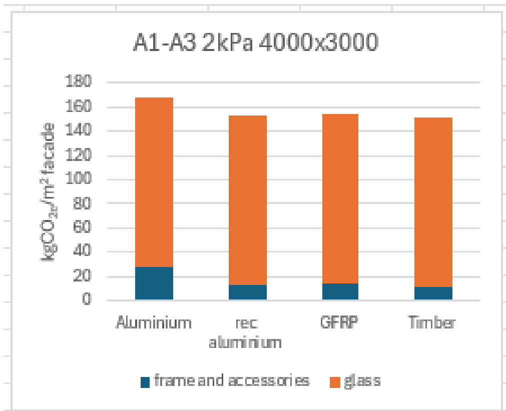

Figure 5.39. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

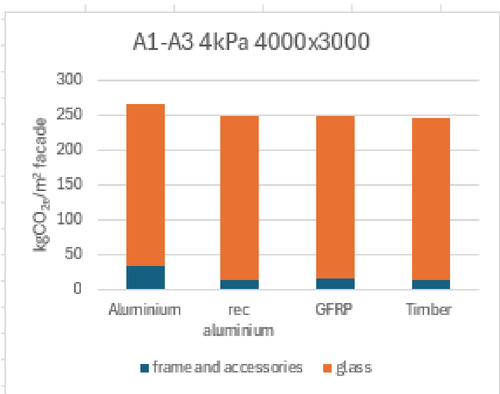

Figure 5.40. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

Also the results considering the low-carbon glass are shown

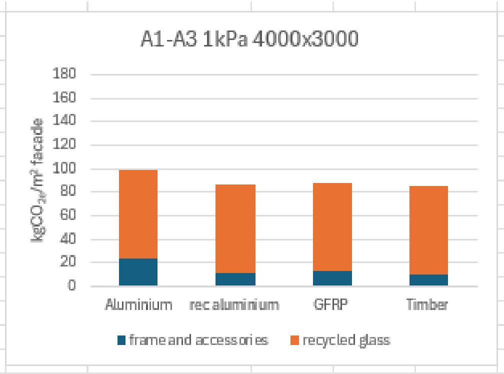

Figure 5.41. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

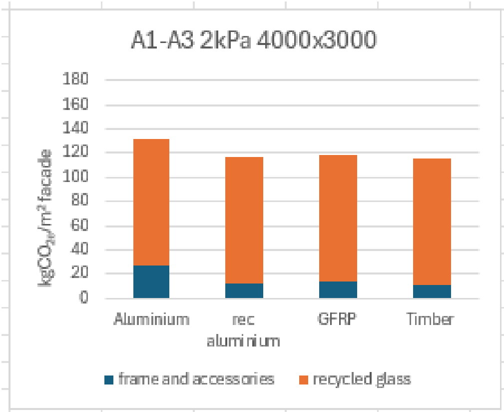

Figure 5.42. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

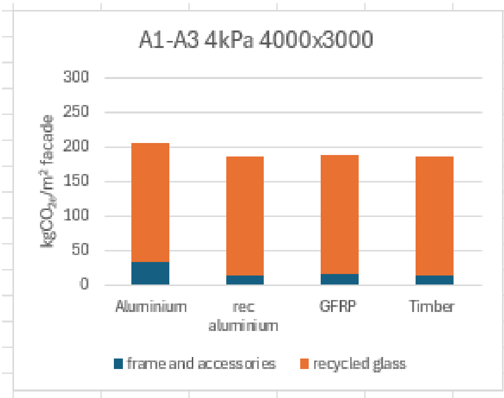

Figure 5.43. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

The main contribution to embodied carbon for stages A1-A3 is represented by glass, which constitutes more than 50% of the emissions in this module. The emissions related to glass are lower if low-carbon glass is considered. In fact, in this case is also possible to appreciate the variation in embodied carbon due to the change in the material for frame. The use of low-carbon glass becomes essential with the increasing of bay dimensions and wind load, since thicker glasses are needed.

5.4.2 50% WWR

Since in this case, the facade is half transparent and half opaque, to obtain the final values of embodied carbon emissions, the results of glass and opaque component expressed in kg/m^2 are multiplied for the percentage of facade they occupy (50%). Then all the

contributions are summed together to obtain the final value of embodied carbon for each facade configuration.
For the bay 4000 mm x 1500 mm:

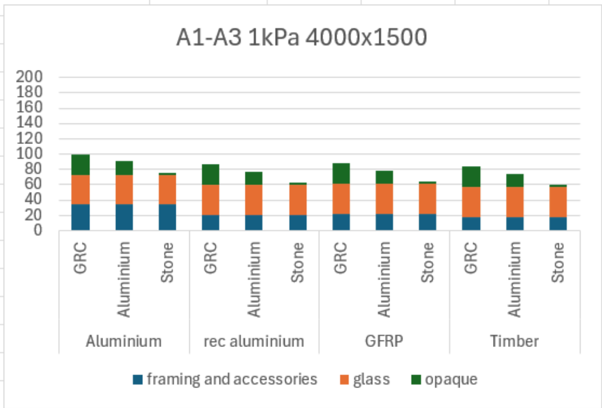

Figure 5.44. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

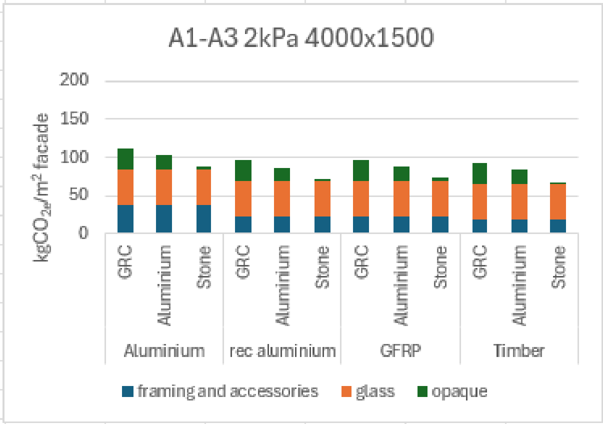

Figure 5.45. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

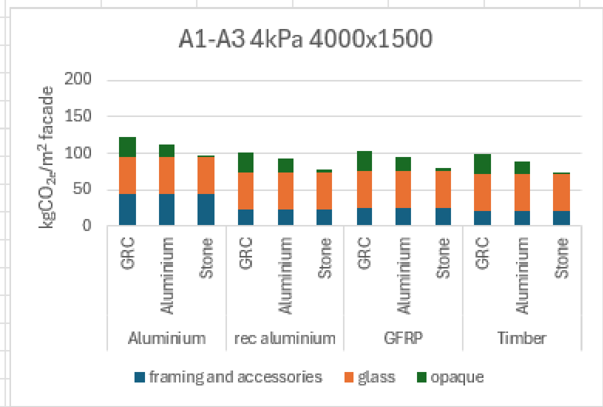

Figure 5.46. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

Also the results considering the low-carbon glass are shown

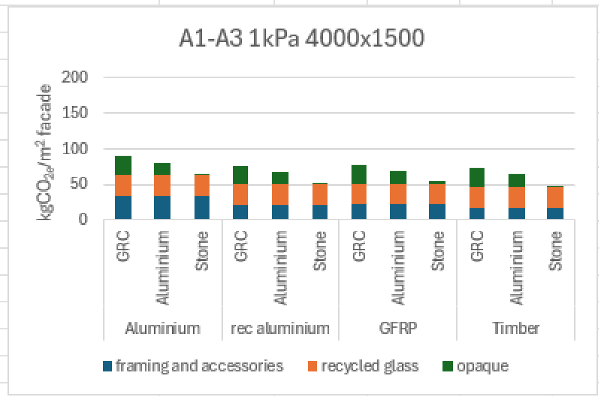

Figure 5.47. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

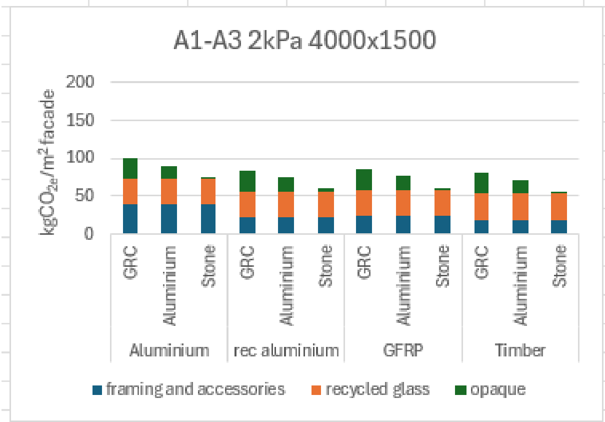

Figure 5.48. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

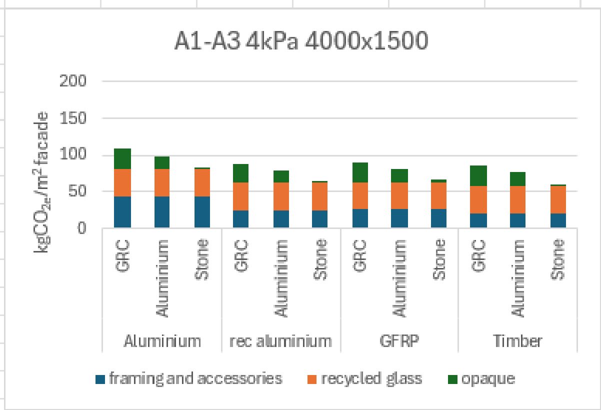

Figure 5.49. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

For the bay 4000 mm x 3000 mm:

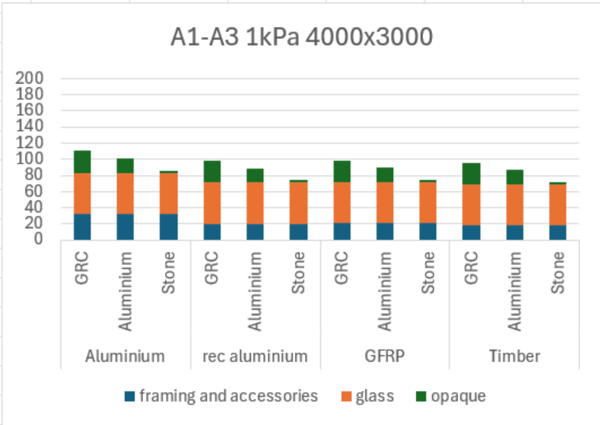

Figure 5.50. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

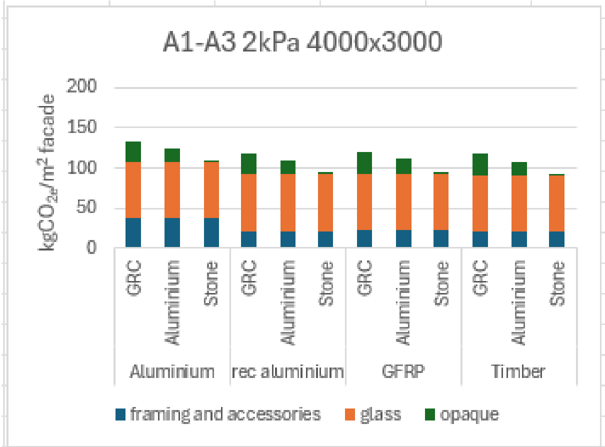

Figure 5.51. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

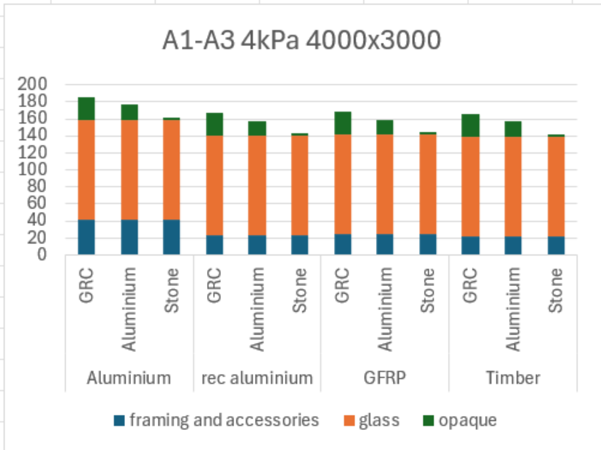

Figure 5.52. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

Also the results considering the low-carbon glass are shown

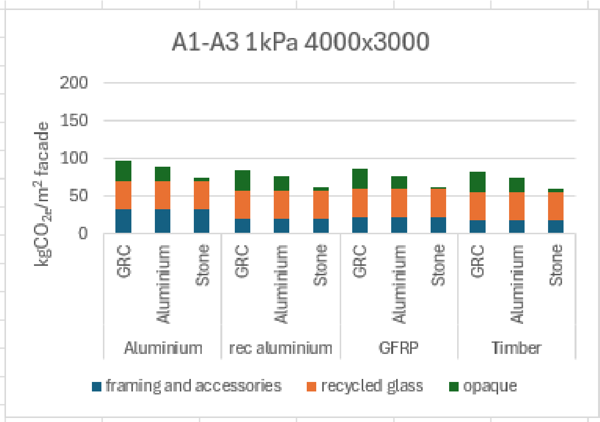

Figure 5.53. Total embodied carbon A1-A3 with 1 kPa of wind acting on it

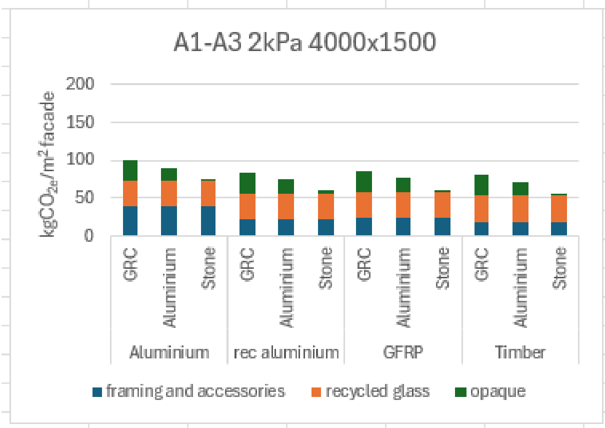

Figure 5.54. Total embodied carbon A1-A3 with 2 kPa of wind acting on it

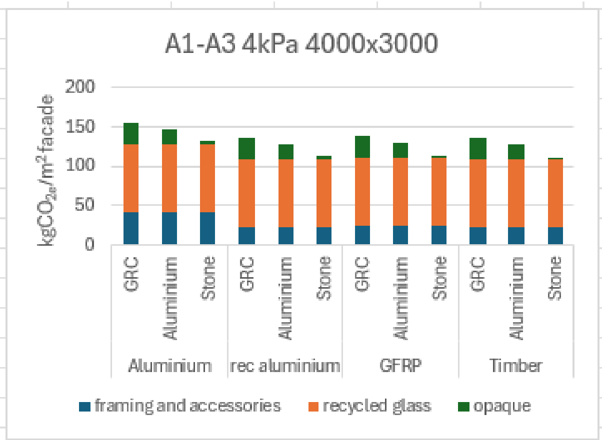

Figure 5.55. Total embodied carbon A1-A3 with 4 kPa of wind acting on it

The embodied carbon emissions are generally lower than in the configuration with the window-to-wall ratio 100%. This happens mainly because the impact of glass is halved and replaced with the emissions of opaque components that are generally lower. In any case, as well as for the facade with 100% WWR, the major impact is related to glass, which is reduced considering low-carbon glass. Again, the reduction in embodied carbon due to low-carbon glass becomes more evident, the more the dimensions of the bay and wind load increase.

Chapter 6

Replacement: stage B4

After having evaluated the embodied carbon related to the production stage, the one regarding the replacement stage is now developed. Module B4 of LCA considers the emissions associated with the planned substitution of facade materials and components over the service life of the building [2].
In this module the main component to consider for replacing in a glazing facade is the insulated glass unit. In fact glass is considered to have a service life of 25 years, this means that should be replaced once over the life of the building. This period is considered in compliance with the UNI EN 1279 standard [8], for which well-performing IGUs have a maximum gas loss of less than 5% and a decrease in the U value of not more than 0.1 W/m^2K over 25 years [16]. But, the durability of the IGU is also determined by physical and chemical stresses that can be subjected to.
So considering a service life of the IGU of 25 years, the embodied carbon due to its replacement is calculated by multiplying the quantity of glass to replace for its ECF, considering both normal and low-carbon glass.
The calculation are carried out for both bay dimensions and window to wall ratio configurations.

6.1 100% WWR

For bay 4000 mm x 1500 mm:

		Glass		**Recycled glass**	
	Quantity to replace	ECF	$kgCO_{2e}/m^2$	ECF	$kgCO_{2e}/m^2$
1 kPa	48 kg/m^2	1.62	77.76 $kgCO_{2e}/m^2$	1.2	57.6 $kgCO_{2e}/m^2$
2 kPa	57.6 kg/m^2	1.62	93.312 $kgCO_{2e}/m^2$	1.2	69.12 $kgCO_{2e}/m^2$
4 kPa	62.4 kg/m^2	1.62	101.09 $kgCO_{2e}/m^2$	1.2	74.88 $kgCO_{2e}/m^2$

Table 6.1. Embodied carbon stage B4 for bay 4000 mm x 1500 mm

For bay 4000 mm x 3000 mm:

		Glass		Recycled glass	
	Quantity to replace	ECF	$kgCO_{2e}/m^2$	ECF	$kgCO_{2e}/m^2$
1 kPa	$62.4\ kg/m^2$	1.62	$101.09\ kgCO_{2e}/m^2$	1.2	$74.88\ kgCO_{2e}/m^2$
2 kPa	$86.4\ kg/m^2$	1.62	$139.97\ kgCO_{2e}/m^2$	1.2	$103.68\ kgCO_{2e}/m^2$
4 kPa	$144\ kg/m^2$	1.62	$233.28\ kgCO_{2e}/m^2$	1.2	$172.8\ kgCO_{2e}/m^2$

Table 6.2. Embodied carbon stage B4 for bay 4000 mm x 3000 mm

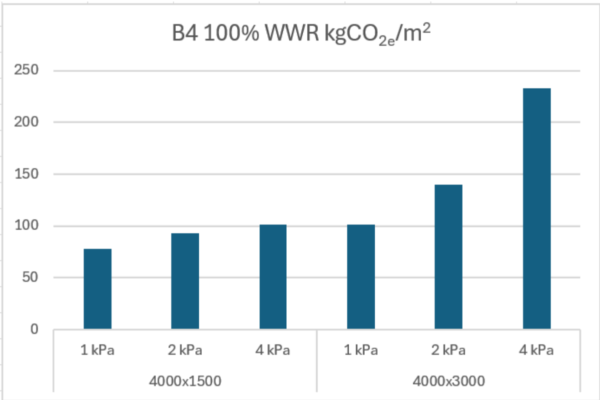

Figure 6.1. Embodied carbon stage B4

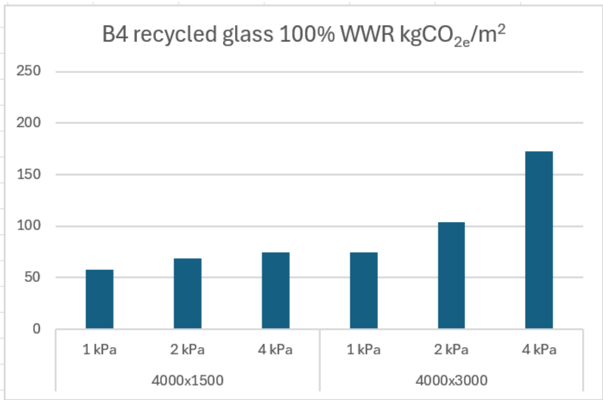

Figure 6.2. Embodied carbon stage B4 recycled glass

As well as in the production stage, also in the replacement stage, glass has a great impact on embodied carbon emissions, especially in the largest bay considered. In fact its emissions increase with the augmentation of both the wind load and bay dimensions, until reaching the maximum embodied carbon emission for bay 4000 mm x 3000 mm with 4 kPa of wind where a great thickness of glass is necessary to withstand the load. For this reason, especially for larger bays and great loads, using low-carbon glass is a good option also in this stage of LCA to reduce emissions.

6.2 50% WWR

For bay 4000 mm x 1500 mm:

		Glass		Recycled glass	
	Quantity to replace	ECF	$kgCO_{2e}/m^2$	ECF	$kgCO_{2e}/m^2$
1 kPa	24 kg/m^2	1.62	38.88 $kgCO_{2e}/m^2$	1.2	28.8 $kgCO_{2e}/m^2$
2 kPa	28.8 kg/m^2	1.62	46.66 $kgCO_{2e}/m^2$	1.2	34.56 $kgCO_{2e}/m^2$
4 kPa	31.2 kg/m^2	1.62	50.54 $kgCO_{2e}/m^2$	1.2	37.44 $kgCO_{2e}/m^2$

Table 6.3. Embodied carbon stage B4 for bay 4000 mm x 1500 mm

For bay 4000 mm x 3000 mm:

		Glass		Recycled glass	
	Quantity to replace	ECF	$kgCO_{2e}/m^2$	ECF	$kgCO_{2e}/m^2$
1 kPa	31.2 kg/m^2	1.62	50.54 $kgCO_{2e}/m^2$	1.2	37.44 $kgCO_{2e}/m^2$
2 kPa	43.2 kg/m^2	1.62	69.98 $kgCO_{2e}/m^2$	1.2	51.84 $kgCO_{2e}/m^2$
4 kPa	72 kg/m^2	1.62	116.64 $kgCO_{2e}/m^2$	1.2	86.4 $kgCO_{2e}/m^2$

Table 6.4. Embodied carbon stage B4 for bay 4000 mm x 3000 mm

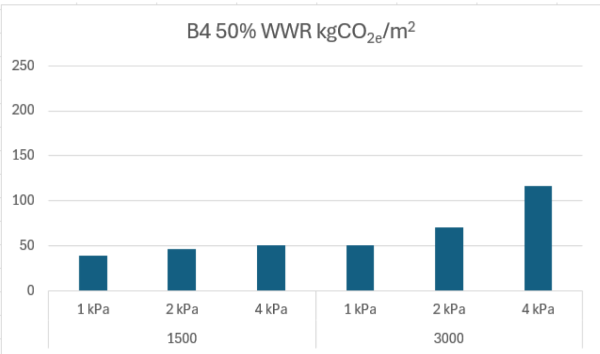

Figure 6.3. Embodied carbon stage B4

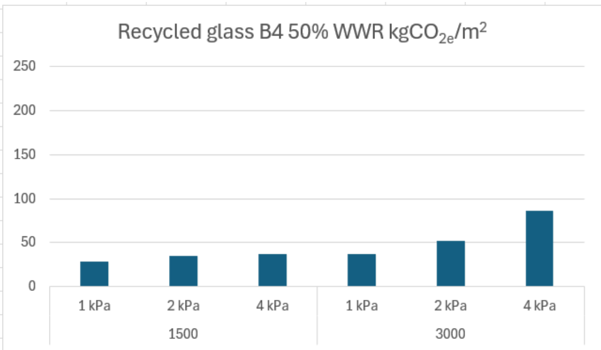

Figure 6.4. Embodied carbon stage B4 recycled glass

In this configuration the impacts are obviously halved of the previous case since glass occupies half of the facade, but they have still an important role in the embodied carbon of the whole facade. As for 100% WWR, the impacts of glass increases while increasing the magnitude of wind load and the dimensions of the bay, with the highest impact for the last configuration. For this reason, again the use of low-carbon glass should be considered especially for bigger bay dimensions to reduce the impact of glass on the embodied carbon.

Chapter 7

Operational Carbon

The term operational carbon refers to emissions associated with the "operation" of a building, such as energy used to power, heat, cool and ventilate the building itself and the water consumed during a building's life cycle for heating, filtration, or sewer processing [20]. So that is an important quote to take into account in addition to the embodied carbon.
Operational carbon is calculated by multiplying the energy demand of the building for heating, cooling, ventilation and lighting for the emission factor of the grid. The energy demand is obtained from the software COMFEN5 where the calculations are made considering both bays with 100% window to wall ratio and 50% window to wall ratio. Furthermore, three different hypothesis are made regarding the emission factor of the grid to consider its evolution over the service life of the building.
First of all, to calculate the energy demand of the building, the following input parameters are considered to set software calculations.

- Building type: office
- Location: Turin
- HVAC system type: electric for both cooling and heating
- Flow rate based on flow/person

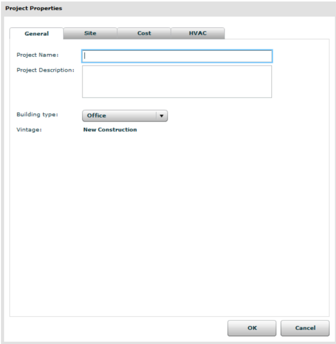

Figure 7.1. General input for defining the building

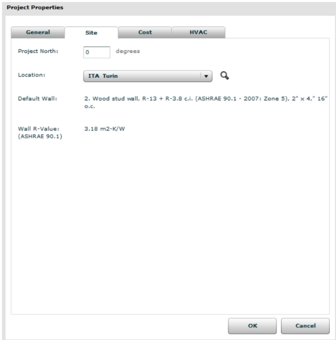

Figure 7.2. Input for defining building location

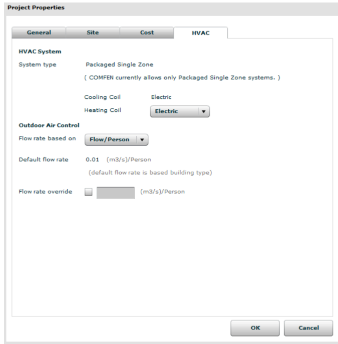

Figure 7.3. Input for defining HVAC system

Furthermore, other input data should be set in COMFEN5 to calculate the energy demand of a specific room. These information concern the dimension of the room, lighting control, HVAC economizer, lighting load, equipment load and occupants. The room is defined with a fixed surface of 6 m x 8 m. Lighting and equipment loads as well as the number of occupants of the room are defined following the standard EN 16798-1:2019 [10] and its national annex. Since an office building is considered, lighting load is 8-12 W/m^2, equipment load is 12 W/m^2 and the occupants 0.1 pers/m^2. Then, as lighting control a continuous/off system is chosen as the most suitable option considering the location of the building for which in some parts of the day the lights can be completely switched off thanks to the sufficient natural daylight; while for the HVAC economizer the option temperature and enthalpy is chosen since is the most appropriate for the climate of the chosen location.
Furthermore, also the IGUs are designed in compliance with the ones calculated with glassAdvisor as regards both thickness and performances.

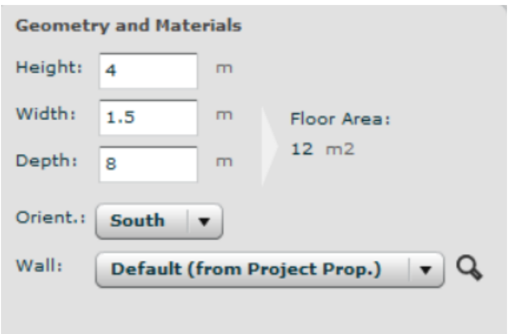

Figure 7.4. Input data for the geometry of the room

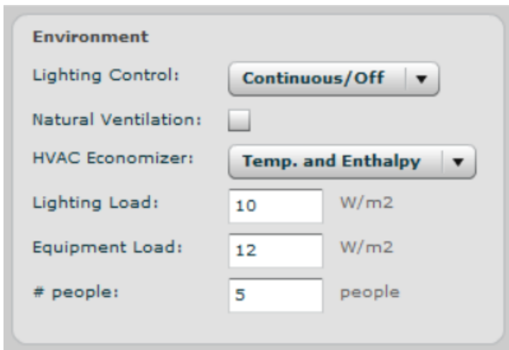

Figure 7.5. Input data for the energy loads

Once all these input data are inserted in the software, the room is designed with the proper facade. COMFEN5 calculates the energy demand per year per m^2 of internal floor area. Then that result is transformed into energy demand per year per m^2 of facade considering the different $\frac{facade}{floor}$ ratio.

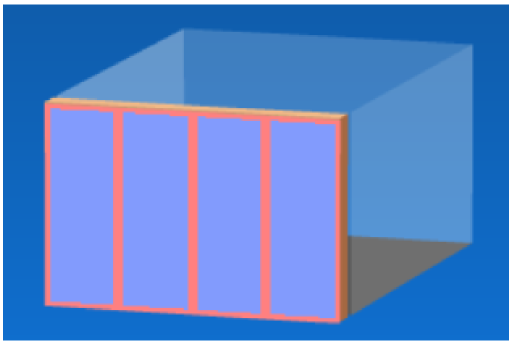

Figure 7.6. Scheme on COMFEN5 for 100% WWR

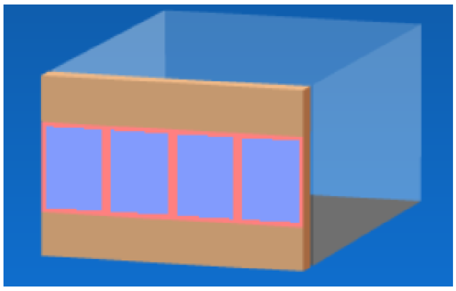

Figure 7.7. Scheme on COMFEN5 for 50% WWR

The following, are the obtained results for the energy demand for each room configuration for both 100% WWR and 50% WWR:

facade/floor	100% WWR	50% WWR
50%	152.14 kWh/m^2	120.53 kWh/m^2
30%	253.32 kWh/m^2	200.68 kWh/m^2
20%	380.36 kWh/m^2	301.32 kWh/m^2

Table 7.1. Energy demand for heating, cooling, ventilation and lighting

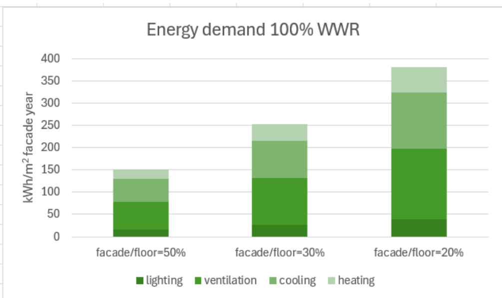

Figure 7.8. Energy demand of 100% WWR facade

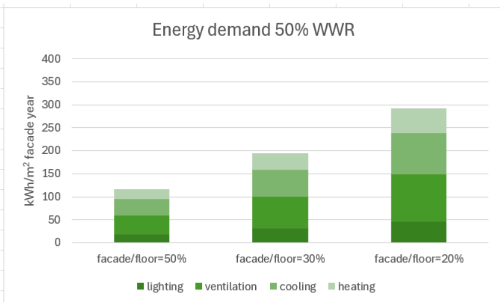

Figure 7.9. Energy demand of 50% WWR facade

The energy demand decreases by reducing the window to wall ratio of the glazing facade. In fact reducing the window area the building energy demand for heating and

cooling decreases. This happens because opaque components have lower U-values than transparent components, so reducing the glazing area, both heat losses in winter and heat gains in summer decrease. Furthermore, glazing allows solar radiation to enter in the building by causing overheating. So higher WWR means higher cooling loads and electricity use, while lower WWR means less cooling and lower energy demand. Hence, by reducing the window to wall ratio, also the energy needed for heating and cooling the building decreases.
Furthermore, by decreasing the $\frac{facade}{floor}$ ratio, this means increasing the dimension of the room with respect to the facade, the energy demand also increases in both facade configurations because the larger the room, also the greater the quantity of electricity needed to heat, cool and ventilate it.

But since the energy demand of the building intrinsically depends on the characteristics and performances of the IGU present in the facade, it does not remain constant over the service life of glass because of its loss of performances for degradation. In fact as said in the previous chapter IGUs should last at least 25 years without having significantly variations in gas loss and U-value, but its performances and durability depend also on the stresses to which the glass is subjected. These physical and chemical stresses can cause a loss of the gas infilled in the cavity, and an increasing in the U-value with a consequent decreasing in performances of the IGU and an increasing in operational carbon. The mentioned stresses have an influence especially on the dual edge seal system of the dual-seal insulated glass unit.
A dual seal system consists of a primary sealant, typically made of polysobutylene (PIB), which provides gas retention properties, and a secondary seal of varied polymeric materials that provides structural integrity for the unit. Both the secondary and primary sealants play a role in life expectancy [19].

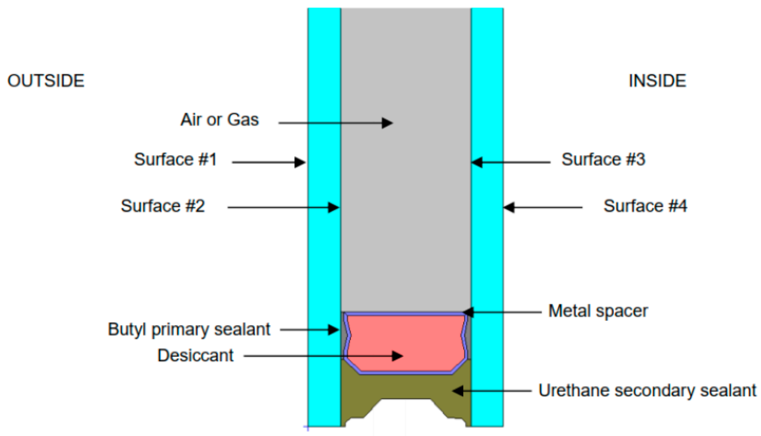

Figure 7.10. Scheme of the section of a dual-seal insulated glass unit [19]

As reported by Andreas T. Wolf [25], the environmental influences that can cause degradation of the IGU are the following:

- Temperature variations produce a difference in pressure in the insulated glass unit that causes strong mechanical stress on the edge seal. In particular low temperatures may have a negative effect on the flexibility of the edge seal, while high temperatures accelerate processes such as aging of the sealant and diffusion of water vapour through the edge seal.
- Changes in atmospheric pressure produce mechanical stresses on the edge seal.
- Working loads resulting from the normal usage of the window generally does not have an effect on the life expectancy of the insulated glass unit, presuming that it is glazed into the window casement in compliance with accepted technical guidelines.
- Sunlight causes both physical and chemical stresses on the edge seal. In fact the infrared component of the radiation thermally charges the insulated glass unit, while the short wave component can introduce photochemical processes in the sealants by irreversibly damaging them.
- Water and water vapour can also cause both physical and chemical stresses on the edge seal. Both water vapour diffusion through the edge seal into the inter-pane space and the water absorption cause the swelling of the sealant that results in an opening of the primary seal and, consequently, a higher water vapour diffusion into the interior of the insulated glass unit. Furthermore, water and water vapour can produce also the hydrolysis of chemical bonds at the glass surface and damage the adhesion of the sealant.
- Oxygen and ozone lead to gradual oxidation of organic insulating glass sealants, especially at high temperatures.
- Aggressive atmospheric contaminants such as chlorine, hydrogen chloride, sulphur dioxide and nitric oxides can generate considerable chemical stresses on the edge seal.

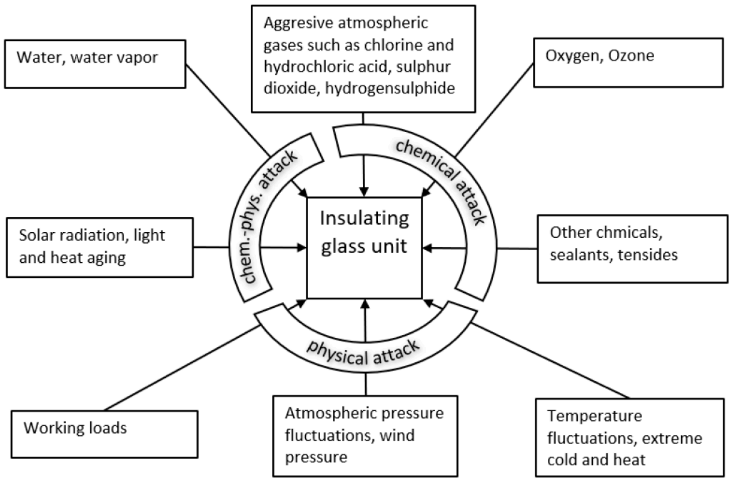

Figure 7.11. Environmental influences on aging process of insulated glass units [25]

All these factors cause the reduction of insulated glass unit performances especially due to the lack of sealants that produces loss of insulating gas present in the cavity. The decrease in gas concentration is directly correlated to the U-value of the window which hence will lead to a larger thermal loss through the building envelope [23], this means higher values of both energy demand and operational carbon.
Hence, to take into account the degradation of the IGU, an increase in the U-value over its service life is considered as well as the reduction in performances of the selective coating applied on the glass surface.
So two scenarios are considered compared to the base one at 25 years from the installation of the IGU.

- base scenario: the infilled gas is Argon 90%, the coating has an emissivity of 0.01 and the U-value of the IGU corresponds to almost 1 W/m^2K.
- scenario 1: the infilled Argon is completely substituted with air but the performances of the coating do not decrease, so the emissivity is still 0.01 and the U-value corresponds of almost 1.2 W/m^2K
- scenario 2: the infilled Argon is completely substituted with air and also the coating looses its performances, so the emissivity becomes 0.15 and the U-values is almost 1.6 W/m^2K

So, the energy demand is calculated for the scenario 1 and 2 with the software COMFEN5 by designing the different IGUs with the properties explained above. The energy demand for each scenario is calculated corresponding to year 25 of use. Then a linear prevision is done to evaluate the variation in energy demand for each year, from the beginning to the year corresponding to the substitution of the IGU.
So the variation in energy demand over time is reported below for all room dimensions

and facade configurations.

For the bay with 100% WWR:

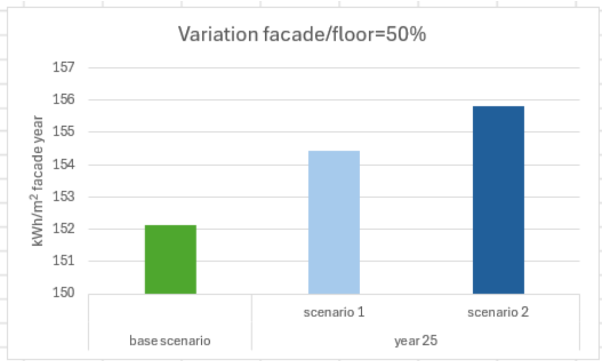

Figure 7.12. Variation of energy demand in the bay with 100% WWR and facade/floor=50%

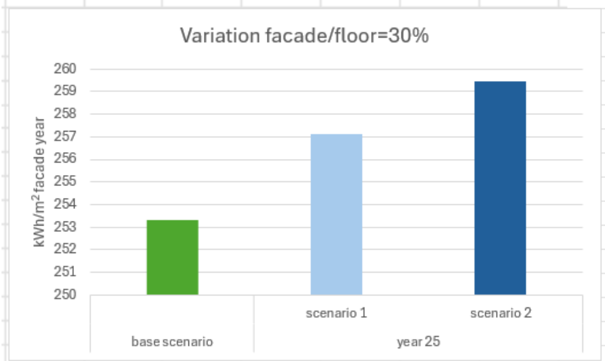

Figure 7.13. Variation of energy demand in the bay with 100% WWR and facade/floor=30%

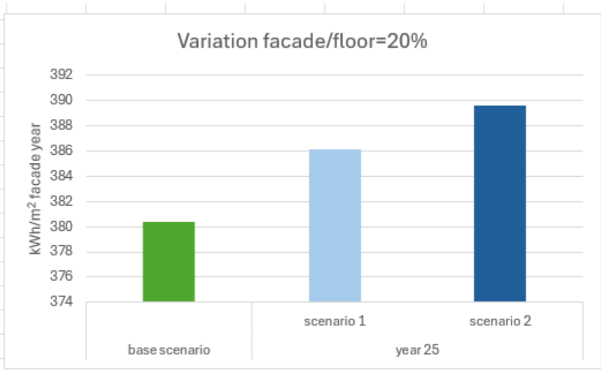

Figure 7.14. Variation of energy demand in the bay with 100% WWR ams facade/floor=20%

For the bay with 50% WWR:

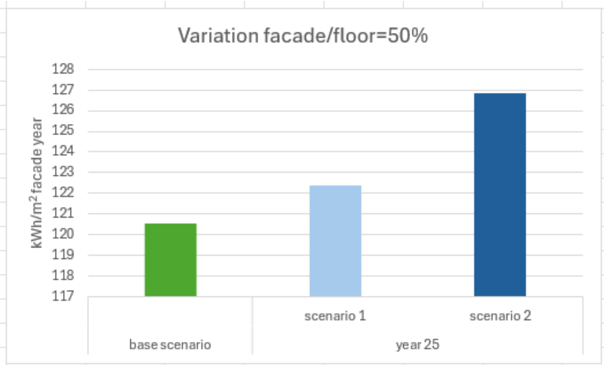

Figure 7.15. Variation of energy demand in the bay with 100% WWR and facade/floor=50%

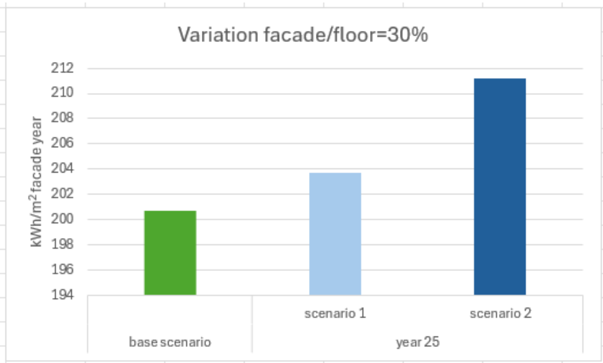

Figure 7.16. Variation of energy demand in the bay with 100% WWR and facade/floor=30%

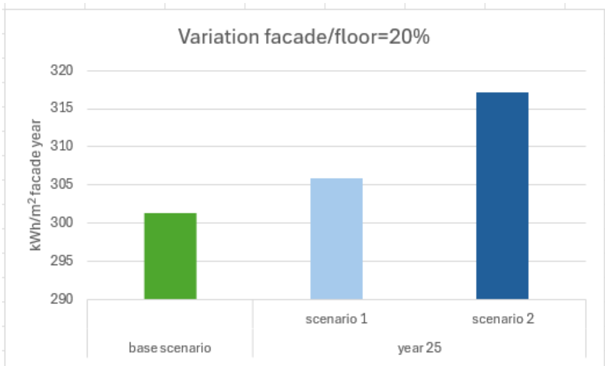

Figure 7.17. Variation of energy demand in the bay with 100% WWR ams facade/floor=20%

Now that the energy demand of the building is calculated and its variation considered, it can be converted in operational carbon through the emission factor that characterized the Italian electrical grid. The emission factor of the grid is taken from the ISPRA 2025 report [22], that for the year 2024, the last one available, corresponds to 0.1989 $kgCO_2/kWh$. Multiplying the energy demand for the emission factor of 2024, the operational carbon corresponding to the first year is obtained. To calculate the total operational carbon, that means the emissions the building produces over its entire service life, two scenarios are considered.

- Scenario 1: the mix used to produce electricity for the grid remains constant over the 50 years of service life of the building, so the energy demand of each year is multiplied for the actual emission factor.

So the following are the values of the operational carbon over the service life of the building.
If the base scenario is considered for which the performances of the IGU remains constant over its entire service life as well as the enrgy demand:

	Operational carbon [$kgCO_2/m^2$]					
	100% WWR			50% WWR		
year	50%	30%	20%	50%	30%	20%
entire service life	30.26	50.38	75.65	23.97	39.92	59.93
total	**1543.34**	**2569.66**	**3858.35**	**1222.62**	**2035.67**	**3056.55**

Table 7.2. Operational Carbon over years in scenario 1

If the variation of energy demand is considered in compliance with scenario 1:

Table 7.3: Operational carbon over years in scenario 1

	Operational carbon [$kgCO_2/m^2$]					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2024	30.26	50.38	75.65	23.97	39.92	59.93
2025	30.28	50.41	75.70	23.99	39.94	59.97
2026	30.30	50.44	75.75	24.00	39.96	60.01
2027	30.32	50.48	75.79	24.02	39.99	60.04
2028	30.33	50.51	75.84	24.03	40.01	60.08
2029	30.35	50.54	75.88	24.05	40.04	60.11
2030	30.37	50.57	75.92	24.06	40.06	60.15
2031	30.39	50.59	75.97	24.08	40.09	60.19
2032	30.40	50.63	76.02	24.09	40.11	60.22
2033	30.43	50.66	76.06	24.10	40.13	60.26
2034	30.44	50.68	76.11	24.12	40.16	60.29
2035	30.46	50.72	76.16	24.15	40.18	60.33
2036	30.48	50.75	76.20	24.16	40.20	60.37
2037	30.50	50.78	76.25	24.16	40.23	60.41
2038	30.52	50.81	76.29	24.18	40.26	60.44
2039	30.54	50.84	76.34	24.19	40.28	60.48
2040	30.55	50.87	76.38	24.21	40.30	60.52
2041	30.57	50.90	76.43	24.22	40.33	60.55
2042	30.59	50.93	76.47	24.23	40.35	60.59
2043	30.61	50.96	76.48	24.25	40.38	60.63
2044	30.63	50.99	76.52	24.26	40.40	60.66
2045	30.64	51.02	76.61	24.28	40.43	60.70
2046	30.66	51.05	76.65	24.29	40.44	60.73
2047	30.68	51.08	76.70	24.30	40.47	60.77
2048	30.70	51.12	76.74	24.32	40.50	60.81
2049	30.71	51.15	76.79	24.34	40.52	60.814
2050	30.26	50.38	75.65	23.97	39.92	59.93
2051	30.28	50.41	75.70	23.99	39.94	59.97
2052	30.30	50.44	75.75	24.00	39.96	60.01
2053	30.32	50.48	75.79	24.02	39.99	60.04
2054	30.33	50.51	75.84	24.03	40.01	60.08
2055	30.35	50.54	75.88	24.05	40.04	60.11
2056	30.37	50.57	75.92	24.06	40.06	60.15
2057	30.39	50.59	75.97	24.08	40.09	60.19
2058	30.40	50.63	76.02	24.09	40.11	60.22
2059	30.43	50.66	76.06	24.10	40.13	60.26

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	Operational carbon $[kgCO_2/m^2]$					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2060	30.44	50.68	76.11	24.12	40.16	60.29
2061	30.46	50.72	76.16	24.15	40.18	60.33
2062	30.48	50.75	76.20	24.16	40.20	60.37
2063	30.50	50.78	76.25	24.16	40.23	60.41
2064	30.52	50.81	76.29	24.18	40.26	60.44
2065	30.54	50.84	76.34	24.19	40.28	60.48
2066	30.55	50.87	76.38	24.21	40.30	60.52
2067	30.57	50.90	76.43	24.22	40.33	60.55
2068	30.59	50.93	76.47	24.23	40.35	60.59
2069	30.61	50.96	76.48	24.25	40.38	60.63
2070	30.63	50.99	76.52	24.26	40.40	60.66
2071	30.64	51.02	76.61	24.28	40.43	60.70
2072	30.66	51.05	76.65	24.29	40.44	60.73
2073	30.68	51.08	76.70	24.30	40.47	60.77
2074	30.70	51.12	76.74	24.32	40.50	60.81
total	**1554.75**	**2588.65**	**3886.87**	**1231.74**	**2050.84**	**3079.34**
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Figure 7.18. Variation of operational carbon for the 100% WWR bay

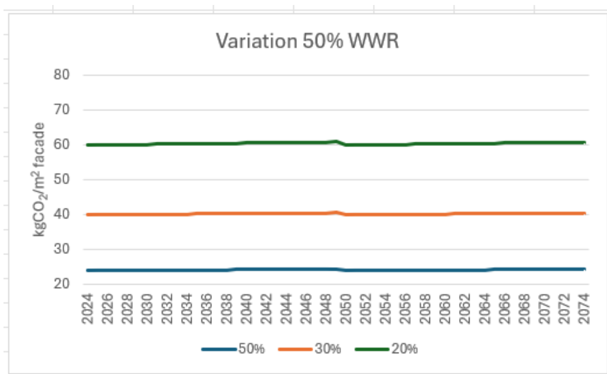

Figure 7.19. Variation of operational carbon for the 100% WWR bay

If the variation of energy demand is considered in compliance with scenario 2:

Table 7.4: Operational carbon over years in scenario 1

	Operational carbon [$kgCO_2/m^2$]					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2024	30.26	50.39	75.65	23.97	39.92	59.93
2025	30.29	50.43	75.73	24.02	39.99	60.06
2026	30.32	50.48	75.80	24.07	40.08	60. 18
2027	30.35	50.53	75.87	24.12	40.17	60.31
2028	30.38	50.58	75.95	24.17	40.25	60.43
2029	30.41	50.63	76.02	24.22	40.33	60.56
2030	30.44	50.68	76.09	24.27	40.41	60.68
2031	30.47	50.73	76.17	24.32	40.50	60.81
2032	30.49	50.78	76.24	24.37	40.58	60.93
2033	30.52	50.82	76.31	24.42	40.66	61.06
2034	30.55	50.87	76.39	24.47	40.75	61.19
2035	30.58	50.92	76.46	24.52	40.83	61.31
2036	30.61	50.97	76.53	24.57	40.91	61.44
2037	30.64	51.02	76.60	24.62	40.99	61.56
2038	30.67	51.07	76.68	24.67	41.08	61.69
2039	30.70	51.12	76.75	24.72	41.17	61.81
2040	30.73	51.16	76.82	24.77	41.25	61.93
2041	30.76	51.21	76.90	24.83	41.33	62.06
2042	30.79	51.26	76.97	24.88	41.42	62.19
2043	30.82	51.31	77.04	24.93	41.50	62.31
2044	30.85	51.36	77.12	24.98	41.58	62.44
2045	30.88	51.41	77.19	25.03	41.67	62.56
2046	30.91	51.46	77.26	25.08	41.75	62.69
2047	30.93	51.51	77.33	25.12	41.83	62.81
2048	30.96	51.55	77.40	25.17	41.92	62.94
2049	30.99	51.60	77.48	25.23	42.00	63.07
2050	30.26	50.39	75.65	23.97	39.92	59.93
2051	30.29	50.43	75.73	24.02	39.99	60.06
2052	30.32	50.48	75.80	24.07	40.08	60. 18
2053	30.35	50.53	75.87	24.12	40.17	60.31
2054	30.38	50.58	75.95	24.17	40.25	60.43
2055	30.41	50.63	76.02	24.22	40.33	60.56
2056	30.44	50.68	76.09	24.27	40.41	60.68
2057	30.47	50.73	76.17	24.32	40.50	60.81
2058	30.49	50.78	76.24	24.37	40.58	60.93
2059	30.52	50.82	76.31	24.42	40.66	61.06
2060	30.55	50.87	76.39	24.47	40.75	61.19

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	Operational carbon $[kgCO_2/m^2]$					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2061	30.58	50.92	76.46	24.52	40.83	61.31
2062	30.61	50.97	76.53	24.57	40.91	61.44
2063	30.64	51.02	76.60	24.62	40.99	61.56
2064	30.67	51.07	76.68	24.67	41.08	61.69
2065	30.70	51.12	76.75	24.72	41.17	61.81
2066	30.73	51.16	76.82	24.77	41.25	61.93
2067	30.76	51.21	76.90	24.83	41.33	62.06
2068	30.79	51.26	76.97	24.88	41.42	62.19
2069	30.82	51.31	77.04	24.93	41.50	62.31
2070	30.85	51.36	77.12	24.98	41.58	62.44
2071	30.88	51.41	77.19	25.03	41.67	62.56
2072	30.91	51.46	77.26	25.08	41.75	62.69
2073	30.93	51.51	77.33	25.12	41.83	62.81
2074	30.96	51.55	77.40	25.17	41.92	62.94
total	**1561.63**	**2600.11**	**3904.06**	**1253.95**	**2087.82**	**3134.87**
End of table						

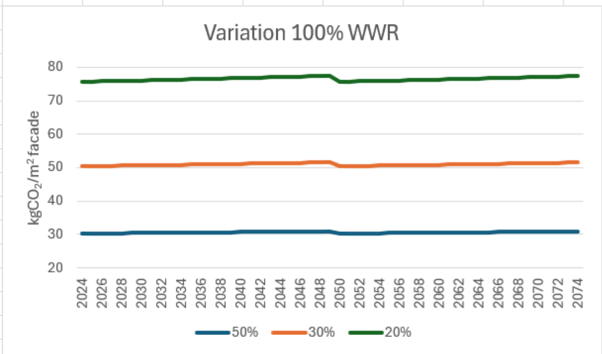

Figure 7.20. Variation of operational carbon for the 100% WWR bay

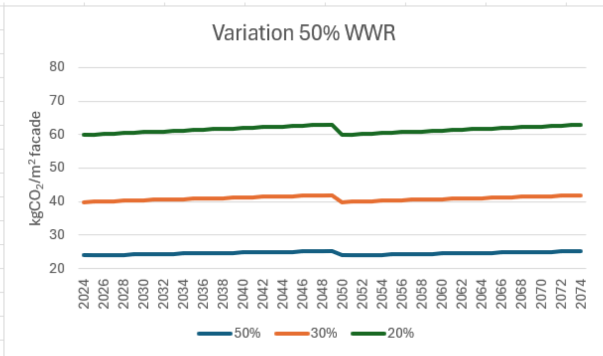

Figure 7.21. Variation of operational carbon for the 100% WWR bay

- Scenario 2: the decarbonization goals of the European Union that set a zero emission grid in 2050 are considered and starting from that value a linear prevision is done to obtain the emission factor from 2024 to 2050.
  These are the obtained values:

year	emission factor $[kgCO_2/kWh]$
2025	0.01913
2026	0.1836
2027	0.1759
2028	0.1683
2029	0.1607
2030	0.1530
2031	0.1454
2032	0.1377
2033	0.1301
2034	0.1224
2035	0.1148
2036	0.1071
2037	0.0994
2038	0.0918
2039	0.0842
2040	0.0765
2041	0.0689
2042	0.0612
2043	0.0536
2044	0.0459
2045	0.0383
2046	0.0306
2047	0.0229
2048	0.0153
2049	0.0077
2050 and after	0

Table 7.5. Emission factors over years

This is a prevision that is less optimistic than the one obtained considering the emission factors of the past 20 years taken by ISPRA report [22] to evaluate the ones in the next years.
The emission factors from 1990 to 2024 to consider for this scenario are the ones named as "consumi elettrici" in the following table.

Tabella 1.3 – Fattori di emissione nel settore elettrico (g CO_2/kWh).

Anno	Produzione termoelettrica lorda (solo fossili)	Produzione termoelettrica lorda[1]	Produzione elettrica lorda[2]	Consumi elettrici[3]	Perdite di rete[4]	Produzione termoelettrica lorda e calore[1,5]	Produzione elettrica lorda e calore[2,5]	Produzione di calore[5]
1990	709.2	709.0	593.0	577.8	505.6	709.0	593.0	
1995	681.5	681.7	562.2	548.1	481.6	681.7	562.2	
2000	638.1	636.0	517.6	500.2	440.7	636.0	517.6	
2005	583.1	574.5	487.6	467.2	415.1	516.5	450.4	244.4
2010	548.7	528.1	407.4	392.8	352.9	473.3	382.3	249.0
2015	547.6	493.8	335.8	318.2	286.7	429.5	316.0	221.7
2020	454.4	405.2	263.7	258.8	235.5	358.3	255.2	215.0
2021	456.8	410.9	271.6	259.0	235.3	364.9	261.9	213.7
2022	477.4	435.1	307.3	293.0	265.4	388.3	293.4	223.8
2023	460.2	414.9	256.3	234.7	213.3	369.6	251.3	225.1
*2024**	*422.4*	*382.2*	*215.9*	*198.9*	*180.6*	*344.2*	*217.7*	*227.4*

[1] Inclusa elettricità da bioenergia.
[2] Incluse rinnovabili, al netto di apporti da pompaggio e da accumulo stand alone.
[3] Incluse le perdite di rete e la quota importata.
[4] Fattore di emissione della produzione elettrica per la quota di perdite di energia elettrica prodotta.
[5] Incluse le emissioni di CO_2 per la produzione di calore.
* Dati preliminari.

Figure 7.22. Emission factors from 1990 to 2024 [22]

Starting from these values a prevision is done for knowing the evolution of the factors over the service life of the building. The following are the obtain factors for each year.

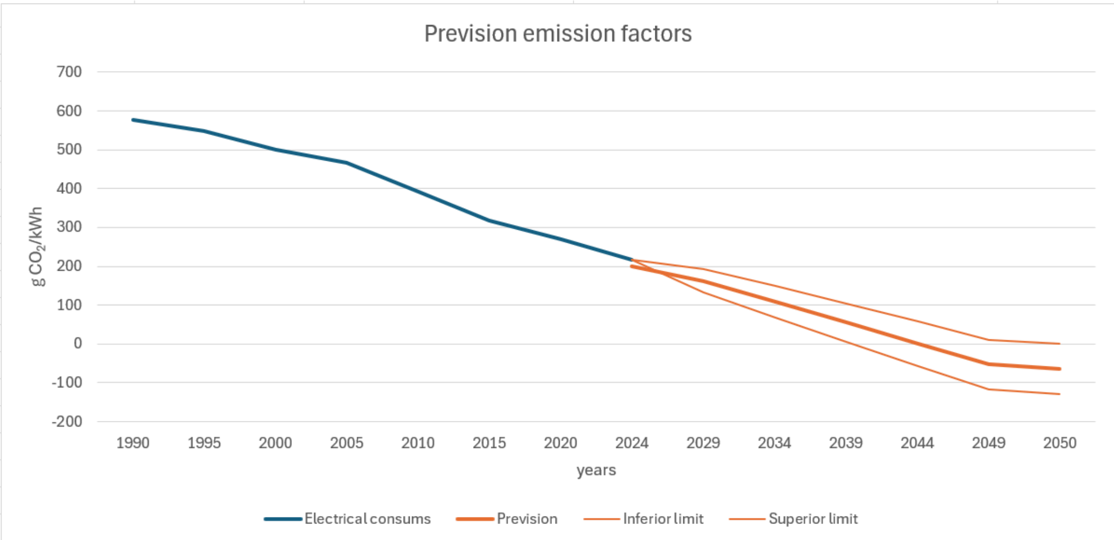

Figure 7.23. Prevision emission factors

year	emission factor $[kgCO_2/kWh]$
2025	0.1976
2026	0.1872
2027	0.1768
2028	0.1665
2029	0.1561
2030	0.1457
2031	0.1354
2032	0.1250
2033	0.1146
2034	0.1043
2035	0.0939
2036	0.0835
2037	0.0732
2038	0.0628
2039	0.0524
2040	0.0421
2041	0.0317
2042	0.0214
2043	0.0110
2044	0.0001
2045 and after	0

Table 7.6. Emission factors over years

In fact using the real past values of emission factors the operational carbon is canceled by 2045 instead of 2050. In any case the goals of EU are used for this scenario and the results in operational carbon are shown below.
If the base scenario is considered:

Table 7.7: Operational carbon over years in scenario 2

	Operational carbon $[kgCO_2/m^2]$					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2024	30.26	50.38	75.65	23.97	39.92	59.93
2025	29.09	48.45	72.74	23.05	38.38	57.63
2026	27.93	46.50	69.83	22.13	36.84	55.32
2027	26.77	44.57	66.92	21.21	35.31	53.02
2028	25.61	42.63	64.01	20.28	33.77	50.71
2029	24.44	40.70	61.10	19.36	32.24	48.41
2030	23.28	38.76	58.20	18.44	30.70	46.10

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	Operational carbon $[kgCO_2/m^2]$					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2031	22.11	36.82	55.29	17.52	29.17	43.79
2032	20.95	34.88	52.38	16.59	27.63	41.49
2033	19.79	32.94	49.47	15.67	26.09	39.19
2034	18.62	31.01	46.55	14.75	24.56	36.88
2035	14.42	28.99	43.54	13.79	22.97	34.49
2036	16.29	27.13	40.74	12.91	21.49	32.27
2037	15.13	25.19	37.83	11.99	19.96	29.97
2038	13.97	23.25	34.92	11.06	18.42	27.66
2039	12.80	21.32	32.01	10.14	16.89	25.36
2040	11.64	19.38	29.09	9.22	15.35	23.05
2041	10.48	17.44	26.19	8.29	13.82	20.75
2042	9.31	15.50	23.28	7.37	12.28	18.44
2043	8.15	13.56	20.37	6.45	10.75	16.14
2044	6.98	11.63	17.46	5.53	9.21	13.83
2045	5.81	9.69	14.55	4.61	7.68	11.53
2046	4.66	7.75	11.64	3.69	6.14	9.22
2047	3.49	5.81	8.73	2.77	4.61	6.92
2048	2.33	3.88	5.82	1.84	3.07	4.61
2049	1.16	1.93	2.91	0.92	1.54	2.31
total	**408.49**	**680.13**	**1021.22**	**323.60**	**538.79**	**809.01**
						End of table

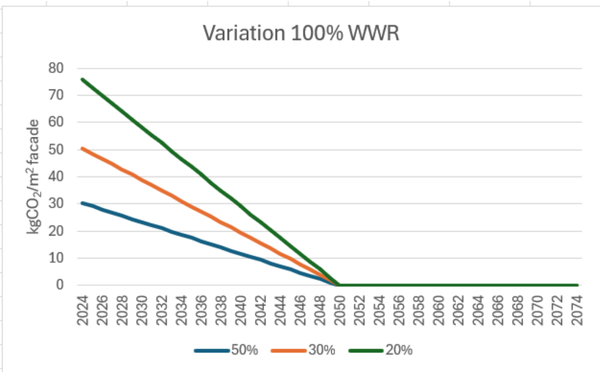

Figure 7.24. Variation of operational carbon for the 100% WWR bay

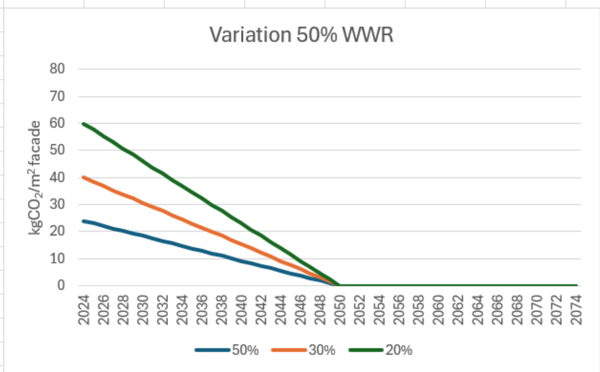

Figure 7.25. Variation of operational carbon for the 100% WWR bay

If the variation of energy demand is considered in compliance with scenario 1:

Table 7.8: Operational carbon over years in scenario 2

	Operational carbon [$kgCO_2/m^2$]					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2024	30.26	50.39	75.65	23.97	39.92	59.93
2025	29.12	48.48	72.79	23.06	38.40	57.66
2026	27.97	46.57	69.92	22.16	36.89	55.39
2027	36.82	44.65	67.05	21.25	35.38	53.11
2028	25.67	42.74	64.17	20.33	33.86	50.84
2029	24.52	40.82	61.29	19.42	32.34	48.55
2030	23.36	38.89	58.41	18.51	30.82	46.27
2031	22.21	36.98	55.52	17.59	29.30	43.98
2032	21.05	35.05	52.63	16.68	27.77	41.69
2033	19.89	33.12	49.73	15.76	26.24	39.40
2034	18.73	31.19	46.83	14.84	24.71	37.11
2035	17.53	29.19	43.83	13.89	23.13	34.72
2036	16.41	27.33	41.03	13.00	21.65	32.51
2037	15.25	25.39	38.12	12.08	20.12	30.20
2038	14.08	23.45	35.21	11.16	18.58	27.89
2039	12.92	21.51	32.29	10.24	17.04	25.58
2040	11.75	19.57	29.38	9.31	15.50	23.27
2041	10.58	17.62	26.46	8.38	13.96	20.96
2042	9.41	15.67	23.53	7.45	12.42	18.64
2043	8.24	13.72	20.60	6.52	10.87	16.32
2044	7.07	11.76	17.66	5.59	9.32	13.99
2045	5.89	9.81	14.73	4.66	7.77	11.67
2046	4.71	7.85	11.79	3.73	6.22	9.34
2047	3.54	5.89	8.85	2.80	4.67	7.01
2048	2.36	3.93	5.90	1.87	3.11	4.67
2049	1.81	1.97	2.95	0.93	1.55	2.34
2050 and after	0	0	0	0	0	0
total	**410.54**	**683.55**	**1026.36**	**325.24**	**541.53**	**813.11**

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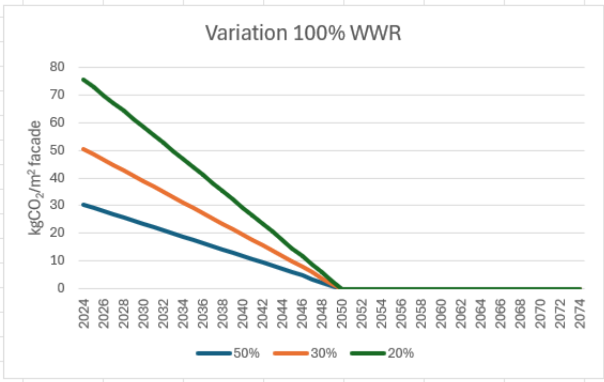

Figure 7.26. Variation of operational carbon for the 100% WWR bay

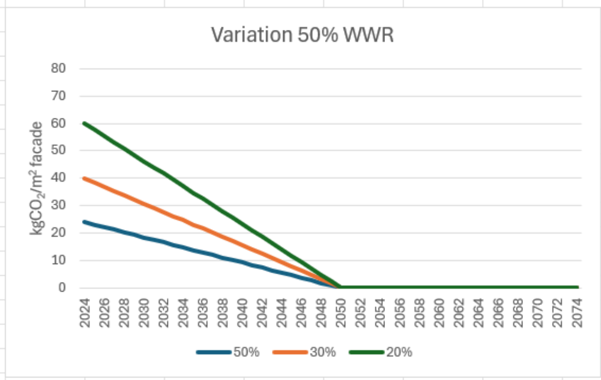

Figure 7.27. Variation of operational carbon for the 100% WWR bay

If the variation of energy demand is considered in compliance with scenario 2:

Table 7.9: Operational carbon over years in scenario 2

	Operational carbon [$kgCO_2/m^2$]					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2024	30.26	50.39	75.65	23.97	39.92	59.93
2025	29.13	48.49	72.81	23.09	38.46	57.75
2026	27.99	46.60	69.97	22.22	36.99	55.55
2027	26.84	44.70	67.12	21.34	35.53	53.35
2028	25.70	42.80	64.26	20.45	34.06	51.13
2029	24.56	40.89	61.40	19.56	32.57	48.91
2030	23.41	38.98	58.53	18.67	31.09	46.68
2031	22.26	37.07	55.66	17.78	29.59	44.44
2032	21.11	35.15	52.78	16.87	28.09	42.19
2033	19.96	33.23	49.89	15.97	26.59	39.92
2034	18.81	31.30	47.01	15.06	25.08	37.65
2035	17.60	29.31	44.01	14.11	23.50	35.29
2036	16.48	27.44	41.21	13.23	22.03	33.08
2037	15.32	25.51	38.30	12.31	20.5	30.78
2038	14.16	23.56	35.39	11.39	18.96	28.47
2039	12.99	21.63	32.47	10.46	17.41	26.15
2040	11.82	19.68	29.55	9.52	15.87	23.82
2041	10.64	17.73	26.62	8.59	14.31	21.48
2042	9.47	15.77	23.68	7.65	12.74	19.13
2043	8.29	13.81	20.74	6.71	11.17	16.78

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	Operational carbon $[kgCO_2/m^2]$					
	100% WWR			50% WWR		
Year	50%	30%	20%	50%	30%	20%
2044	7.12	11.85	17.80	5.76	9.59	14.40
2045	5.93	9.88	14.84	4.81	8.01	12.03
2046	4.75	7.91	11.89	3.85	6.42	9.64
2047	3.56	5.94	8.92	2.89	4.82	7.25
2048	2.38	3.96	5.95	1.94	3.22	4.84
2049	1.19	1.98	2.98	0.97	1.62	2.43
total	**411.78**	**685.61**	**1029.45**	**329.24**	**548.19**	**823.10**
						End of table

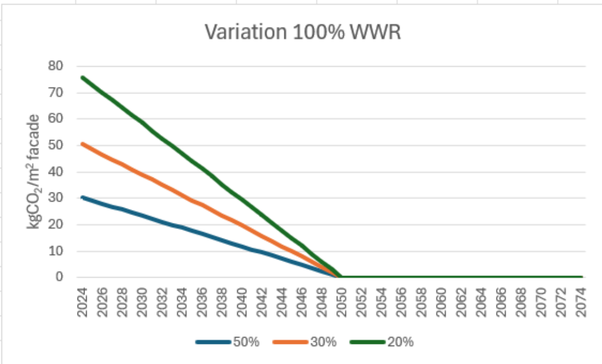

Figure 7.28. Variation of operational carbon for the 100% WWR bay

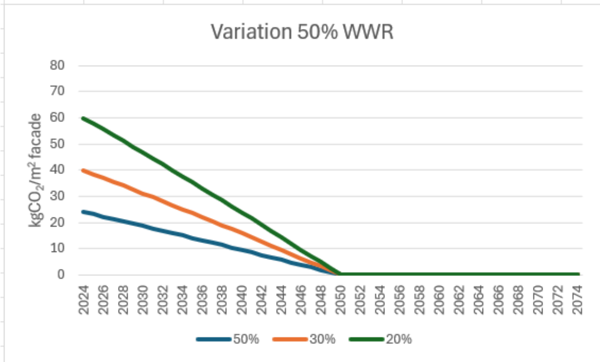

Figure 7.29. Variation of operational carbon for the 100% WWR bay

Comparing the different scenarios, obviously the second one is the more optimistic even if is close to the real one if the decarbonization trend of the electrical grid continues. While in the first scenarios, the final total values of operational carbon are higher since the emission factor is considered constant over time. In this scenario there is not a great variation of values over the life of the building since the variation in energy demand caused by the degradation of the IGU is not so elevated.

Trying to decarbonize the building sector, from an energetic point of view, it is also interesting to compare a double glazing unit with a triple glazing unit to evaluate the consequent decreasing in energy need and operational carbon that this design choice produces.
Hence a triple glazing unit is designed on COMFEN5 considering Argon 90% as infilled gas, the coating with an emissivity of 0.01 and a U-value of 0.7 W/m^2K, and the energy demand in both cases of window to wall ratio and $\frac{facade}{floor}$ ratio is calculated.

facade/floor	100% WWR	50% WWR
50%	141.13 kWh/m^2	115.16 kWh/m^2
30%	234.99 kWh/m^2	191.73 kWh/m^2
20%	352.83 kWh/m^2	287.89 kWh/m^2

Table 7.10. Energy demand for heating, cooling, ventilation and lighting

These values are compared with the one calculated for a double glazing unit:

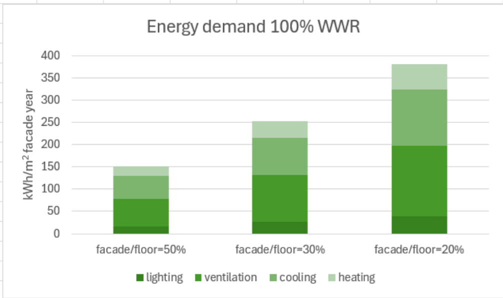

Figure 7.30. Energy demand of 100% WWR facade with a DGU

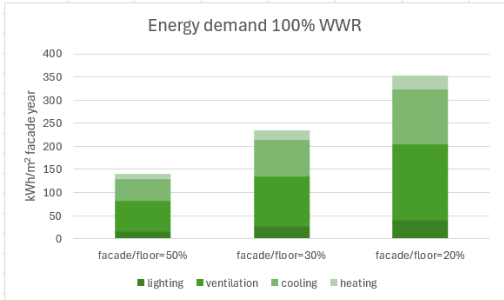

Figure 7.31. Energy demand of 100% WWR facade with a TGU

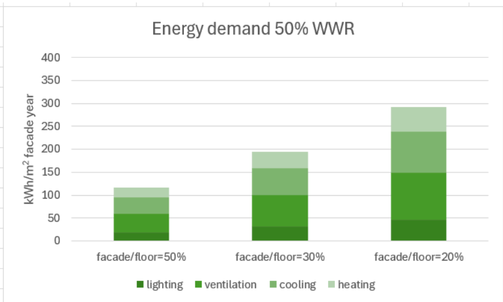

Figure 7.32. Energy demand of 50% WWR facade with a DGU

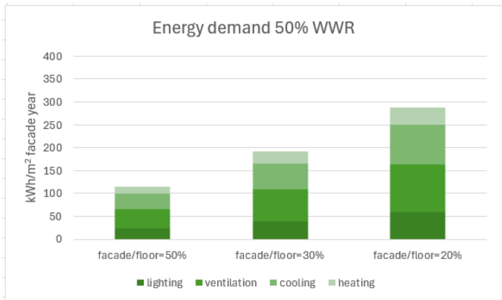

Figure 7.33. Energy demand of 50% WWR facade with a TGU

In general, energy demand decreases when using a triple-glazed unit instead of a double-glazed unit. This reduction is more evident in the bay with 100% WWR where the values decrease of about 20-30 kWh/m^2year in all $\frac{facade}{floor}$ ratio. While for the bay with 50% WWR the values decrease of about 10-20 20-30 kWh/m^2year in all $\frac{facade}{floor}$ ratio. More specifically the heating demand is the one that decreases the most, followed by the cooling demand. While the energy needed for ventilation and lighting is almost comparable in the two cases.
The variation in time of the energy demand is also studied considering that after 25

years of use, the Argon infilled in the cavity is completely substituted by air and also the coating looses its performances.
The following are the obtained values of energy demand after 25 years considering this scenario.

facade/floor	100% WWR	50% WWR
50%	146.39 kWh/m^2	120.33 kWh/m^2
30%	243.74 kWh/m^2	200.35 kWh/m^2
20%	352.83 kWh/m^2	300.82 kWh/m^2

Table 7.11. Energy demand for heating, cooling, ventilation and lighting after 25 years

As for the double glazing unit, the energy demand is now transformed in operational carbon considering the two different scenarios of decarbonization of the grid. The results are shown below:

- scenario 1:

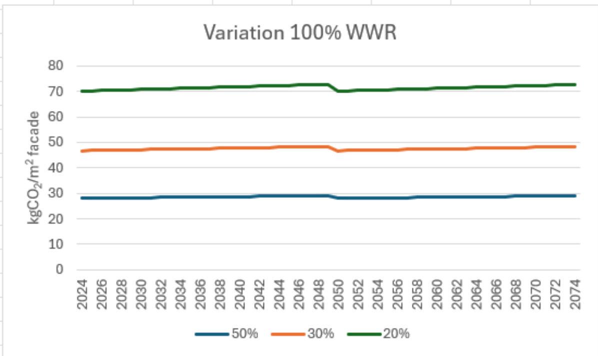

Figure 7.34. Variation of energy demand of 100% WWR facade

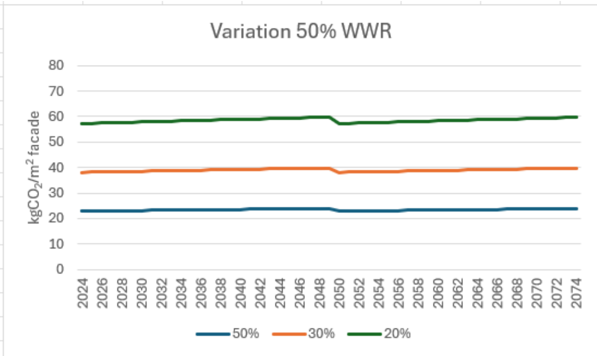

Figure 7.35. Variation of energy demand of 50% WWR facade

The results are now compared with the ones found for the double glazing unit.

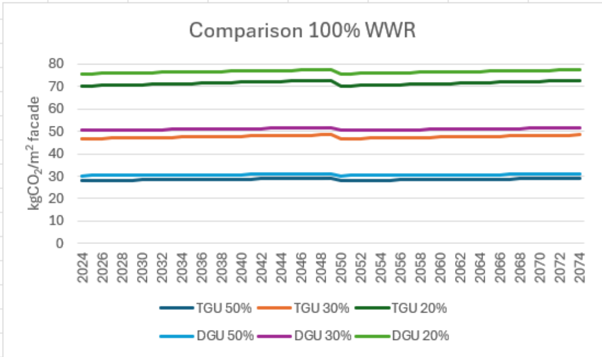

Figure 7.36. Comparison of energy demand of 100% WWR facade

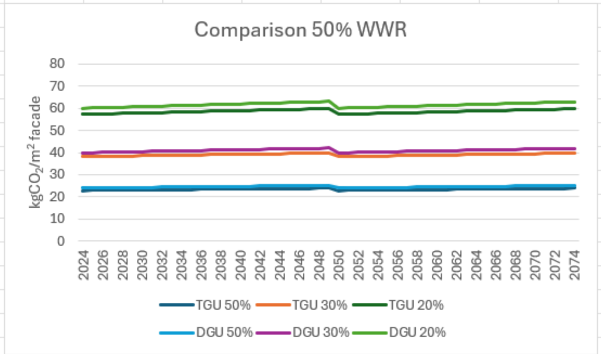

Figure 7.37. Comparison of energy demand of 50% WWR facade

The difference in operational carbon due to the use of a triple glazing unit instead of a double glazing unit is greater in 100% WWR configuration and increases with the decreasing of the $\frac{facade}{floor}$ ratio.

- scenario 2:

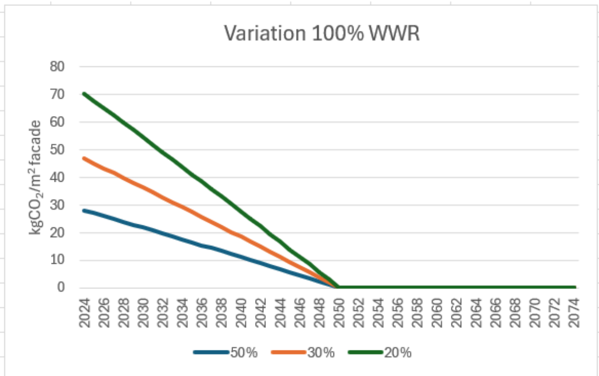

Figure 7.38. Variation of energy demand of 100% WWR facade

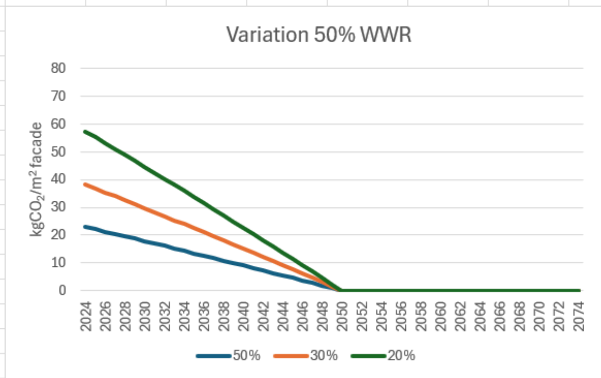

Figure 7.39. Variation of energy demand of 50% WWR facade

The results are now compared with the ones found for the double glazing unit.

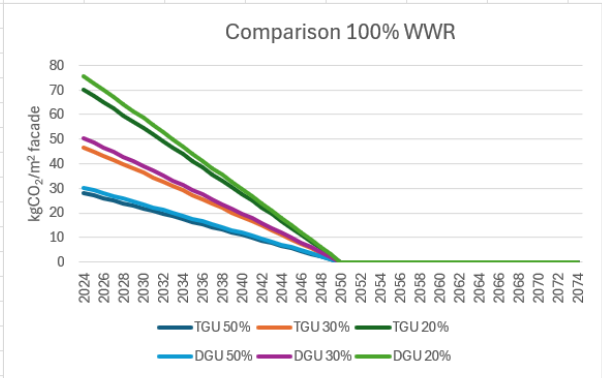

Figure 7.40. Comparison of energy demand of 100% WWR facade

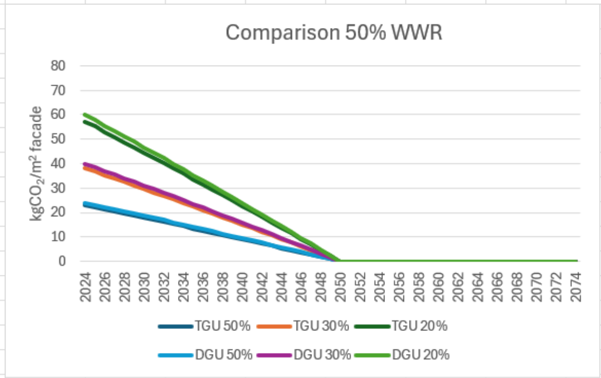

Figure 7.41. Comparison of energy demand of 50% WWR facade

As for the scenario 1 it is possible to see greater differences in operational carbon in the configuration of 100% WWR and with the decrease of the $\frac{facade}{floor}$ ratio.

Therefore, in general, the use of TGU instead of DGU has greater impact on emissions if the facade is completely transparent and the internal space has greater dimensions with respect to the facade. While for a facade half transparent and half opaque the decrease in operational carbon due to the use of a TGU is so small that it could not compensate the increase of embodied carbon due to it.

Chapter 8

Results

Now that all stages that affect the most the embodied and operational carbon were analyzed, the obtained impacts are combined to have a general overview on the emissions of glazing facades over their entire life cycle when different materials and design options are used for their components.

8.1 Total embodied carbon

Firstly the total embodied carbon is analyzed summing together the found emissions of stages of production (A1-A3) and replacement (B4). The two bays will be evaluated in the two configurations of window to wall ratio.

8.1.1 4000 mm x 1500 mm bay

The results for bay of dimensions 4000 mm x 1500 mm are shown for both configurations of 100% and 50% window to wall ratio on which different magnitudes of wind load act.

Firstly the total contribution of embodied carbon are shown for the configuration with 100% WWR considering both the stages of production (A1-A3) and replacement (B4). The results is also compared with the average limit for embodied carbon of 314 $kgCO_2/m^2$ found from the analysis of the software One Click LCA discussed in chapter 2. The results are divided based on the magnitude of wind load acting on the bay. Moreover, the results are shown also considering low-carbon glass as material for the IGU.

Embodied carbon with 1 kPa of wind load			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	102.94	77.76	180.70
Recycled Aluminium	89.74	77.76	167.50
GFRP	91.01	77.76	168.77
Laminated Timber	86.58	77.76	164.34

Table 8.1. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 1 kPa of wind

Embodied carbon with 1 kPa of wind load with low-carbon glass			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	82.78	57.6	140.38
Recycled Aluminium	69.58	57.6	127.18
GFRP	70.85	57.6	128.45
Laminated Timber	66.42	57.6	124.02

Table 8.2. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 1 kPa of wind with low-carbon glass

Embodied carbon with 2 kPa of wind load			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	122.86	93.31	216.17
Recycled Aluminium	106.70	93.31	200.01
GFRP	108.15	93.31	201.47
Laminated Timber	103.26	93.31	196.58

Table 8.3. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 2 kPa of wind

Embodied carbon with 2 kPa of wind load with low-carbon glass			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	98.66	69.12	167.78
Recycled Aluminium	82.50	69.12	151.62
GFRP	83.96	69.12	153.08
Laminated Timber	79.07	69.12	148.19

Table 8.4. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 2 kPa of wind with low-carbon glass

Embodied carbon with 4 kPa of wind load			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	135.99	101.09	237.08
Recycled Aluminium	116.11	101.09	217.20
GFRP	117.92	101.09	219.01
Laminated Timber	113.17	101.09	214.26

Table 8.5. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 4 kPa of wind

Embodied carbon with 4 kPa of wind load with low-carbon glass			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	109.78	74.88	184.66
Recycled Aluminium	89.90	74.88	164.78
GFRP	91.71	74.88	166.60
Laminated Timber	86.96	74.88	161.84

Table 8.6. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 4 kPa of wind with low-carbon glass

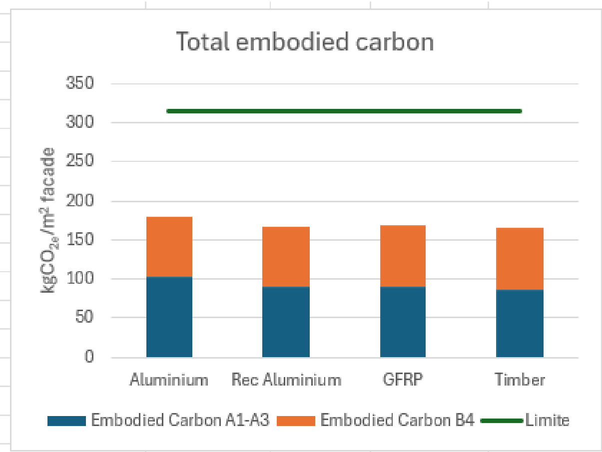

Figure 8.1. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 1 kPa of wind

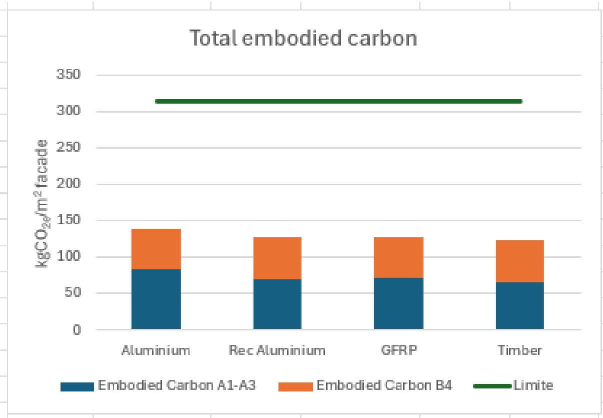

Figure 8.2. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 1 kPa of wind with low-carbon glass

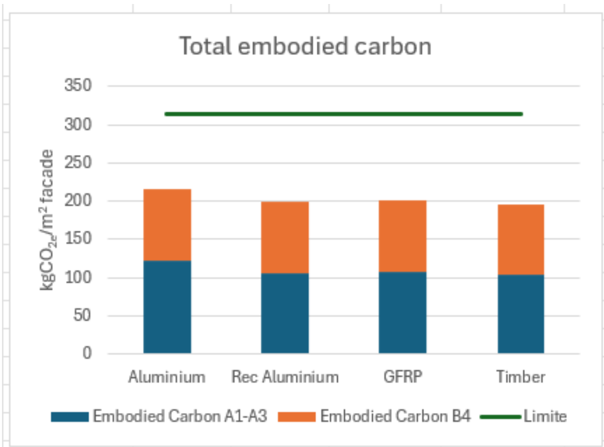

Figure 8.3. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 2 kPa of wind

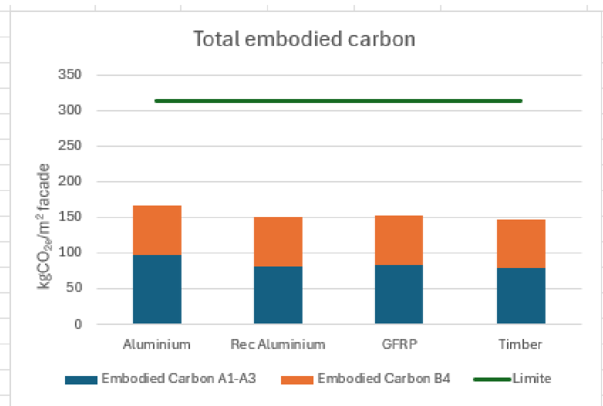

Figure 8.4. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 2 kPa of wind with low-carbon glass

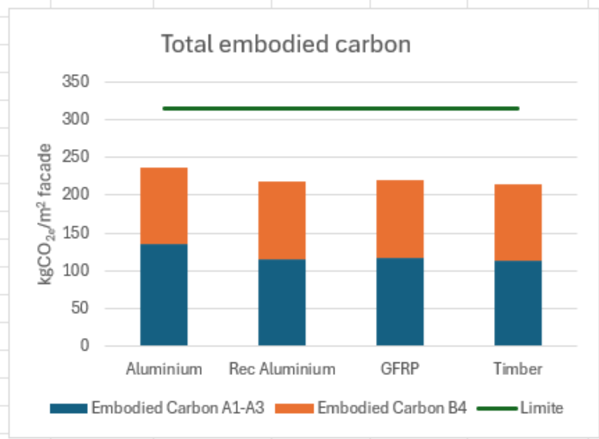

Figure 8.5. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 4 kPa of wind

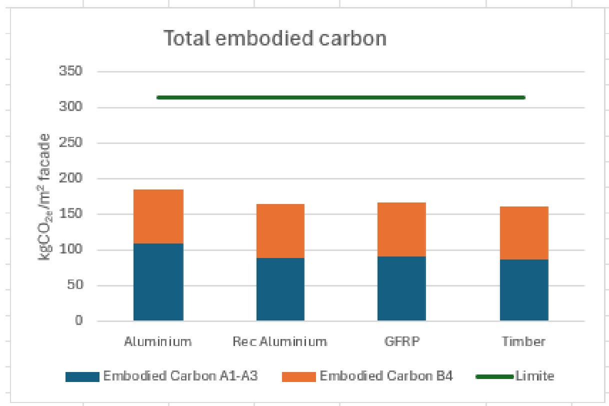

Figure 8.6. Total embodied carbon for 4000 mm x 1500 mm bay with 100% WWR and 4 kPa of wind with low-carbon glass

Embodied carbon increases of almost 50 $kgCO_2/m^2$ increasing the magnitude of wind load for each configuration of the bay.The difference in emissions between the bays with different frames is not as big as the difference in emissions given by the materials of the frames themselves alone. This happens because the majority of embodied carbon emissions of the bay depends on the glazing part instead of the frame. In fact the difference in embodied carbon for each magnitude of wind load between the most emissive frame (aluminium), and the one with lower emissions (timber) is only of 20 $kgCO_2/m^2$. This highlights how important is acting on the material used for the glazing part.
Using low-carbon glass, the embodied carbon decreases of about 40-50 $kgCO_2/m^2$ for each configuration and magnitude of wind. This reduction is more evident especially for the highest magnitude of wind where thicker glass panes are necessary.

Now the total embodied carbon regarding the facade with 50% WWR is shown for all configurations of wind acting on the bay and considering all materials for frame, IGU and opaque components.

Embodied carbon with 1 kPa of wind load				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	99.81	38.88	138.69
	Aluminium	90.58	38.88	129.46
	Stone	75.61	38.88	114.49
Recycled Aluminium	GRC	86.61	38.88	125.49
	Aluminium	77.37	38.88	116.25
	Stone	60.41	38.88	101.29
GFRP	GRC	87.88	38.88	126.76
	Aluminium	78.64	38.88	117.52
	Stone	63.68	38.88	102.56
Laminated Timber	GRC	83.45	38.88	122.33
	Aluminium	74.22	38.88	113.10
	Stone	59.25	38.88	98.13

Table 8.7. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 1 kPa of wind

Embodied carbon with 1 kPa of wind load with low-carbon glass				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	89.73	28.8	118.53
	Aluminium	80.50	28.8	109.30
	Stone	65.53	28.8	94.33
Recycled Aluminium	GRC	76.53	28.8	105.35
	Aluminium	67.29	28.8	96.09
	Stone	52.33	28.8	81.13
GFRP	GRC	77.80	28.8	106.60
	Aluminium	68.56	28.8	97.36
	Stone	53.60	28.8	82.40
Laminated Timber	GRC	73.37	28.8	102.17
	Aluminium	64.14	28.8	92.94
	Stone	49.17	28.8	77.97

Table 8.8. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 1 kPa of wind with low-carbon glass

Embodied carbon with 2 kPa of wind load				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	111.95	46.65	158.61
	Aluminium	102.72	46.65	149.37
	Stone	87.75	46.65	134.41
Recycled Aluminium	GRC	95.79	46.65	142.45
	Aluminium	86.56	46.65	133.21
	Stone	71.59	46.65	118.24
GFRP	GRC	97.25	46.65	143.90
	Aluminium	88.01	46.65	134.67
	Stone	73.05	46.65	119.70
Laminated Timber	GRC	92.36	46.65	139.01
	Aluminium	83.12	46.65	129.78
	Stone	68.16	46.65	114.81

Table 8.9. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 2 kPa of wind

Embodied carbon with 2 kPa of wind load with low-carbon glass				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	99.85	34.56	134.41
	Aluminium	90.65	34.56	125.18
	Stone	75.65	34.56	110.21
Recycled Aluminium	GRC	83.69	34.56	118.25
	Aluminium	74.45	34.56	109.02
	Stone	59.49	34.56	94.05
GFRP	GRC	85.15	34.56	119.71
	Aluminium	75.92	34.56	110.48
	Stone	60.95	34.56	95.51
Laminated Timber	GRC	80.26	34.56	114.82
	Aluminium	71.03	34.56	105.59
	Stone	56.06	34.56	90.62

Table 8.10. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 2 kPa of wind with low-carbon glass

Embodied carbon with 4 kPa of wind load				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	121.20	50.54	171.74
	Aluminium	111.96	50.54	162.51
	Stone	96.99	50.54	147.54
Recycled Aluminium	GRC	101.32	50.54	151.86
	Aluminium	92.08	50.54	142.63
	Stone	77.12	50.54	127.66
GFRP	GRC	103.13	50.54	153.67
	Aluminium	93.90	50.54	144.44
	Stone	78.93	50.54	129.47
Laminated Timber	GRC	98.38	50.54	148.92
	Aluminium	89.14	50.54	139.69
	Stone	74.177	50.54	124.72

Table 8.11. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 4 kPa of wind

Embodied carbon with 4 kPa of wind load with low-carbon glass				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	108.09	37.44	145.53
	Aluminium	98.86	37.44	136.3
	Stone	83.89	37.44	121.33
Recycled Aluminium	GRC	88.21	37.44	125.65
	Aluminium	78.98	37.44	116.42
	Stone	64.01	37.44	101.45
GFRP	GRC	90.03	37.44	127.47
	Aluminium	80.79	37.44	118.23
	Stone	65.83	37.44	103.27
Laminated Timber	GRC	85.27	37.44	122.71
	Aluminium	76.04	37.44	113.48
	Stone	61.07	37.44	98.51

Table 8.12. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 4 kPa of wind with low-carbon glass

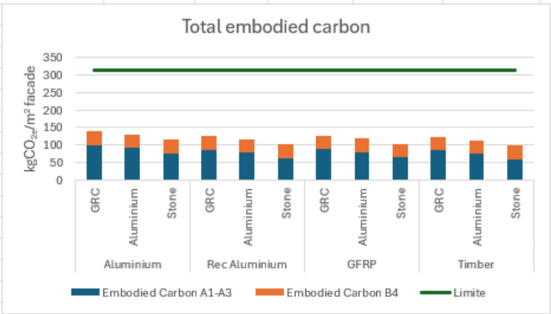

Figure 8.7. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 1 kPa of wind

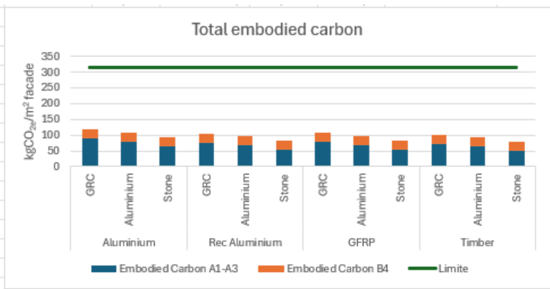

Figure 8.8. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 1 kPa of wind with low-carbon glass

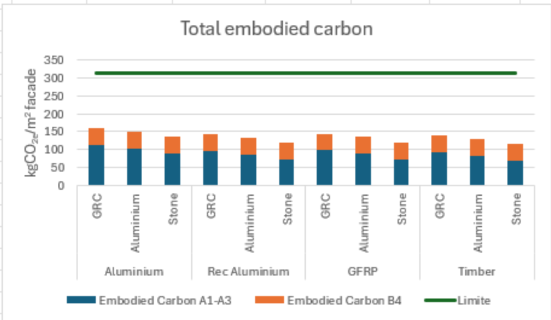

Figure 8.9. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 2 kPa of wind

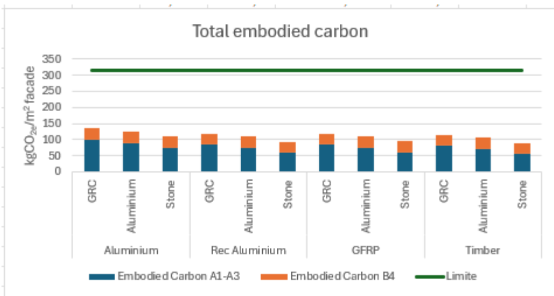

Figure 8.10. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 2 kPa of wind with low-carbon glass

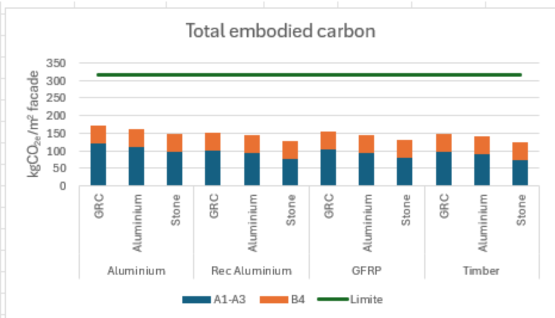

Figure 8.11. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 4 kPa of wind

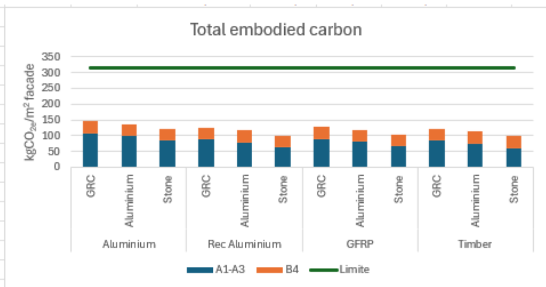

Figure 8.12. Total embodied carbon for 4000 mm x 1500 mm bay with 50% WWR and 4 kPa of wind with low-carbon glass

Since 50% WWR is now considered, the embodied carbon decreases of about 100 $kgCO_2/m^2$ with respect to the configuration with 100% WWR. This reduction is mainly due to the minor presence of glass in this configuration, even if it remains responsible of the most of the emissions. Furthermore, what changes from the 100% WWR configuration is also the contribution in embodied carbon of the stage B4 with respect to the stage A1-A3. In fact in the 50% WWR the stage of production is predominant in embodied carbon emissions since the quantity of glass, the one involved in the stage of replacement, is halved than the 100% WWR configuration.
If low-carbon glass is considered, the emissions due to the glazing part of the facade decrease even more. This means that for a facade with 50% window to wall ratio, the attention should be focused on the material from frame and opaque components to reduce the embodied carbon emissions of the facade itself.

8.1.2 4000 mm x 3000 mm bay

Also the obtained results for bay of dimensions 4000 mm x 3000 mm are shown for both configurations of 100% and 50% window to wall ratio on which different magnitudes of wind load act.

Firstly the configuration with 100% WWR is considered. As for the smallest bay, the total results related to embodied carbon are shown, summing together the contribution from production (A1-A3) and replacement stages (B4). The limits to which the values are compared is always 314 $kgCO_2/m^2$ since this threshold does not depend on the dimension of the considered bay.

Embodied carbon with 1 kPa of wind load			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	125.36	101.09	226.45
Recycled Aluminium	112.84	101.09	213.93
GFRP	113.71	101.09	214.80
Laminated Timber	110.98	101.09	212.07

Table 8.13. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 1 kPa of wind

Embodied carbon with 1 kPa of wind load with low carbon glass			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	99.15	74.88	174.03
Recycled Aluminium	86.63	74.88	161.51
GFRP	87.50	74.88	162.38
Laminated Timber	84.77	74.88	159.65

Table 8.14. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 1 kPa of wind with low carbon glass

Embodied carbon with 2 kPa of wind load			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	167.78	139.97	307.75
Recycled Aluminium	152.81	139.97	292.78
GFRP	153.95	139.97	293.92
Laminated Timber	151.16	139.97	291.13

Table 8.15. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 2 kPa of wind

Embodied carbon with 2 kPa of wind load with low carbon glass			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	131.49	103.68	235.17
Recycled Aluminium	116.52	103.68	220.20
GFRP	117.66	103.68	221.34
Laminated Timber	114.88	103.68	218.56

Table 8.16. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 2 kPa of wind with low carbon glass

Embodied carbon with 4 kPa of wind load			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	266.50	233.28	499.78
Recycled Aluminium	247.69	233.28	480.97
GFRP	249.06	233.28	482.34
Laminated Timber	246.94	233.28	480.22

Table 8.17. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 4 kPa of wind

Embodied carbon with 4 kPa of wind load with low carbon glass			
Material for frame	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	206.02	172.8	378.82
Recycled Aluminium	187.21	172.8	360.01
GFRP	188.58	172.8	361.38
Laminated Timber	186.46	172.8	359.26

Table 8.18. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 4 kPa of wind with low carbon glass

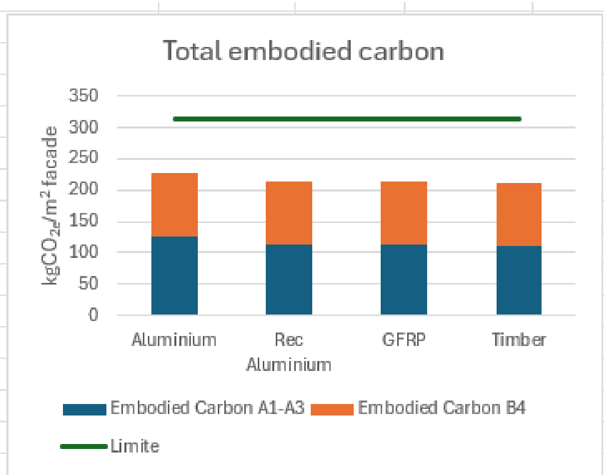

Figure 8.13. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 1 kPa of wind

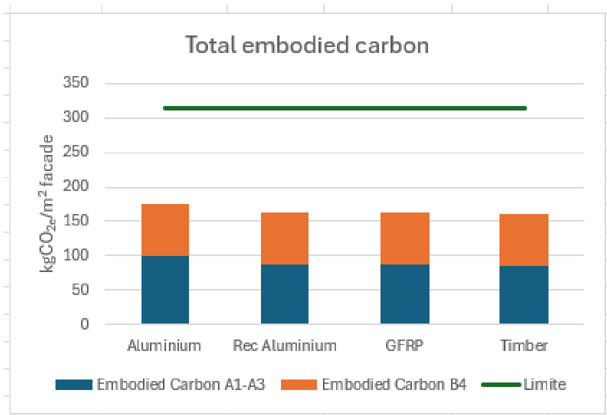

Figure 8.14. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 1 kPa of wind with recycled glass

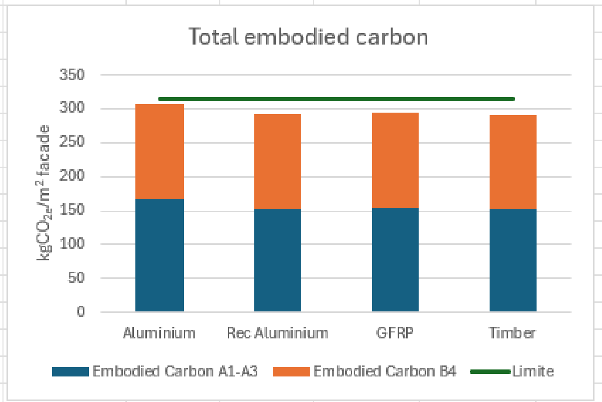

Figure 8.15. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 2 kPa of wind

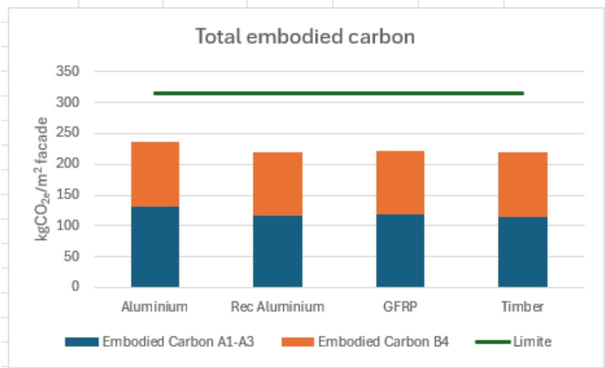

Figure 8.16. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 2 kPa of wind

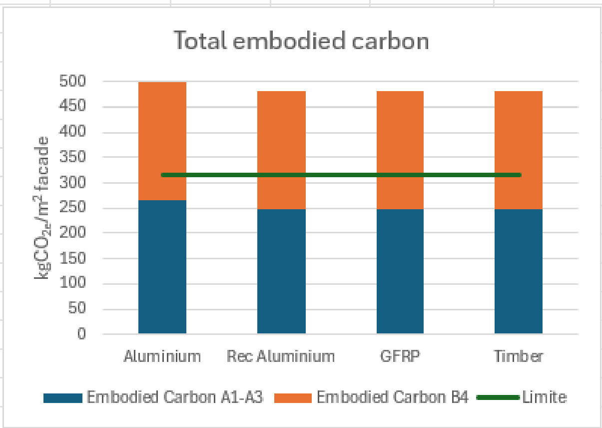

Figure 8.17. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 4 kPa of wind

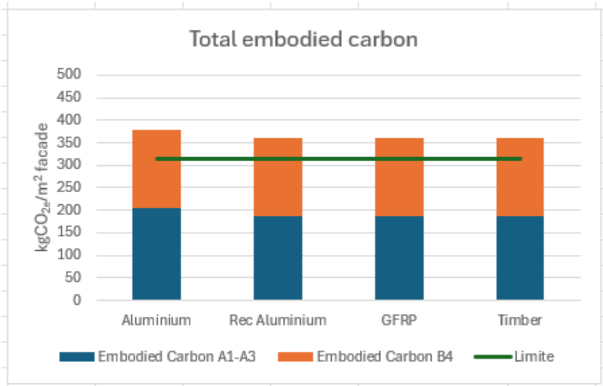

Figure 8.18. Total embodied carbon for 4000 mm x 3000 mm bay with 100% WWR and 4 kPa of wind

Since the dimensions of the bay are doubled with respect to the previous case, the emissions now are much higher than before. As a consequence of bigger bay, also thicker glass are needed to withstand the wind load, so the emissions increase a lot until being very close to the limit for 2 kPa of wind load and exceed it for 4 kPa of wind load acting on the bay. So acting on the material for the transparent part is much important with the increase of the dimension of the bay to reduce embodied carbon emissions.
As mentioned before, increasing the bay also the impact of glass increases exponentially, especially for the configuration that should withstand 4 kPa of wind load acting on the glass. Hence for greater dimensions of the bay is even more important to consider the use

of low-carbon glass. The reduction in embodied carbon due to the use of low-carbon glass increases with the increasing thickness of the glass panes used to withstand the applied wind load. Furthermore, the use of low-carbon glass is sufficient for being far from the limit for the configuration with 2 kPa of wind load, while the one with 4 kPa still exceeds it. This happens because having a large bay with great load applied on it requires great thicknesses of glass panes, so for these magnitudes of load generally smaller bays are used.

Now the total embodied carbon for bay with 50% WWR configuration is shown.

Embodied carbon with 1 kPa of wind load				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	110.56	50.54	161.11
	Aluminium	101.33	50.54	151.87
	Stone	86.36	50.54	136.91
Recycled Aluminium	GRC	98.05	50.54	148.59
	Aluminium	88.81	50.54	139.36
	Stone	73.85	50.54	124.39
GFRP	GRC	98.92	50.54	149.46
	Aluminium	89.68	50.54	140.23
	Stone	74.72	50.54	125.26
Laminated Timber	GRC	96.18	50.54	146.73
	Aluminium	86.95	50.54	137.49
	Stone	71.98	50.54	122.53

Table 8.19. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 1 kPa of wind

Embodied carbon with 1 kPa of wind load with low carbon glass				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	97.46	37.44	134.90
	Aluminium	88.23	37.44	125.67
	Stone	73.26	37.44	110.70
Recycled Aluminium	GRC	84.94	37.44	122.38
	Aluminium	75.71	37.44	113.15
	Stone	60.74	37.44	98.18
GFRP	GRC	85.81	37.44	123.25
	Aluminium	76.58	37.44	114.02
	Stone	61.61	37.44	99.05
Laminated Timber	GRC	83.08	37.44	120.52
	Aluminium	73.85	37.44	111.29
	Stone	58.88	37.44	96.32

Table 8.20. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 1 kPa of wind with low carbon glass

Embodied carbon with 2 kPa of wind load				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	133.55	69.98	203.53
	Aluminium	124.31	69.98	194.30
	Stone	109.35	69.98	179.33
Recycled Aluminium	GRC	118.57	69.98	188.56
	Aluminium	109.34	69.98	179.32
	Stone	94.37	69.98	164.36
GFRP	GRC	119.72	69.98	189.70
	Aluminium	110.48	69.98	180.47
	Stone	95.52	69.98	165.50
Laminated Timber	GRC	116.93	69.98	186.91
	Aluminium	107.70	69.98	177.68
	Stone	92.73	69.98	162.71

Table 8.21. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 2 kPa of wind

Embodied carbon with 2 kPa of wind load with low carbon glass				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	115.40	51.84	167.24
	Aluminium	106.17	51.84	158.01
	Stone	91.20	51.84	143.04
Recycled Aluminium	GRC	100.43	51.84	152.27
	Aluminium	91.19	51.84	143.03
	Stone	76.23	51.84	128.07
GFRP	GRC	101.57	51.84	153.41
	Aluminium	92.34	51.84	144.18
	Stone	77.37	51.84	129.21
Laminated Timber	GRC	98.79	51.84	150.63
	Aluminium	89.55	51.84	141.39
	Stone	74.59	51.84	126.43

Table 8.22. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 2 kPa of wind with low carbon glass

Embodied carbon with 4 kPa of wind load				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	185.61	116.64	302.25
	Aluminium	176.38	116.64	293.02
	Stone	161.41	116.64	278.05
Recycled Aluminium	GRC	166.80	116.64	283.44
	Aluminium	157.56	116.64	274.20
	Stone	142.60	116.64	259.24
GFRP	GRC	168.17	116.64	284.81
	Aluminium	158.94	116.64	275.58
	Stone	143.97	116.64	260.61
Laminated Timber	GRC	166.05	116.64	282.69
	Aluminium	156.81	116.64	27345
	Stone	141.85	116.64	258.49

Table 8.23. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 4 kPa of wind

Embodied carbon with 4 kPa of wind load with low carbon glass				
Material for frame	Opaque	Production (A1-A3) $kgCO_{2e}/m^2$	Replacement (B4) $kgCO_{2e}/m^2$	Total embodied carbon $kgCO_{2e}/m^2$
Aluminium	GRC	155.37	86.4	241.77
	Aluminium	146.14	86.4	232.54
	Stone	131.17	86.4	217.57
Recycled Aluminium	GRC	136.56	86.4	222.96
	Aluminium	127.32	86.4	213.72
	Stone	112.36	86.4	198.76
GFRP	GRC	137.93	86.4	224.33
	Aluminium	128.70	86.4	215.10
	Stone	113.73	86.4	200.13
Laminated Timber	GRC	135.81	86.4	222.21
	Aluminium	126.57	86.4	212.97
	Stone	111.61	86.4	198.01

Table 8.24. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 4 kPa of wind with low carbon glass

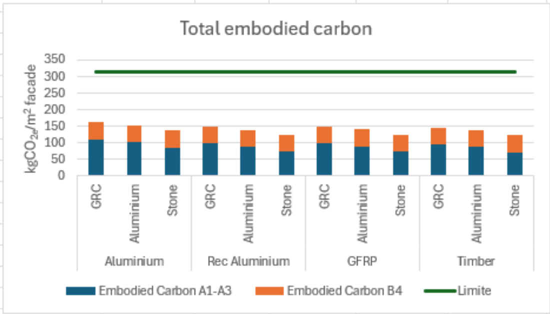

Figure 8.19. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 1 kPa of wind

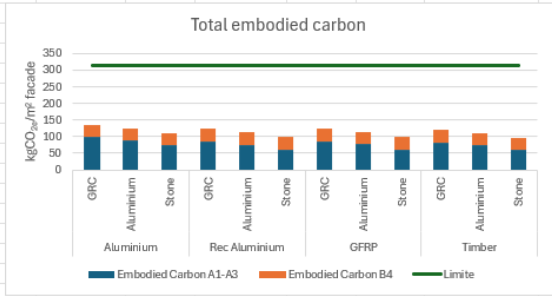

Figure 8.20. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 1 kPa of wind

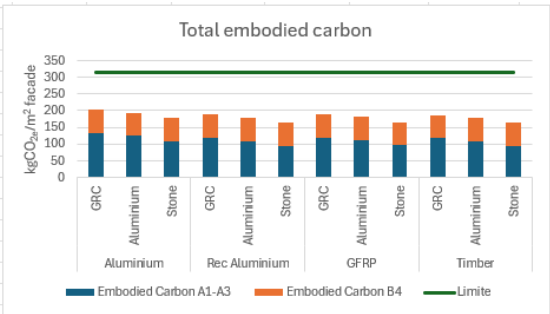

Figure 8.21. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 2 kPa of wind

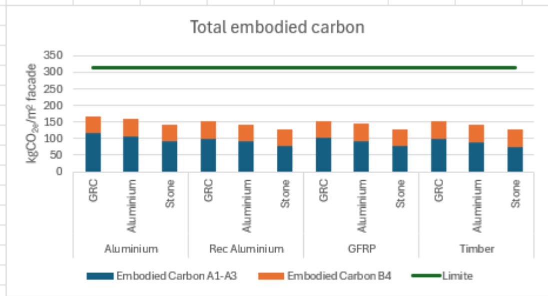

Figure 8.22. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 2 kPa of wind

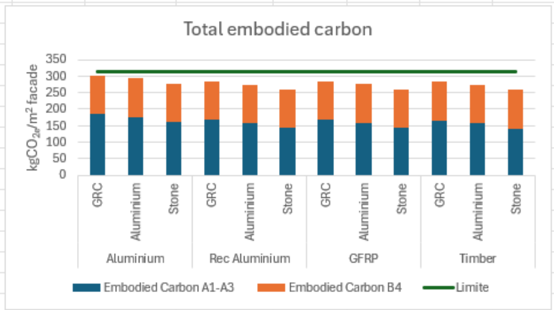

Figure 8.23. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 4 kPa of wind

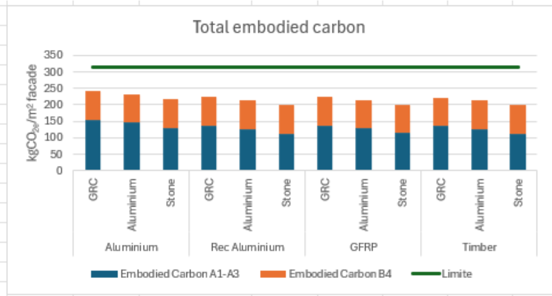

Figure 8.24. Total embodied carbon for 4000 mm x 3000 mm bay with 50% WWR and 4 kPa of wind

As for the 100% WWR configuration, also in this case, embodied carbon emissions increase passing from the bay with dimensions 4000 mm x 1500 mm to the one with dimensions 4000 mm x 1500 mm. In the 50% WWR configuration glass occupies only half of the facade bay, but considering the greatness of the bay itself and the magnitude of loads, the embodied carbon emissions are close to the limit especially in the last configuration. So even if the window to wall ratio is decreased, when the dimension of the bay increases, the emissions associated to glass remains of relevant importance.
Furthermore, considering low-carbon glass depending on the configuration of the bay, embodied carbon decreases of almost 40-50 $kgCO_2/m^2$. Thus reduction is relevant especially when the greatest magnitudes of wind are applied to the facade bay.

8.2 Total operational carbon over time

Now the total embodied carbon is compared with the operational carbon results coming from the previous chapter in all configurations of the considered bay and room over the building life expectancy. A period of 50 years is considered where the embodied carbon of stages A1-A3 is completely emitted in the first year when the materials are manufactured, while the emissions related to stage B4 are emitted in year 25 when glass is replaced.
As regards the operational carbon emissions, they are emitted over the whole life of the building depending on the considered scenario.
Comparing the total embodied carbon emitted by the facade with its total operational carbon, the effects of the embodied carbon over time becomes minimal. This means that changing the materials used for manufacturing the bay in terms of transparent and opaque components and frame has a minimal impact on the total emissions over the entire life cycle of the facade. Even if these emissions are important for today environment. For this reason, in the following analysis, different design options that have an effect on embodied carbon are not taken into account, but it is calculated considering aluminium as material for frame, glass for the transparent components and aluminium for the opaque ones. While the different scenarios for operational carbon are all analyzed. Moreover two

scenarios are considered for the variation of the energy demand over time. In the first case (named as "ed 1" in the graph) the energy demand does not vary over the service life of the facade, this means that the degradation of the IGU is not considered. While in the second scenario (named as "ed 3" in the graph), the degradation of the IGU is taken into account considering that the infilled Argon after 25 years is completely substituted with air and also the coating looses its performances.

8.2.1 4000 mm x 1500 mm bay

Firstly the results over time for the bay with dimensions 4000 mm x 1500 mm and in the configuration of 100% WWR are shown.

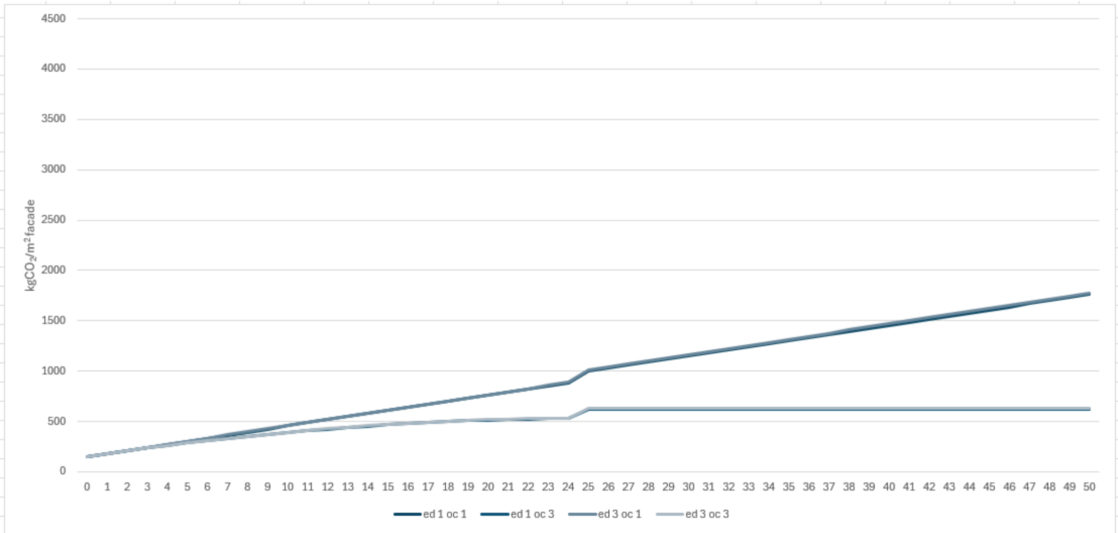

Figure 8.25. Cumulative emission over time considering a facade/floor ratio equal to 50%

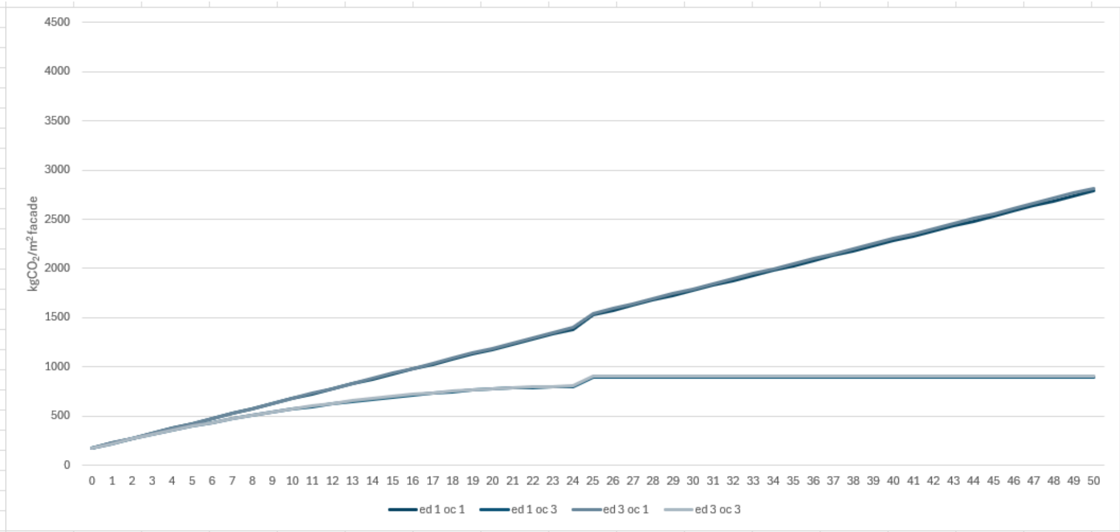

Figure 8.26. Cumulative emission over time considering a facade/floor ratio equal to 30%

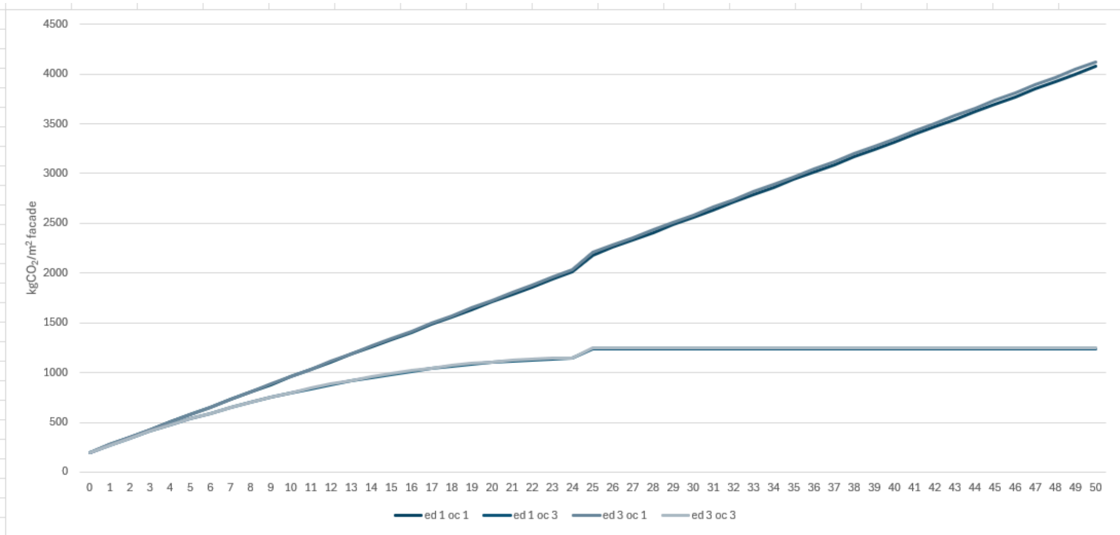

Figure 8.27. Cumulative emission over time considering a facade/floor ratio equal to 20%

For the 100% WWR configuration, emissions are strongly influenced by the assumed decarbonization pathway of the grid. The difference between the two energy demand scenarios is minimal since the variation in U-value produces only a modest increase in energy consumption. However, the difference between grid decarbonization scenarios is substantial: when grid decarbonizes, total cumulative emissions after 50 years are reduced by more than half compared to the static-grid scenario. This demonstrates that future

reductions in the carbon intensity of electricity can outweigh the negative effects of IGU degradation.
Furthermore, at smaller $\frac{facade}{floor}$ ratios, the total emissions increase because a lower ratio corresponds to larger room depth and therefore higher energy needs per square meter of facade. This trend is consistent across both scenarios, although the relative benefit of grid decarbonization becomes even more evident at higher energy-demand configurations, emphasizing the synergy between envelope efficiency and clean energy supply.

Now the results are shown considering the 50% WWR facade configuration.

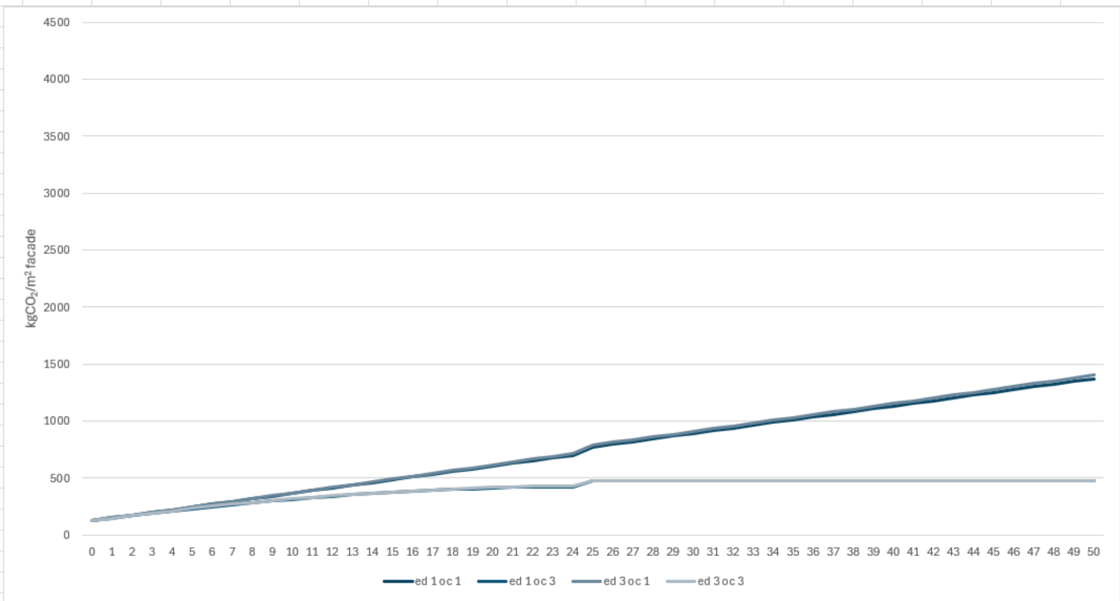

Figure 8.28. Cumulative emission over time considering a facade/floor ratio equal to 50%

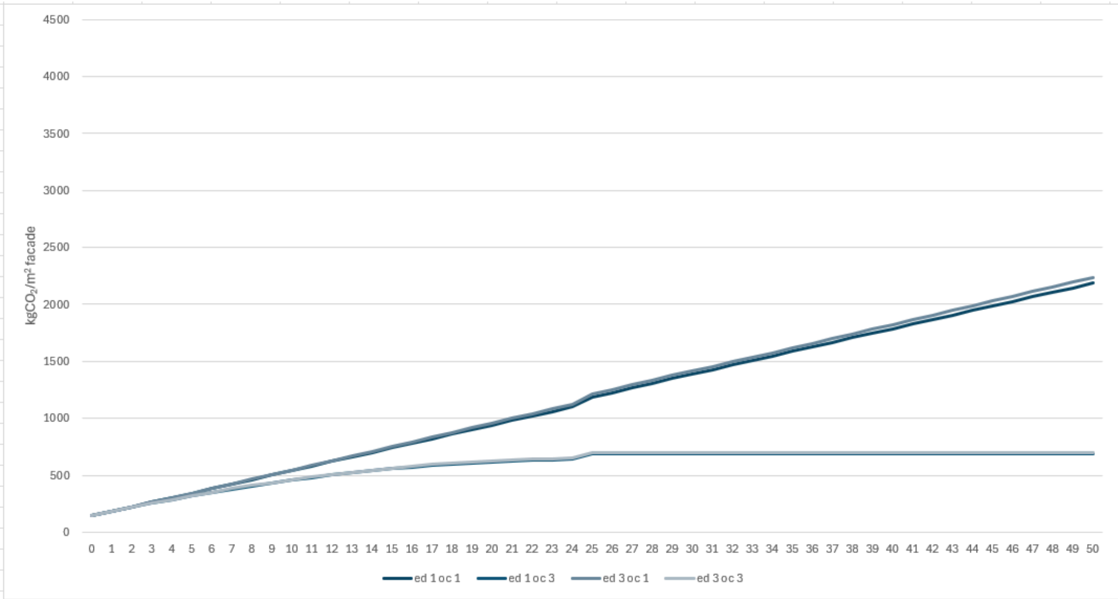

Figure 8.29. Cumulative emission over time considering a facade/floor ratio equal to 30%

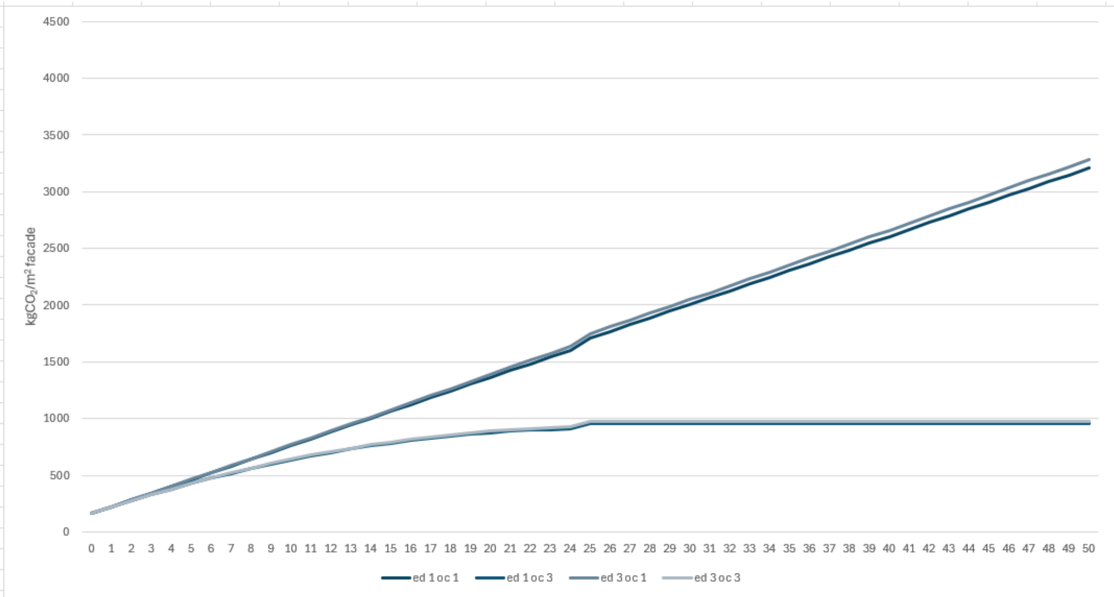

Figure 8.30. Cumulative emission over time considering a facade/floor ratio equal to 20%

For the 50% WWR configuration, emissions decrease significantly compared to the fully glazed case. This reduction results from the higher insulation capacity of the opaque portions of the facade, which lower both heating and cooling loads. The influence of U-value degradation remains modest, but the proportional advantage of grid decarbonization is similar to that observed in the 100% WWR situation. In all cases, the operational phase remains the dominant contributor to total carbon, highlighting that design strategues aiming only at reducing embodied emissions have limited overall effect without considering operational behavior.

8.2.2 4000 mm x 3000 mm bay

Firstly the results for the bay with dimensions 4000 mm x 3000 mm and in the configurations of 100% WWR are shown.

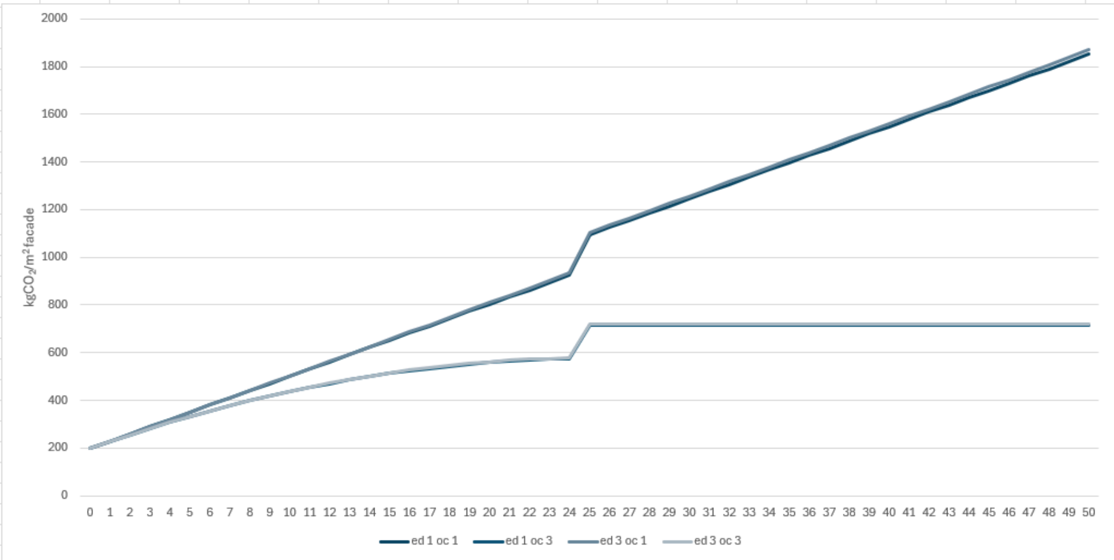

Figure 8.31. Cumulative emission over time considering a facade/floor ratio equal to 50%

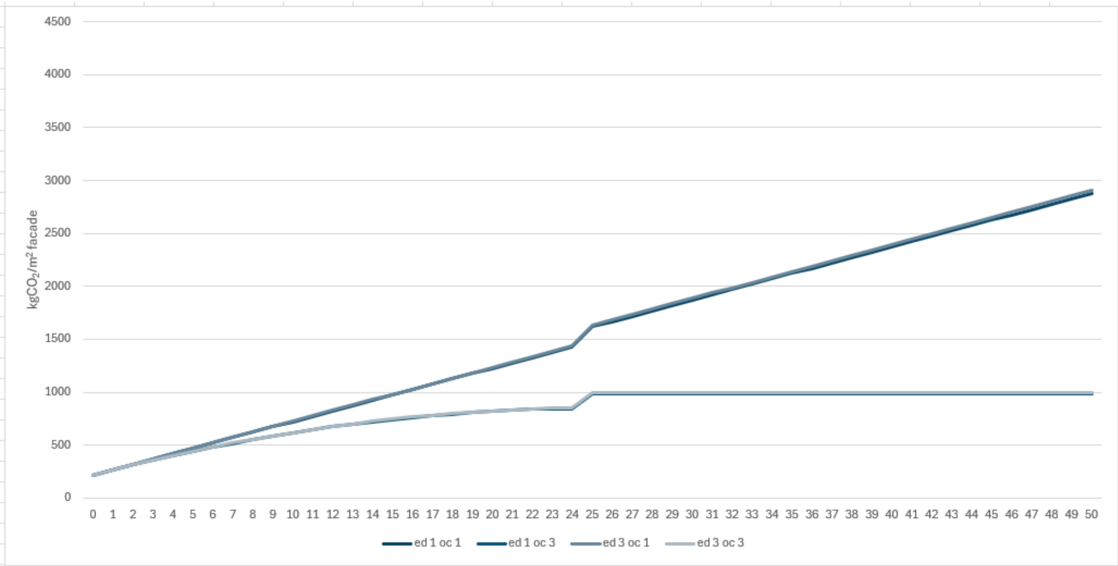

Figure 8.32. Cumulative emission over time considering a facade/floor ratio equal to 30%

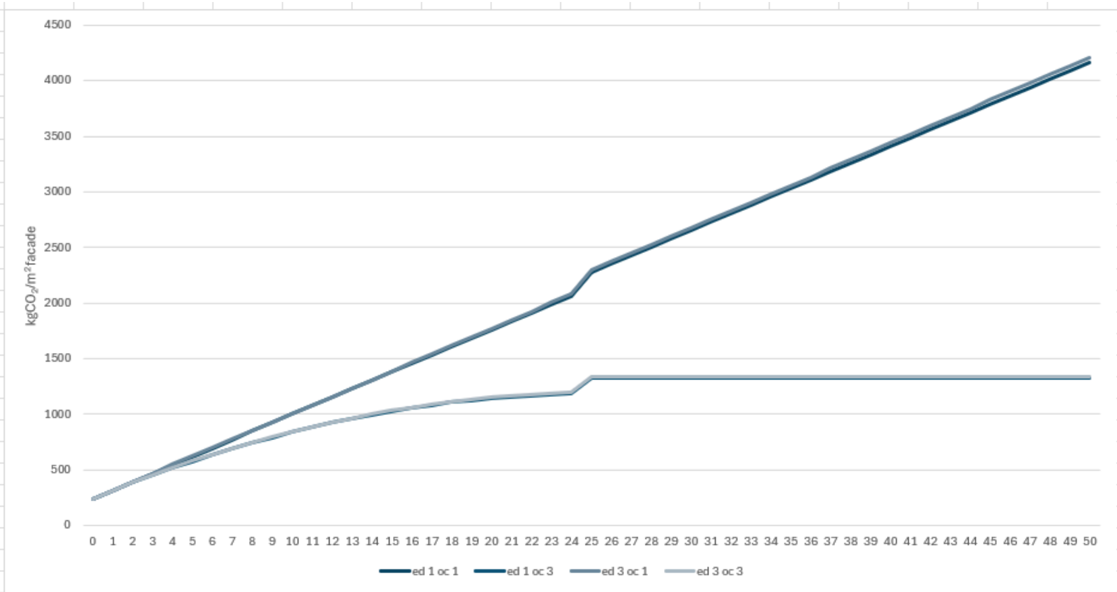

Figure 8.33. Cumulative emission over time considering a facade/floor ratio equal to 20%

For the larger bay (4000 mm x 3000 mm), the trend of emissions over time mirrors that of the smaller bay. Although the embodied carbon increases due to larger glass surfaces and heavier framing, the influence of operational carbon again dominates the

total life-cycle emissions. The difference in cumulative emissions between the two bay sizes is minor, confirming that the facade's thermal behavior has a stronger effect than its material quantity on long-term carbon balance.
For the 100% WWR configuration, the results confirm that the decarbonization of the grid drastically changes the emission trajectory: while the cumulative curve under scenario 1 keeps rising steadily, it tends to flatten after 2040 under scenario 2, approaching a quasi-stable value as the emission factor of the grid approaches to zero. This clearly shows how strongly operational emissions depend on the energy system context rather than only on the facade's design.

Now the results are shown considering the 50% WWR facade configuration.

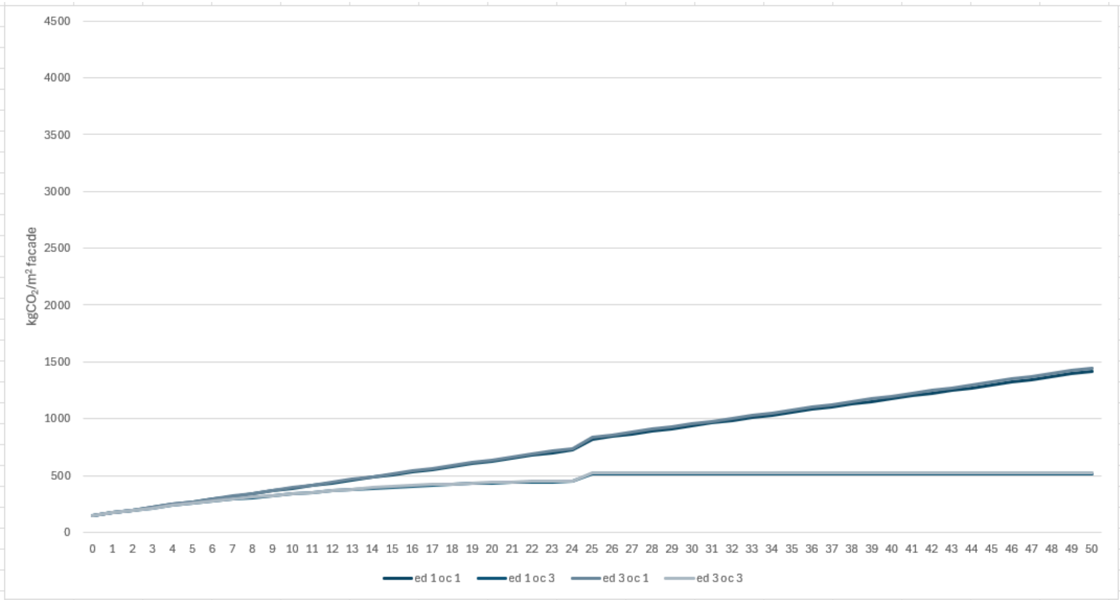

Figure 8.34. Cumulative emission over time considering a facade/floor ratio equal to 50%

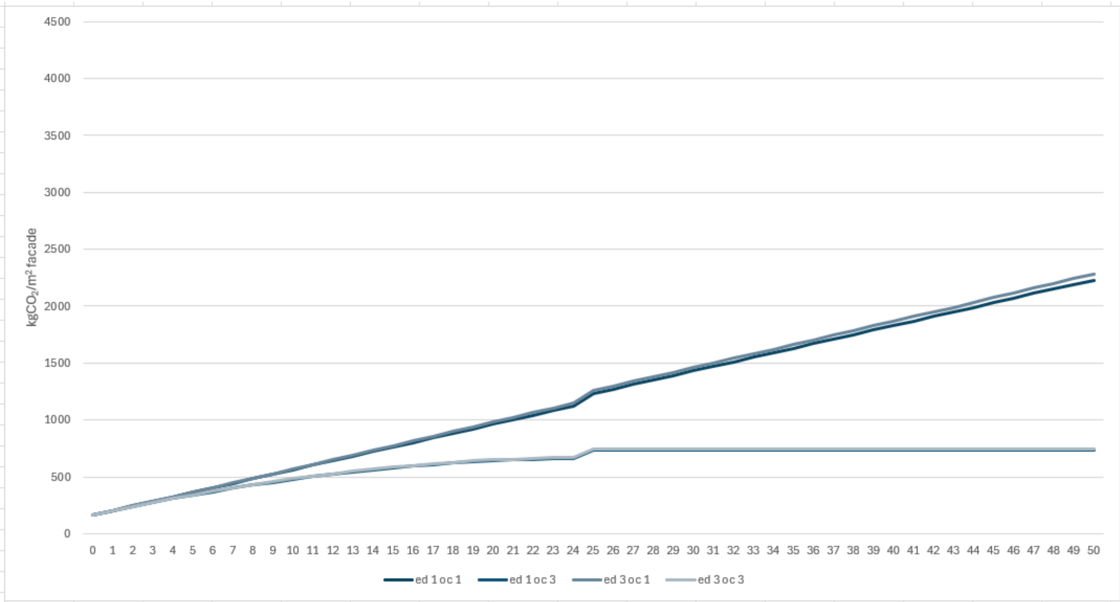

Figure 8.35. Cumulative emission over time considering a facade/floor ratio equal to 30%

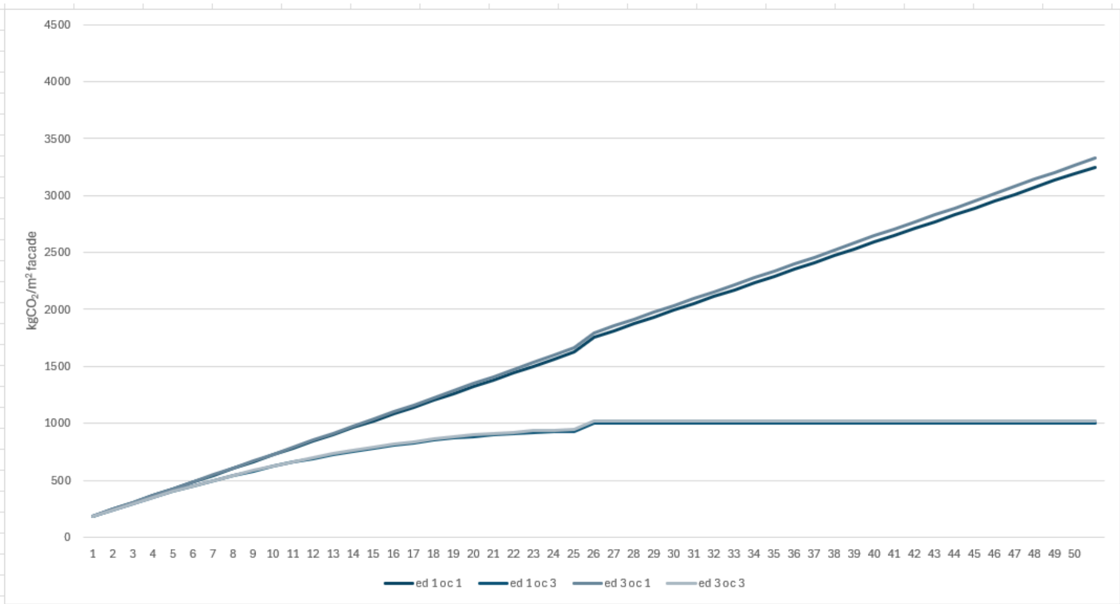

Figure 8.36. Cumulative emission over time considering a facade/floor ratio equal to 20%

In the 50% WWR configuration, total emissions decrease further. Although the relative difference between the two U-value scenarios is slightly more visible due to the larger

surface, it still remains secondary compared to the effect of grid decarbonization. Emissions increase with decreasing $\frac{facade}{floor}$ ratio, confirming once again that deeper rooms with the same facade exposure lead to higher operational carbon intensity.
Overall, the results underline that optimizing the window to wall ratio is one of the most effective passive strategies for reducing lifetime emissions of facade, and building in general.

To summarize a table showing all the total emissions at the end of the building life cycle is presented below.
For 100% WWR:

bay dimension	facade/floor	energy variation scenario	grid scenario	embodied carbon [kgCO$_2$/m^2 facade]	operational carbon [kgCO$_2$/m^2 facade]	total emissions [kgCO$_2$/m^2 facade]
4000 mm x 1500 mm	50%	1	no decarbonization	216,17	1543,34	1759,51
		3	decarbonization	216,17	408,49	624,66
		1	no decarbonization	216,17	1561,66	1777,82
		3	decarbonization	216,17	411,78	627,95
	30%	1	no decarbonization	216,17	2569,66	2785,83
		3	decarbonization	216,17	680,13	896,30
		1	no decarbonization	216,17	2600,11	2816,28
		3	decarbonization	216,17	685,61	901,78
	20%	1	no decarbonization	216,17	3858,35	4074,51
		3	decarbonization	216,17	1021,22	1237,39
		1	no decarbonization	216,17	3904,06	4120,23
		3	decarbonization	216,17	1029,45	1245,62
4000 mm x 3000 mm	50%	1	no decarbonization	307,75	1543,34	1851,09
		3	decarbonization	307,75	408,49	716,24
		1	no decarbonization	307,75	1561,63	1869,37
		3	decarbonization	307,75	411,78	719,53
	30%	1	no decarbonization	307,75	2569,66	2877,41
		3	decarbonization	307,75	680,13	987,88
		1	no decarbonization	307,75	2600,11	2907,85
		3	decarbonization	307,75	685,61	993,36
	20%	1	no decarbonization	307,75	3858,35	4166,09
		3	decarbonization	307,75	1021,22	1328,97
		1	no decarbonization	307,75	3904,06	4211,81
		3	decarbonization	307,75	1029,45	1337,20

Figure 8.37. Summarized values for 100% WWR

For 50% WWR:

bay dimension	facade/floor	energy variation scenario	grid scenario	embodied carbon [$kgCO_2/m^2$ facade]	operational carbon [$kgCO_2/m^2$ facade]	total emissions [$kgCO_2/m^2$ facade]
4000 mm x 1500 mm	50%	1	no decarbonization	149,37	1191,34	1340,72
		3	decarbonization	149,37	315,32	464,70
		1	no decarbonization	149,37	1238,00	1387,38
		3	decarbonization	149,37	323,72	473,09
	30%	1	no decarbonization	149,37	1983,59	2132,96
		3	decarbonization	149,37	525,01	674,39
		1	no decarbonization	149,37	2061,28	2210,65
		3	decarbonization	149,37	539,00	688,37
	20%	1	no decarbonization	149,37	2978,36	3127,73
		3	decarbonization	149,37	788,31	937,68
		1	no decarbonization	149,37	3095,01	3244,38
		3	decarbonization	149,37	809,30	958,67
4000 mm x 3000 mm	50%	1	no decarbonization	194,30	1191,34	1385,64
		3	decarbonization	194,30	315,32	509,62
		1	no decarbonization	194,30	1238,00	1432,30
		3	decarbonization	194,30	323,72	518,02
	30%	1	no decarbonization	194,30	1983,59	2177,88
		3	decarbonization	194,30	525,01	719,31
		1	no decarbonization	194,30	2061,28	2255,57
		3	decarbonization	194,30	539,00	733,29
	20%	1	no decarbonization	194,30	2978,36	3172,66
		3	decarbonization	194,30	788,31	982,60
		1	no decarbonization	194,30	3095,01	3289,30
		3	decarbonization	194,30	809,30	1003,60

Figure 8.38. Summarized values for 50% WWR

8.2.3 Comparison between DGU and TGU

As explained in the previous chapter a comparison between the double glazing unit and the triple glazing unit is done to understand if there are advantages in using the TGU considering its whole life cycle. The comaprison is made considering the 4000 mm x 1500 mm bay.
Hence before presenting the graphs about the emissions over the entire life cycle of the facade, the embodied carbon of the TGU is calculated.
A TGU with a total thickness of glass equal to 30 mm is considered, this means 72 kg/m^2 of facade. The Emission Carbon Factor (ECF) of a triple glazing unit is 1.75, that is higher than the one of a double glazing unit that was 1.62. Hence, the embodied emissions for which the TGU is responsible are equal to 126 $kgCO_2/m^2 of facade$. To this value, the emissions regarding the frame are added, and the total embodied carbon of stage A1-A3 are 148.68 $kgCO_2/m^2 of facade$ in case of 100% WWR and 119.06 $kgCO_2/m^2 of facade$ in case of 50% WWR. To find the total embodied carbon the emissions related to the replacement stage are added. These are equal to 126 $kgCO_2/m^2 of facade$ in case of 100% WWR and 63 $kgCO_2/m^2 of facade$ in case of 50% WWR.
After calculating the embodied carbon emissions of the facade considering a TGU applied on it, the cumulative emissions over time of the facade are shown.

As regards the 100% WWR configuration.

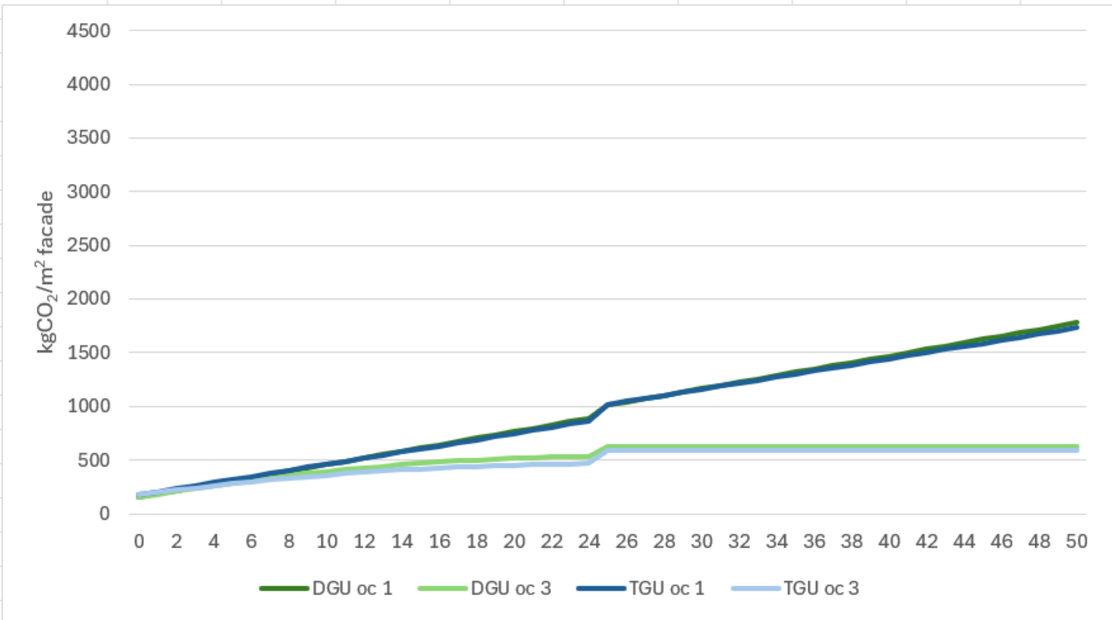

Figure 8.39. Cumulative emission over time considering a facade/floor ratio equal to 50%

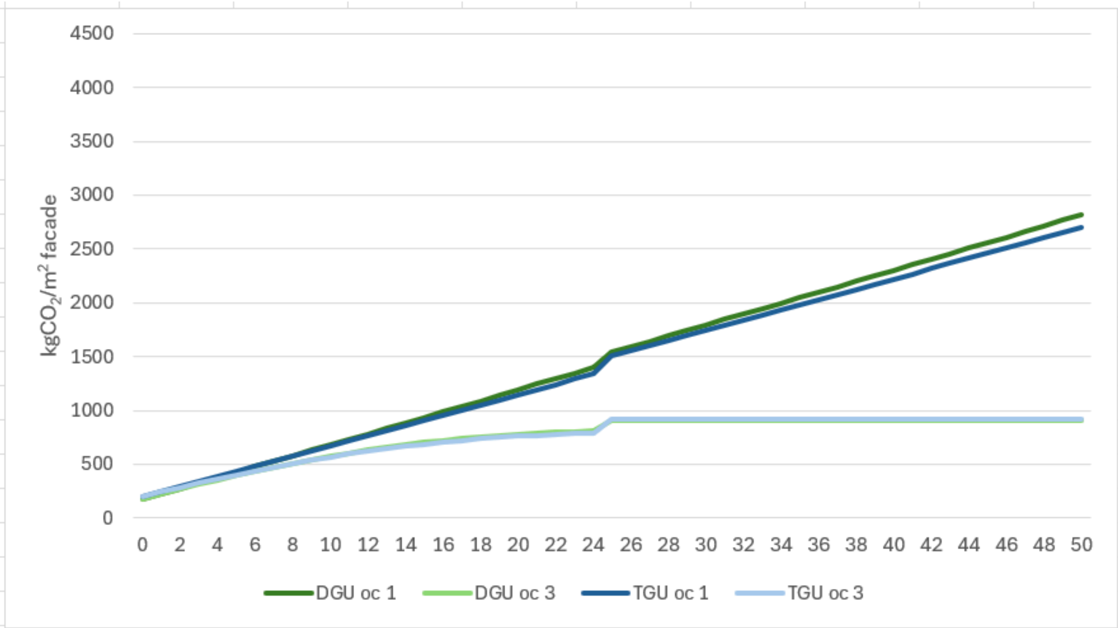

Figure 8.40. Cumulative emission over time considering a facade/floor ratio equal to 30%

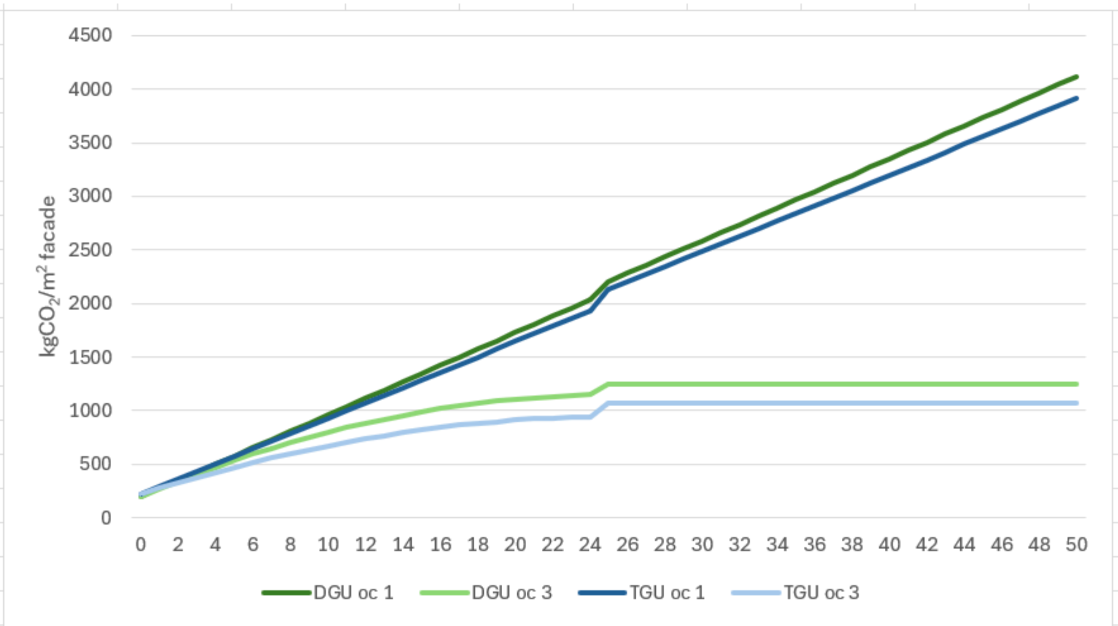

Figure 8.41. Cumulative emission over time considering a facade/floor ratio equal to 20%

For the 100% WWR configuration, the use of TGU results in a significant reduction of total operational carbon, especially under scenario 1 (no grid decarbonization). The improved insulation reduces annual energy demand, leading to cumulative emission savings that offset the higher embodied carbon within the first 10-15 years of operation. Under scenario 2 (with decarbonization of the grid), the advantage of TGU diminishes over time because the grid's emission factor approaches zero, meaning that energy savings yield smaller carbon benefits. Nevertheless, for high-transparency facades and small $\frac{facade}{floor}$ ratios, the TGU remains the most advantageous solution, as its better insulation mitigates thermal looses in absolute terms.

Now the results regarding the 50% WWR configuration are shown.

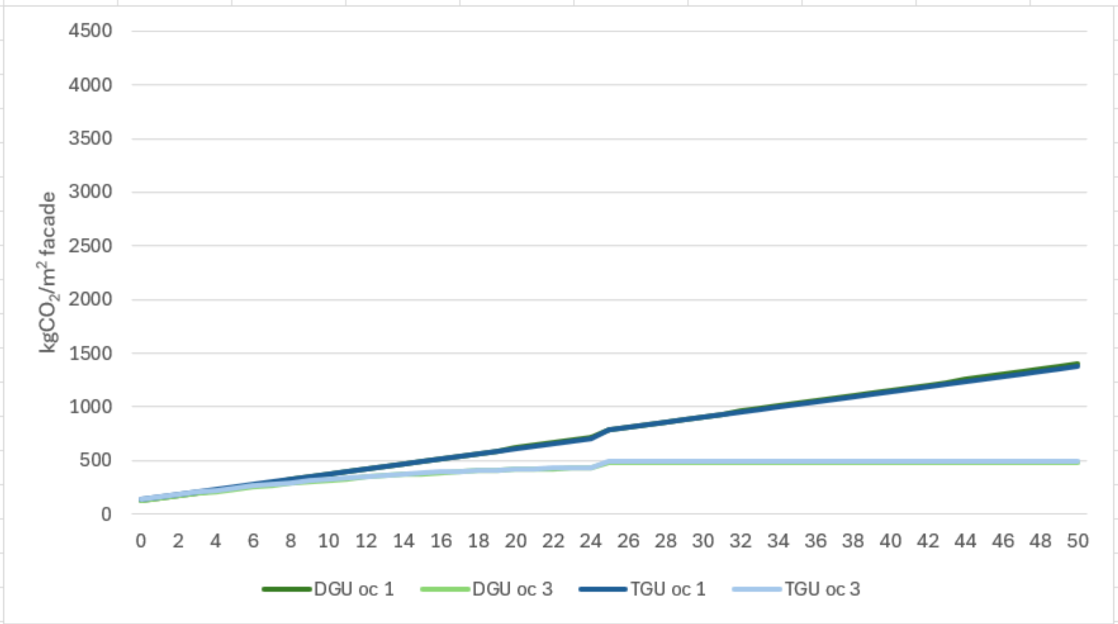

Figure 8.42. Cumulative emission over time considering a facade/floor ratio equal to 50%

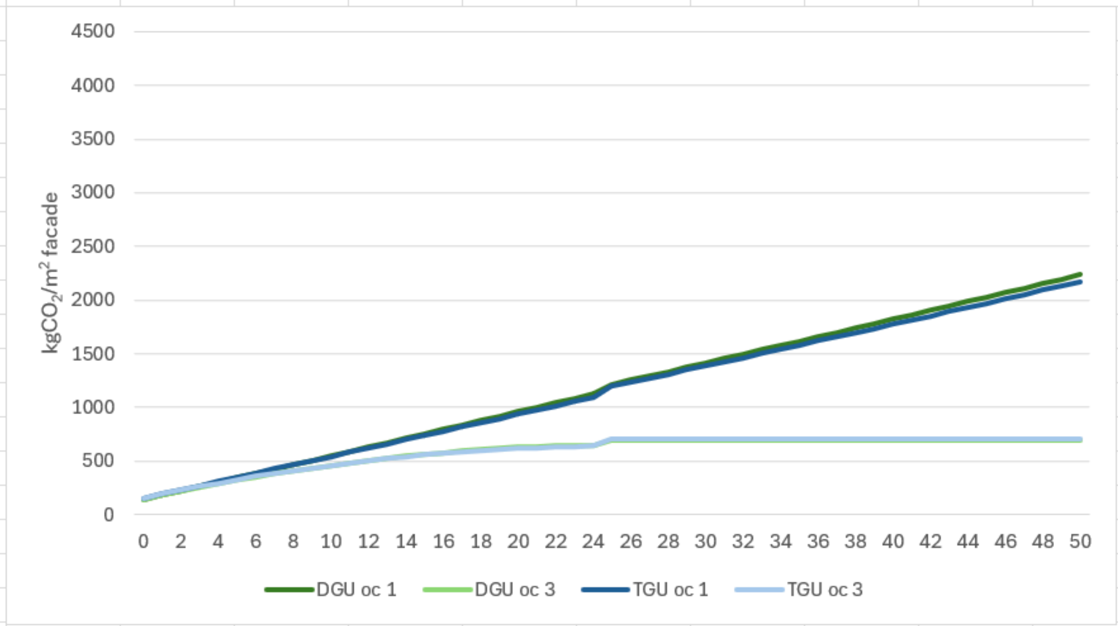

Figure 8.43. Cumulative emission over time considering a facade/floor ratio equal to 30%

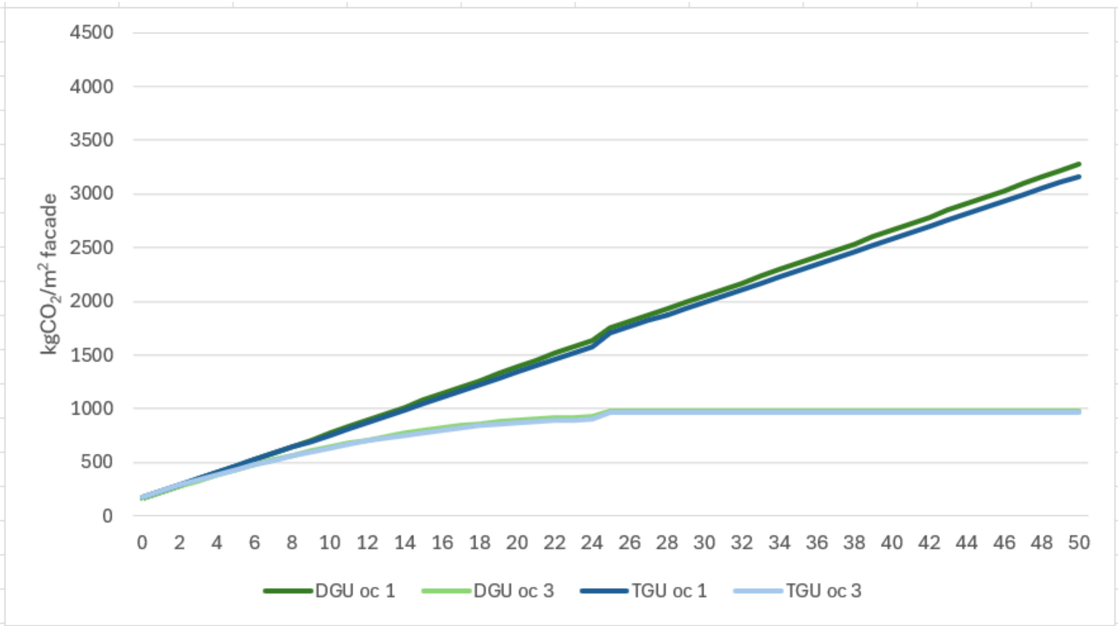

Figure 8.44. Cumulative emission over time considering a facade/floor ratio equal to 20%

For the 50% WWR configuration, the difference between DGU and TGU is much smaller. Since the transparent area is halved, the contribution of glass performance to the total energy demand becomes secondary, and the impact of the opaque portion dominates. In the static-grid scenario, TGU still offers a slight reduction in cumulative emissions, but in the decarbonized-grid case, the two systems perform almost equivalently. Hence, the use of TGU is recommended primarily for fully glazed facades or for cases where energy supply is expected to remain carbon-intensive, while for mixed facades (50% WWR) its adoption may not justify the additional embodied carbon.

To summarize a table showing all the total emissions at the end of the building life cycle is presented below.
For 100% WWR:

type of IGU	facade/floor	energy variation scenario	grid scenario	embodied carbon [$kgCO_2/m^2$ facade]	operational carbon [$kgCO_2/m^2$ facade]	total emissions [$kgCO_2/m^2$ facade]
DGU	50%	1	no decarbonization	216,17	1543,34	1759,51
		3	decarbonization	216,17	408,49	624,66
		1	no decarbonization	216,17	1561,66	1777,82
		3	decarbonization	216,17	411,78	627,95
	30%	1	no decarbonization	216,17	2569,66	2785,83
		3	decarbonization	216,17	680,13	896,30
		1	no decarbonization	216,17	2600,11	2816,28
		3	decarbonization	216,17	685,61	901,78
	20%	1	no decarbonization	216,17	3858,35	4074,51
		3	decarbonization	216,17	1021,22	1237,39
		1	no decarbonization	216,17	3904,06	4120,23
		3	decarbonization	216,17	1029,45	1245,62
TGU	50%	1	no decarbonization	274,69	1503,14	1777,82
		3	decarbonization	274,69	353,26	627,95
		1	no decarbonization	274,69	1457,78	1732,46
		3	decarbonization	274,69	318,97	593,66
	30%	1	no decarbonization	274,69	2541,59	2816,28
		3	decarbonization	274,69	627,10	901,78
		1	no decarbonization	274,69	2427,20	2701,88
		3	decarbonization	274,69	638,74	913,43
	20%	1	no decarbonization	274,69	3845,55	4120,23
		3	decarbonization	274,69	970,93	1245,62
		1	no decarbonization	274,69	3644,44	3919,13
		3	decarbonization	274,69	797,44	1072,12

Figure 8.45. Comparison of summarized values for 100% WWR

For 50% WWR:

type of IGU	facade/floor	energy variation scenario	grid scenario	embodied carbon [$kgCO_2/m^2$ facade]	operational carbon [$kgCO_2/m^2$ facade]	total emissions [$kgCO_2/m^2$ facade]
DGU	50%	1	no decarbonization	149,37	1191,34	1340,72
		3	decarbonization	149,37	315,32	464,70
		1	no decarbonization	149,37	1238,00	1387,38
		3	decarbonization	149,37	323,72	473,09
	30%	1	no decarbonization	149,37	1983,59	2132,96
		3	decarbonization	149,37	525,01	674,39
		1	no decarbonization	149,37	2061,28	2210,65
		3	decarbonization	149,37	539,00	688,37
	20%	1	no decarbonization	149,37	2978,36	3127,73
		3	decarbonization	149,37	788,31	937,68
		1	no decarbonization	149,37	3095,01	3244,38
		3	decarbonization	149,37	809,30	958,67
TGU	50%	1	no decarbonization	182,06	1205,32	1387,38
		3	decarbonization	182,06	291,03	473,09
		1	no decarbonization	182,06	1193,85	1375,91
		3	decarbonization	182,06	313,81	495,87
	30%	1	no decarbonization	182,06	2028,59	2210,65
		3	decarbonization	182,06	506,31	688,37
		1	no decarbonization	182,06	1987,75	2169,81
		3	decarbonization	182,06	522,49	704,55
	20%	1	no decarbonization	182,06	3062,32	3244,38
		3	decarbonization	182,06	776,61	958,67
		1	no decarbonization	182,06	2984,61	3166,67
		3	decarbonization	182,06	784,52	966,58

Figure 8.46. Comparison of summarized values for 50% WWR

In summary, the comparative analysis highlights that:

- Grid decarbonization exerts the strongest influence on total operational carbon
- U-value degradation has a secondary but non-negligible effect, especially in non-decarbonized contexts
- The advantage of TGU over DGU depends on both WWR and the future carbon intensity of the energy mix
- For 100% WWR facades, TGU consistently outperforms DGU, while for 50% WWR facades their performance converges

Chapter 9

Conclusion

The transition toward a low-carbon built environment is one of the greatest challenges faced by the construction industry today. As demonstrated throughout this thesis, reducing the environmental impact of buildings requires not only improving their operational energy efficiency but also addressing the emissions embedded in their materials and construction processes. The facade, as an interface between indoor and outdoor environments, plays a decisive role in both aspects. A focus on curtain wall facades was done, one of the most carbon-intensive facade systems, to quantify and reduce their carbon footprint by developing a comprehensive life cycle approach.
Glazing facades are responsible for a significant share of the total embodied carbon in the construction sector. In fact the combination of glass, aluminium, and other energy-intensive materials makes their production and maintenance highly emissive. For this reason, this thesis addresses the need to understand and mitigate both the embodied carbon and operational carbon associated with these systems, aiming to identify facade configurations that achieve a better environmental performance without compromising structural integrity or thermal comfort.

The analyses conducted confirmed that glass and aluminium are the main contributors to the embodied carbon of curtain wall facades. Within the production stage (modules A1-A3 of LCA), glass alone accounts for more than half of total emissions, due to the high temperature and fossil-fuel energy required for its manufacturing. For this reason, low-carbon glass can help to reduce significantly the emissions related to the transparent part of the facade.
Moreover, the frame system represents the second most emissive component especially when virgin aluminium is used. The study also highlighted that recycled aluminium and laminated timber can considerably reduce emissions, despite requiring larger sections to maintain structural performance. While regarding the opaque components, the analysis demonstrated that materials such as stone panels can achieve much lower embodied carbon compared to GRC panels and aluminium sheets. This happens mainly because of their lower emission factors and simpler manufacturing processes. Furthermore, opaque components have also lower impact than the transparent ones, therefore reducing the window to wall ratio, the total embodied carbon of facades decreases significantly.

As regards the replacement stage (module B4 of LCA), results showed that the substitution of insulated glass units has a strong influence on the life cycle impact. In fact assuming a service life of 25 years for glass, its replacement can increase the embodied carbon of the facade by more than 30%. This underlines the importance of extending the service life of glazing systems through higher-quality seals, improved maintenance, and the adoption of durable materials.

From the operational perspective, simulations conducted with the software *COMFEN5* showed that facades with smaller transparent areas also achieve better energy performance, reducing the operational carbon by up to 20-30% compared with fully glazed facades. The reason is that opaque materials have higher insulation capacity than glazing, reducing both heat losses in winter and solar gains in summer. However, the study also revealed that an optimal balance must be found: increasing the glazing area can decrease embodied carbon at the production stage, but it simultaneously increases the operational carbon because of higher energy consumption. Therefore, the most sustainable facade design results from a careful trade-off between embodied and operational emissions.
As regards operational carbon, an additional focus should be done on the aging of insulated glass units. In fact over a 25-year service life, the U-value of glass can increase due to gas leakage, seal and coating degradation, which corresponds in a rise in operational carbon. This dynamic behavior underlines the necessity of considering time-dependent performance in facade design and to plan for maintenance and replacement strategies as part of the life cycle assessment. But also the decarbonization of the grid and its impact on how operational carbon evolves in time should be considered. In fact even if the energy demand increases during the life of the building due to the degradation of the IGU; operational carbon can decrease thanks to the decarbonization of the grid based on the considered scenario.
Finally a focus is done on the comparison between triple glazing units and double glazing units to evaluate the advantages in terms of emissions of using the first one. This analysis underlines how the energy savings thanks to the use of TGU can be of great importance especially for fully transparent facades and low values of $\frac{facade}{floor}$ ratio.

To summarize, throughout a comparative analysis, this study identifies low-carbon design strategies including:

- the use of laminated timber for frames where possible instead of virgin aluminium, or at least recycled aluminium and GFRP can be used

- the use of low-carbon glass which reduces emission by approximately 25%

- the optimization of window to wall ratio to achieve a balance between light transmission, thermal comfort, and carbon footprint

- the adoption of durable materials and design details that extend the service life of components, reducing the need for replacement

- the use of TGU instead of DGU for 100% WWR facade configuration and low values of $\frac{facade}{floor}$ ratio

Together, these strategies demonstrate that significantly reductions up to 30-40% in total emissions can be achieved without altering the architectural character or functional performance of curtain wall facades.

While the research provided a detailed and data-driven evaluation, certain limitations remain. The embodied carbon values were calculated using database and environmental product declarations (EPDs) that represent average industry data, and may depending on specific manufacturers, supply chains, and regional practices. While the operational simulations were conducted under standardized conditions and do not fully capture the variability of building locations, climate zones, and occupant behavior. Furthermore, the energy demands over time are evaluated without considering the climate change for which probably the energy need will increase for coolin the buildings.
Future developments could focus on expanding the analysis to other facade typologies, and on incorporating dynamic modeling tools that couple daylighting, thermal comfort, and energy generation. Another promising direction is the assessment of circular design principles, where facade components are conceived for disassembly and reuse, minimizing waste and maximizing material recovery.
In addition, integrating economic evaluation with life cycle carbon analysis would allow designers and decision-makers to identify solutions that are not only environmentally beneficial but also cost-effective over the building's service life.

The results of this thesis confirm that achieving carbon-neutral buildings requires an integrated perspective that spans the entire life cycle of materials and components as well as the one of the entire building.
Curtain wall facades can be re-imagined as sustainable systems through innovative material choices and design optimization. By quantifying the relationship between structural, thermal, and environmental parameters, this research provides guidelines to reduce the carbon footprint of building designs. A balance between aesthetic, performance, and sustainability is not only possible but essential for the future of the built environment.

Bibliography

[1] Landsec-Urban Opps Net Zero Carbon Strategy. *BURO HAPPOLD*, 2021.

[2] A brief introduction to 'How to calculate the embodied carbon of facades: A methodology'. *Centre for Window and Cladding Technology CWCT*, 2022.

[3] Operational Embodied Carbon Explainer Guide. *UK GBC*, 2023.

[4] Global Status Report for Buildings and Construction 2024/25, author=Hamilton I, Hsu S. In *Global Alliance for Buildings and Construction*. GABC, 2024.

[5] J. Vinson A. Briend A. Canta, C. Puertas. carbon footprint of facades: significance of glass. *Arup and Saint-Gobain Glass*.

[6] Circular Ecology. ICE database, https://circularecology.com/embodied-carbon-footprint-database.html. Accesso: 15 luglio 2025.

[7] Parlamento Europeo; Consiglio dell'Unione Europea. Direttiva (UE) 2024/1275 del Parlamento Europeo e del Consiglio del 24 aprile 2024 relativa alla prestazione energetica degli edifici. 2024.

[8] UNI-Ente Italiano di Normazione. UNI EN 1279:2018 - Vetro per edilizia, vetrate isolanti. 2018.

[9] UNI-Ente Italiano di Normazione. UNI EN 16612:2019 - Vetro per edilizia - Determinazione della resistenza delle lastre di vetro ai carichi laterali tramite metodi di calcolo. 2019.

[10] UNI-Ente Italiano di Normazione. UNI EN 16798-1:2019 - Prestazione energetica degli edifici - Ventilazione per gli edifici - Parte 1: Parametri di ingresso dell'ambiente interno per la progettazione e la valutazione della prestazione energetica degli edifici in relazione alla qualita dell'aria interna, all'ambiente termico, all'illuminazione e all'acustica. 2019.

[11] UNI-Ente Italiano di Normazione. UNI CEN/TS 19100:2021- Progetto di strutture in vetro. 2021.

[12] UNI-Ente Italiano di Normazione. UNI EN 13830:2022- Facciate continue-Norma di prodotto. 2022.

[13] UNI-Ente Italiano di Normazione. UNI EN 1991-1:2024- Eurocodice 1- Azioni sulle strutture. 2024.

[14] UNI-Ente Italiano di Normazione. UNI/PdR 13.0:2025- Sostenibilita ambientale nelle construzioni- strumenti operativi per la valutazione della sostenibilita- inquadramento generale e principi metodologici. 2025.

[15] ECO Platform. ECO Platform - ECO Portal, https://eco-portal.eco-platform.org/. Accesso: 10 ottobre 2025.

[16] M. can de Vilet E. Melet E.J. van Nieuwenhuijzen, J.I.A. Tetteroo. In situ detection of product age and argon concentration as measure of the re-use potential of insulating glass units in buildings. 2023.

[17] International Organization for Standardization. ISO 14040:2006 - Environmental management-Life cycle assessment-Principles and framework. 2006.

[18] International Organization for Standardization. ISO 14044:2006 - Environmental management-Life cycle assessment-Requirements and guidelines. 2006.

[19] Robert C. Tenent Madison Likins-White and Zhiqiang (John) Zhai. Degradation of Insulated Glass Units: Thermal Performance Measurements and Energy Impacts. *Buildings*, 2023.

[20] NEEP. Operational carbon in building energy codes.

[21] One Click LCA. One Click LCA, https://oneclicklca.com/. Accesso: 30 luglio 2025.

[22] ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale. Le emissioni di CO2 nel settore elettrico nazionale e regionale. 2025.

[23] Lars Gullbrekken Silje Kathrin Asphaug, Bjorn Petter Jelle and Sivert Uvslokk. Accelerated ageing and durability of double-glazed sealed insulating window panes and imoact on heating demand in buildings. *Energy and Buildings*, 2015.

[24] Racine T.A. Prado Vanessa Montoro Taborianski. Methodology of CO2 emission evaluation in the life cycle of office building facades. *University of Sao Paulo*, 2011.

[25] Andreas T. Wolf. Studies into the LIfe-Expectancy of Insulated Glass Unit. *Building and Environment vol. 27 no.3*, 1992.