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# Identifying Low-Embodied Carbon Façade Solutions for Residential Buildings in Spain

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**Abstract.** The building sector plays a crucial role in global decarbonisation efforts, with façades serving as a key component in reducing both embodied and operational carbon emissions, particularly in the context of Spain. This study provides a detailed analysis of construction solutions for the most commonly used building envelope types and materials in Spain. The study conducted the LCA of more than 30,000 combinations of layers (including different materials and thickness) and covering façade types (including ETICS, ventilated, traditional, and bio-based façades). The findings highlight the significance of each façade layer in calculating embodied carbon emissions, noting that finishing materials contribute most to the embodied carbon footprint for those with the highest impacts. Notably, the highest carbon footprint values do not always correlate with the coldest winter climate zones; rather, they depend more on the materials used and the construction solution type. The study concludes with recommendations to enhance façade design and minimise environmental impact, providing actionable insights to advance sustainable design practices in Spain.

## 1. Introduction

The building sector is one of the largest contributors to global greenhouse gas (GHG) emissions, accounting for nearly 40% of global carbon emissions, with embodied carbon accounting for a significant portion (1). Emissions associated with the extraction, processing, transportation, and installation of building materials, as well as their maintenance, replacement, and eventual disposal, are referred to as embodied carbon (2). Thus, as the urgency to meet global decarbonisation targets increases, optimising façade design to minimise embodied carbon is gaining significant attention among policymakers, architects, engineers, and material manufacturers (3).

Façades play a fundamental role in a building's overall environmental impact in Spain (4). Beyond their functional and aesthetic contributions, they determine energy efficiency, material



consumption, and life cycle impacts. Traditional façade solutions, which often rely on energy-intensive materials such as concrete, aluminium, and glass, substantially contribute to a building's embodied carbon footprint. In contrast, alternative strategies—including the integration of bio-based materials, adaptive reuse of components, and optimised material combinations—offer potential to reduce environmental burdens (5–7). However, the transition to low-carbon materials, such as bio-based options, remains slow in Spain, especially given the country's strong construction tradition based on brick and concrete (8,9). In this context, comprehensive studies evaluating the full range of material combinations across different façade typologies which analyse the key aspects to focus on the transition to low-carbon and affordable solutions are still lacking.

Spain presents favourable conditions exploring façade optimisation strategies due to its diverse climatic conditions, varying regulatory frameworks, and growing commitment to reducing the environmental impacts of buildings. Current initiatives, such as the Spanish Long-Term Renovation Strategy (10), Building Life (11), and INDICATE (4), emphasise the importance and opportunities of lowering the carbon footprint of buildings. While significant strides have been made in improving operational energy efficiency, in-depth analysis of embodied carbon is required. This highlights the need for research-driven design recommendations that facilitate the selection of low-carbon materials and façade systems while maintaining structural integrity, durability, and aesthetic features.

This study seeks to address this gap by analysing more than 30,000 façade solutions, including a combination of different types of materials and products, different façade types, including external thermal insulation composite systems (ETICS), ventilated façades, traditional masonry façades, and bio-based solutions. Therefore, the goal of this study is to identify the façade solutions with the lowest impact, determine which layers have the greatest influence on these results, and analyse how the embodied emissions of the solutions vary according to the thermal transmittance limit values defined for different climate zones in Spain. This research provides a data-driven foundation for optimising façade design by examining how different materials and configurations influence embodied carbon and contributes to achieve decarbonisation objectives in the residential sector.

## 2. Methods

### 2.1 Description of the proposed method

The method used to achieve the objectives of this study consisted of four steps, which are described in detail below. These steps included: defining the solutions to be analysed, identifying the materials and products that compose them, classifying the solutions according to Spain's climatic zones, applying the LCA to the solutions, and finally, obtaining and analysing the results.

### 2.2 Step 1: Definition of analysed façades

Once the types of elements had been defined, the next step was to select the **façade assemblies** (*construction solutions*) to be included in the analysis, using the CTE Construction Elements Catalogue (12) as a reference. These assemblies represent the most commonly used in newly constructed residential buildings in Spain. The definition and breakdown of these envelope configurations into layers and components—such as materials, labour, and machinery—were based on reliable data sources, including the CYPE Construction Cost Generator (13) and the BCCA (14). These sources provide a transparent and systematic basis for compiling the life cycle inventory of the selected wall build-ups. The aim of this study is to incorporate the most frequently used arrangements for each layer of the building envelope, covering a variety of structural support

elements (e.g., bricks, blocks) as well as various insulation materials and interior and exterior finishes. Table 1 provides a summary of the façade typologies analysed in this study, detailing the main layers included for each type. A detailed systematic breakdown of each evaluated assembly was developed, offering a comprehensive material inventory to facilitate the understanding and analysis of the different components that make up each façade configuration (15).

**Table 1.** The façade layers included in the evaluation.

<b>Bioclimatic</b>	<b>Curtain wall</b>	<b>Prefabricated</b>	<b>ETICS</b>	<b>Traditional</b>	<b>Ventilated</b>
Cladding	Structure	Cladding	Cladding	Cladding	Cladding
Support sheet	Glazing	Insulation	Insulation	Support sheet	Auxiliar structure
Insulation		Support sheet	Support sheet		Insulation
Interior sheet		Interior Finishing	Interior Finishing		Support sheet
Interior Finishing				Interior Finishing	Interior Finishing

### 2.3 Step 2: Classification of Solutions According to the Thermal Transmittance Limit Values of CTE

After the thermal transmittance of the enclosures was calculated, the solutions were classified according to the limit values defined for the different winter climate zones, ensuring that they fall within the limit values required to comply with CTE. Table 2 shows the values used for this classification. Different limit values are used for walls such as ETICS, ventilated, traditional masonry façades, bio-based and bioclimatic and prefabricated, and curtain wall.

**Table 2.** Thermal transmittance (U) values were used to classify the climate zones covered in this study.

Climate zones in Spain	<b><math>\alpha</math></b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>
Thermal transmittance of the enclosure (wall) CTE limit value	0,8	0,7	0,56	0,49	0,41	0,37
Thermal transmittance of the enclosure (curtain wall) CTE limit value	3,2	2,7	2,3	2,1	1,8	1,8

### 2.4 Step 3: Application of the LCA method to the solutions

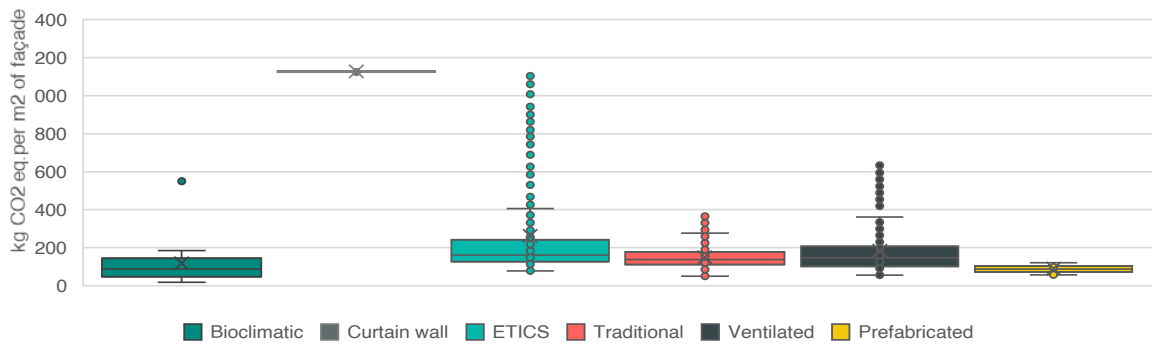
This phase involves data development, specifically the Life Cycle Assessment (LCA) application for the construction solutions defined in Step 2. The primary data sources used to develop this study include: Environmental data (total CO<sub>2</sub> emissions): obtained from the Ecoinvent database, version 3.10 (2023), using the EN 15804 calculation model. A detailed description of the calculation process and methodology used to apply LCA to the construction solutions is provided in (15). The study includes the following LCA information modules: A1-A3, A5, B4, C1, C3, and C4. These modules are included to identify the impact of manufacturing the materials, the resources consumed during the installation process, the impacts resulting from replacement, and the impacts resulting from deconstruction, treatment, and final waste disposal.

### 2.5 Step 4: Data analysis

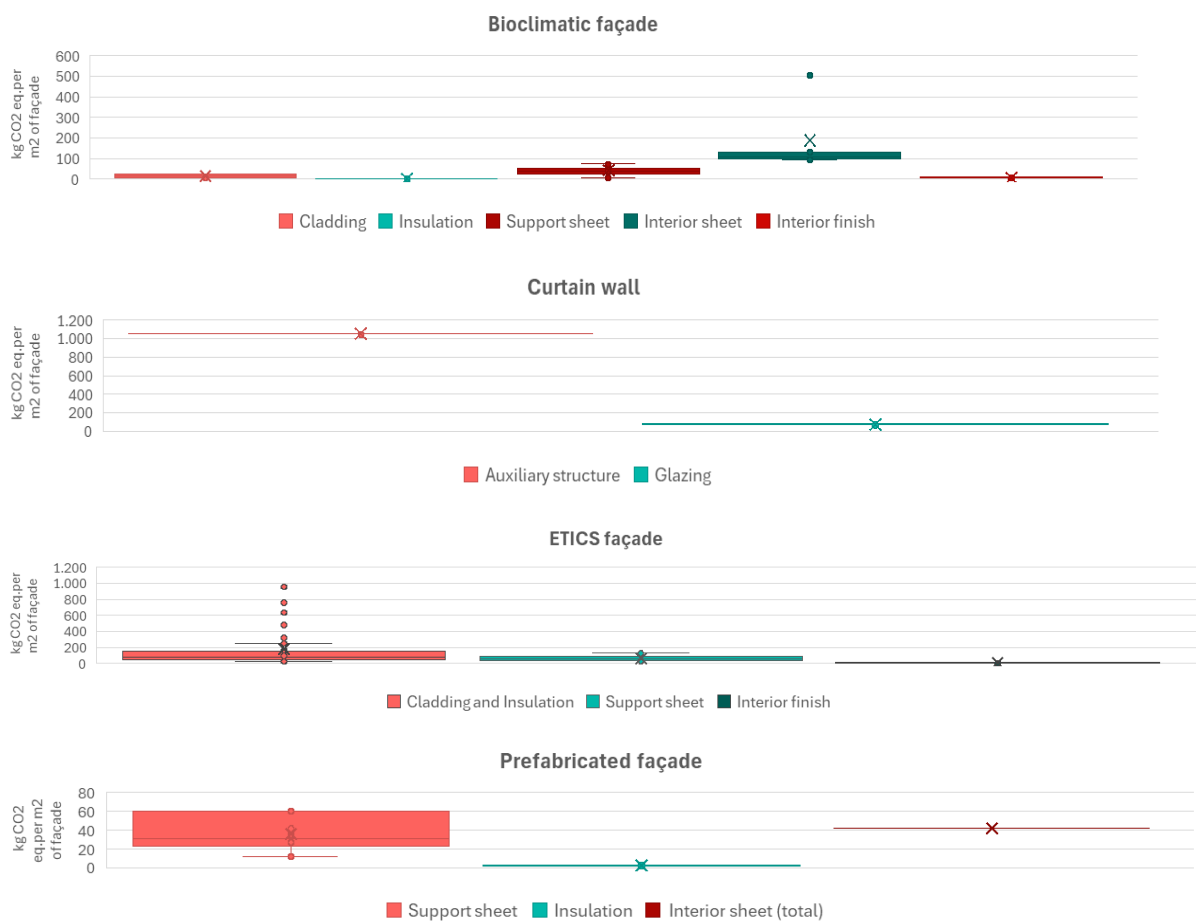
At this stage, graphs and data analysis were developed, encompassing the information obtained for each façade solution, as well as the data corresponding to each layer of the enclosures and those associated with each climatic zone.

### 3 Results

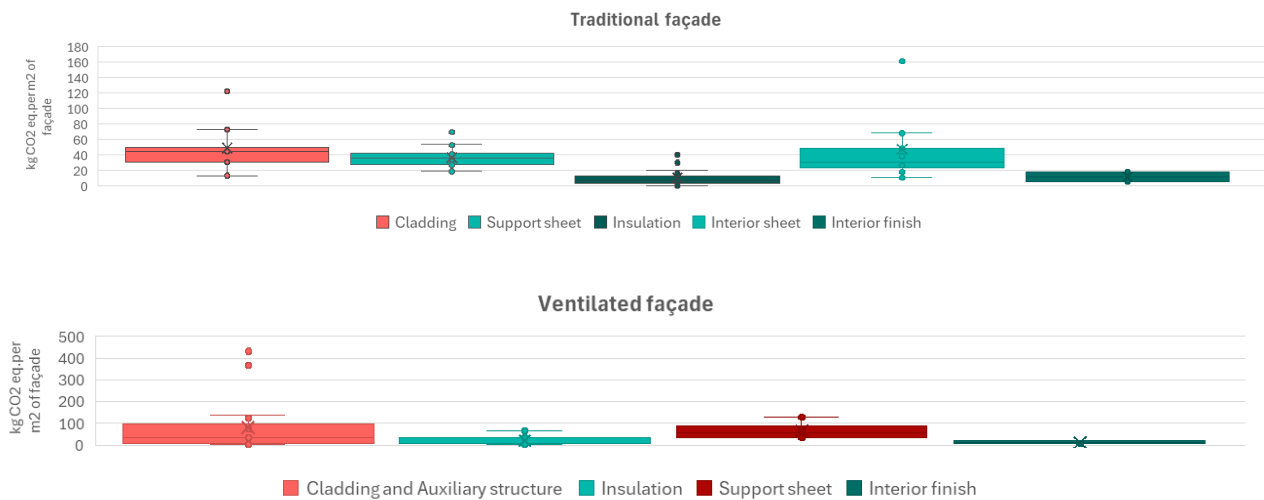
A total of 37,077 façade solutions has been analysed. Figure 1 shows the carbon emissions generated by each type of façades that has been analysed in this study. The façade types with the highest number of atypical solutions are ETICS, traditional, and ventilated. Figures 2 and 3 provide a more detailed analysis of the corresponding values for these types.



**Figure 1.** Carbon emissions per type of façade analysed in the study.

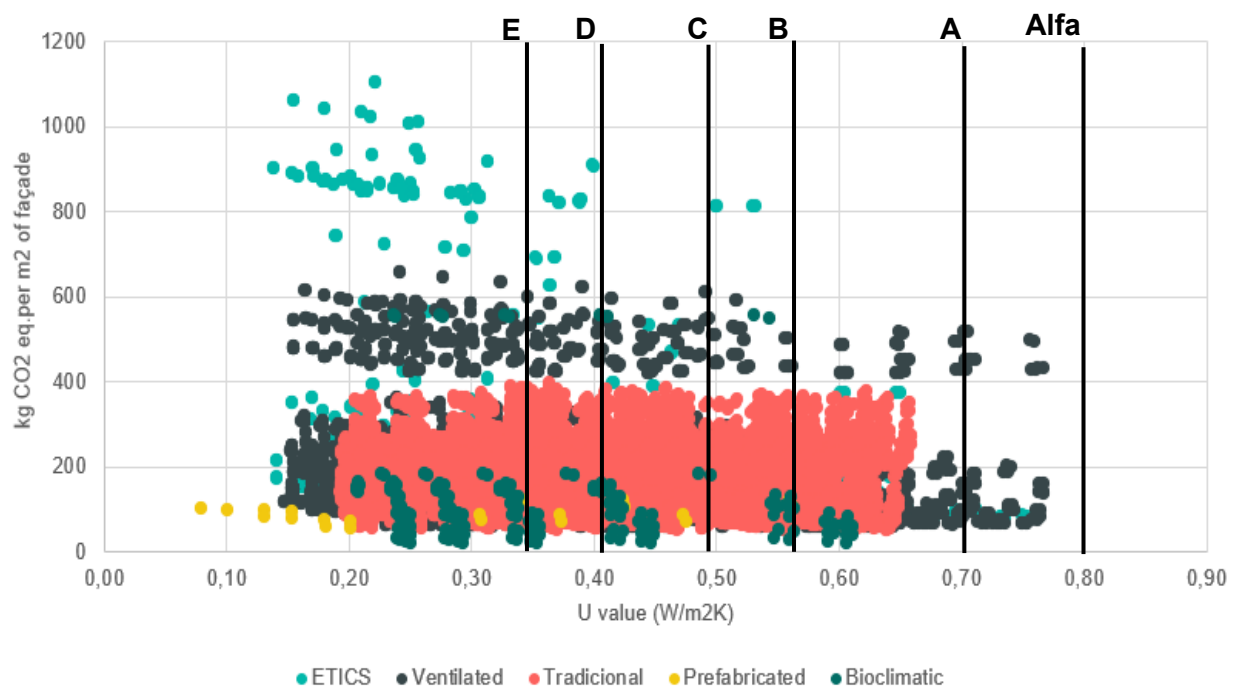


**Figure 2.** Carbon emissions per type of façade and their layers (Bioclimatic, Curtain wall, ETICS façades and prefabricated)

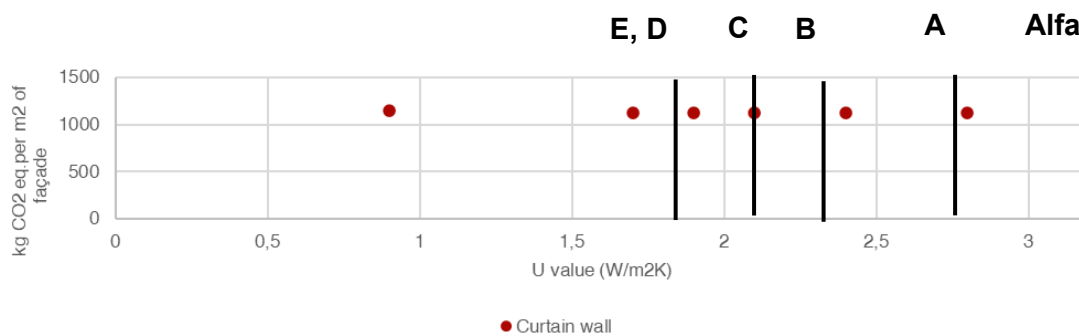


**Figure 3.** Carbon emissions per type of façade and their layers analysed in the study (traditional and ventilated façades).

In the case of the ETICS façade, the outliers correspond to solutions that incorporate exterior cladding materials such as acrylic tiles. Similarly, for ventilated façades, the outliers are those that use aluminium or steel as external cladding. For bioclimatic façades, the unusually high values in the inner leaf are associated with Trombe wall solutions due to the large amount of cement used.



**Figure 4.** Carbon emissions (kg CO<sub>2</sub> eq. per m<sup>2</sup> of façade) and U values (W/m<sup>2</sup>K) and limit values of the type of façade analysed in the study (ETICS, Ventilated, Tradicional, Prefabricated and Bioclimatic).



**Figure 5.** Carbon emissions (kg CO<sub>2</sub> eq. per m<sup>2</sup> of façade) and U values (W/m<sup>2</sup>K) and limit values of the type of façade analysed in the study (curtain wall).

Regarding the thermal transmittance values and carbon emissions of the solutions, Figures 4 and 5 show that the curtain wall and the ETICS façade have the highest values. Figures 5 and 6 also show that low carbon solutions, corresponding to the lower sixth of values, results below 200 kg CO<sub>2</sub> per m<sup>2</sup> of solution, can be found for all the climate zones in Spain.

## 4 Discussion and recommendations

### 4.1 Identification of façade types with low carbon emissions

The results in Figure 2 show that the ETICS, ventilated, traditional, and bioclimatic façade types can achieve emissions below 100 kg CO<sub>2</sub> per m<sup>2</sup>, corresponding to the 25th percentile of the obtained values. Notably, bioclimatic and bio-based façades demonstrate the lowest embodied carbon impact, as they are typically composed of hemp blocks or compressed earth block (CEB). By incorporating low-emission materials, these solutions effectively reduce the environmental impact of the support sheet layer. These solutions effectively reduce the environmental impact of the support sheet layer by incorporating low-emission materials. Additionally, the impact of the finishing layers is minimised using materials such as wood for both exterior and interior surfaces.

### 4.2 Influence of layer materials on LCA results

The results in Figures 3 and 4 show that the environmental impacts vary depending on the type of façade considered. In ventilated and traditional façades, the load-bearing layer has the greatest influence on the overall impact. Substituting high-carbon materials with low-carbon alternatives with similar properties can facilitate the transition to more sustainable construction because both materials use similar building techniques. However, the results also demonstrate that selecting different types of interior and exterior finishes (traditional finishes such as plastering and trimming) can achieve low impact values. Additionally, the impacts associated with the load-bearing layer could be further reduced if these materials are reused and recovered, enabling them to be reused for the construction of new walls.

### 4.3 Influence of the climate zone on the LCA results

The results in Figures 5 and 6 indicate that the lowest environmental impact values tend to correspond to solutions that meet the maximum thermal transmittance thresholds in mild climate zones, such as zones Alfa and A, for example in the case of the façade type ETICS and ventilated. This is because of the direct correlation between the amount of material used and the associated carbon emissions. However, it is also observed that in colder climate zones (C, D, and E), there are solutions with low environmental impact (around 21 kg CO<sub>2</sub> per m<sup>2</sup>). The difference in impact values between colder and milder climate zones can be as low as 5%. This demonstrates that despite the higher thermal insulation requirements in colder zones, low-impact solutions can still

be achieved. In this regard, it is recommended that the selection of low-impact materials and products proves to be more relevant than solely focusing on optimising the thickness of the building envelope layers.

#### *4.4 Limitations of the study*

A key limitation of this study is its exclusive focus on environmental assessment, specifically carbon footprint, without incorporating economic and social dimensions. Expanding future research to include these aspects would provide a more comprehensive understanding of how to enhance the affordability and market feasibility of the evaluated solutions. Additionally, the study is limited by the range of materials and construction solutions analysed. A broader selection could further refine the feasibility assessment of reducing embodied carbon in building façades manufactured in Spain.

## **5 Conclusion**

The present study concludes that when evaluating the embodied carbon emissions of building façade solutions of the most frequently used materials in Spain, it is essential to analyse all layers, especially when incorporating high-impact materials such as acrylics, aluminium, or steel. The selection of materials should take precedence over their thickness, as composition significantly influences the thermal and environmental performance of the overall solution. Additionally, the exterior finish plays a crucial role in the overall material assessment, making it advisable to choose options specifically designed for this function while avoiding unnecessary layers.

In the material selection it is relevant to prioritise the selection of materials with a low carbon footprint and integrating strategies that facilitate disassembly and reuse, particularly in solutions involving bricks or ceramic blocks, generally some of the layers (support and interior sheets) can be the main contributions to CO<sub>2</sub> emissions of the overall solution. This approach reduces the energy and resources consumption associated with new material production. Finally, in terms of insulation, effectiveness is determined more by the material's properties than by its thickness, underscoring the importance of choosing low-carbon and efficient choices in construction materials.

## **6 Declaration of generative AI and AI-assisted technologies**

During the preparation of this work, the authors used GPT-4 to enhance the language and clarity. After using this tool, the author reviewed the texts and edited the content as needed and take full responsibility for the content of this publication.

## **7 Acknowledgements**

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