Towards decarbonisation in the built environment

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Towards decarbonisation in the built environment: a comparative analysis of conventional vs. industrialised façades in nearly zero-energy building renovations

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ABSTRACT

Achieving a climate-neutral European Union requires overcoming challenges in Nearly Zero-Energy Building (NZEB) renovations, including labour shortages and time-intensive traditional methods. Industrialised façade systems offer a promising solution, but their life-cycle impacts remain insufficiently studied.

This research uses life-cycle assessment to compare conventional and industrialised façade systems for renovating a representative residential building typology. Renovation scenarios integrating passive, active and renewable measures were analysed to assess embodied (A1–A5, B4) and operational (B6) carbon emissions. Results show that façade renovations can reduce total carbon emissions by 44 % (industrialised) and 58 % (conventional systems) compared to the current state. Additionally, large pre-fabricated panels significantly reduce construction waste, while modular façades with integrated photovoltaic panels exhibit the highest circular economy potential.

The findings of this study enhance the understanding of industrialised façade systems across their life cycle, highlighting their potential to accelerate NZEB renovations while addressing key barriers to scaling decarbonisation efforts across Europe.

1. Introduction

1.1. Renovating the built environment to achieve carbon neutrality

Decarbonising the built environment is crucial to achieving a climate-neutral European Union (EU) by 2050 [1]. Regulation (EU) 2021/1119 enshrined the increasing of the greenhouse gas (GHG) emissions goal to at least 55 % below 1990 levels by 2030 [1,2]. The building stock represents 40 % of the EU's final energy consumption [1,3] and is responsible for 36 % of its energy-related GHG emissions [1,4]. Consequently, the role of the existing buildings towards energy transition is essential [5,6].

Nealy Zero-Energy Building (NZEB) renovation remains one of the greatest challenges at the European level [7]. To this end, residential buildings constitute an instrumental sector as they represent approximately three-quarters of the European built environment [8]. However, the current annual renovation rate of EU residential buildings ranges between 0.4 % and 1.2 % [4,9–11], with fewer than 5 % meeting the NZEB standards [9]. Setting a higher renovation rate to at least three times the prevailing one is a topic of increasing importance [4]. One of the primary barriers to achieve this milestone is the shortage of available labour, coupled with the time-intensive on-site processes that frequently lead to completion delays. The construction industry must reinvent itself to adapt to these evolving circumstances. To increase the number of renovations on a large scale, industrialised systems are presented as a strategic path for building renovation [12].

In addition to improving renovation rates, the depth of the

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Nomenclature

Acronyms

NZEB	Nearly Zero-Energy Building

Abbreviations

EPBD	Energy Performance of Buildings Directive
LCA	Life Cycle-Assessment
ETICS	External Thermal Insulation Composite System
PV	Photovoltaic panels
FIPV	Façade integrated photovoltaic panels
CS	Current state
mod.	Moderate
H	Heating
DHW	Domestic hot water
OB	Original boiler
CB	Condensing boiler
SC	Solar collectors
HP	Air-to-water heat pump
O. radiators	Original radiators
E. radiators	Existing radiators working at a low-temperature
LT	Low temperature
R. floor	Radiant floor
N. Vent.	Natural ventilation
No HRV	Hybrid ventilation without heat recovery system
HRV	Mechanical ventilation with heat recovery system

implemented measures needs to be increased [13–15]. To renovate existing dwellings into NZEB, three main strategies need to be employed [16]: passive measures, active measures and renewable energy sources. The building envelope is an essential means towards decarbonisation [12,17,18], and particularly the industrialised façade, as it could combine all the aforementioned strategies [19–21]. For instance, pre-fabricated façades with integrated harvesting possibilities (renewable energy sources) [19] exist, as well as pre-fabricated façades that incorporate active components, such as micro-heat pumps [20], or passive components, as in the case of green modular innovations [21].

1.2. Beyond energy efficiency: life-cycle analysis and circularity

Notably, when energy performance improves (as in the case of NZEB renovation), the significance of embodied carbon increases in relation to operational carbon emissions [22–26]. This means that decarbonisation analyses focusing solely on the use phase of the building are incomplete [27]. Indeed, one of the goals of Directive 2023/1791 was to encourage Member States to consider the whole life-cycle performance of carbon emissions (emissions of CO_2) from buildings [1]. In this pursuit, some researchers also envisioned pre-fabrication as a potential strategy to reduce environmental impacts in the building sector [24,28–32].

At present, the construction industry is one of the sectors with the highest waste generation and environmental impacts, despite the efforts to improve energy efficiency since 2002 (Energy Performance of Buildings Directive – EPBD 2002 [33]). It is responsible for 40 % of raw material consumption and 40 % of waste generation [34,35]. If we truly aspire to achieve decarbonisation in 2050, the life-cycle approach and circularity principles must be integrated in the building design process, and in renovation projects, to select the best strategy.

Life-cycle assessment (LCA) is considered to be a key methodology to evaluate the environmental impacts of building systems [36–41]. It encompasses four main stages: product, construction process, use, and end-of-life stage [42]. Most studies focused on product stage and operational energy, which give results regarding embodied and operational carbon, respectively [36]. Nevertheless, construction and demolition waste also have high environmental impacts [43], making the end-of-life stage meaningful [44]. In fact, in many EU countries, only about 50 % of the construction and demolition waste is recycled [45]. Consequently, the recommendation is to consider the whole life-cycle performance of carbon emissions [1], including all direct and indirect environmental impacts [46].

Furthermore, an extra phase must be contemplated regarding the circular economy: *benefits and loads beyond the system boundary* [42]. Circularity is a concept bolstered by the last European Directives [1,4]. It consists of a regenerative system that decouples economic growth from the consumption of resources while preserving natural capital. For instance, the recycling and reuse of construction and demolition waste enable not only the reduction of such waste but also the conservation of natural resources and land use [43]. Circular economy increases the value of the target products by maintaining their integrity at a higher level (durability), using them several times (reuse) and creating beneficial effects in other value chains (avoidance of pollution and toxicity) [39,47]. These three characteristics are concomitant with industrialised systems; they exhibit high resistance owing to their high quality [12] and they are design thinking on the possibility of being disassembled and reused [48,49]. Therefore, as sensed also by other researchers [50], the development of industrialised building systems applied to NZEB renovation is an opportunity to reduce the impacts of raw material consumption and waste generation.

1.3. Industrialised building systems

The concept of industrialised building systems has been shaped since the Modern movement [12,51]. The development of industrialised architecture in Europe has slowly progressed on the commercial level [52]. To understand how it has been changing over the last hundred years, three crucial trends must be noted: pre-fabrication of heavy building systems after World War II (1939–1945) [53,54]; industrialisation of lighter building systems during the second half of the 20th century, such as curtain walls with anchoring systems pre-fabricated off-site in the 60 s [55] (pre-fabrication of small components); and adoption of oversized pre-fabricated modules, e.g. floor-to-floor height panels, with the beginning of the new millennium [12] (pre-fabrication of large modular panels).

The envelope, and particularly the façade in residential constructions, is the most determining building system to ensure energy efficiency [56,57]. In fact, the number of buildings including industrialised façade systems, has increased in Europe at the start of the 21st century, particularly in the last decade [58–62]. Nonetheless, the implementation of this strategy in the renovation field is not so widespread. Although some initiatives are thinly emerging with this goal [19,50,63–71], its market potential remains underexploited [12]. According to [12] the term ‘industrialised renovation’ refers to *the renovation that increases the energy efficiency of the building stock while aiming to maximise reproduction, through an effective combination of all degrees of industrialisation, particularly with the application of pre-fabricated components.*

The main benefits that researchers detected for industrialised construction systems are also attributable to the industrialised renovation of the building envelope. The main advantages of industrialised renovation, include [12,52,72,73] completion time reduction, minimum impact *in situ*, less disturbance for occupants (dust, noise, etc. are reduced) and more convenience for residents as they could stay at home during all the renovation period with no need to move out [74], high quality of manufacturing due to execution control indoors, design and engineering efficiency as well as reduced unforeseen events, reduction of construction waste and material use (environmental and economic benefits) and cost reduction (when upscaling becomes a reality).

Meanwhile, some drawbacks need to be considered [12,72]: size limitation due to vehicles for transport and the factory's equipment and facility dimensions, adaptability (if the building to be renovated was not designed with a module, it could be challenging to design a replicable system) and high initial investment.

1.4. Aim of the study and research questions

The review of the existing literature reveals limited studies analysing embodied and operational carbon in renovation scenarios that adequately incorporate HVAC systems. Additionally, a significant gap exists in understanding the impact of industrialised envelopes on NZEB renovations as a strategy for decarbonising the built environment, particularly in regions such as Spain, where this practice is not yet

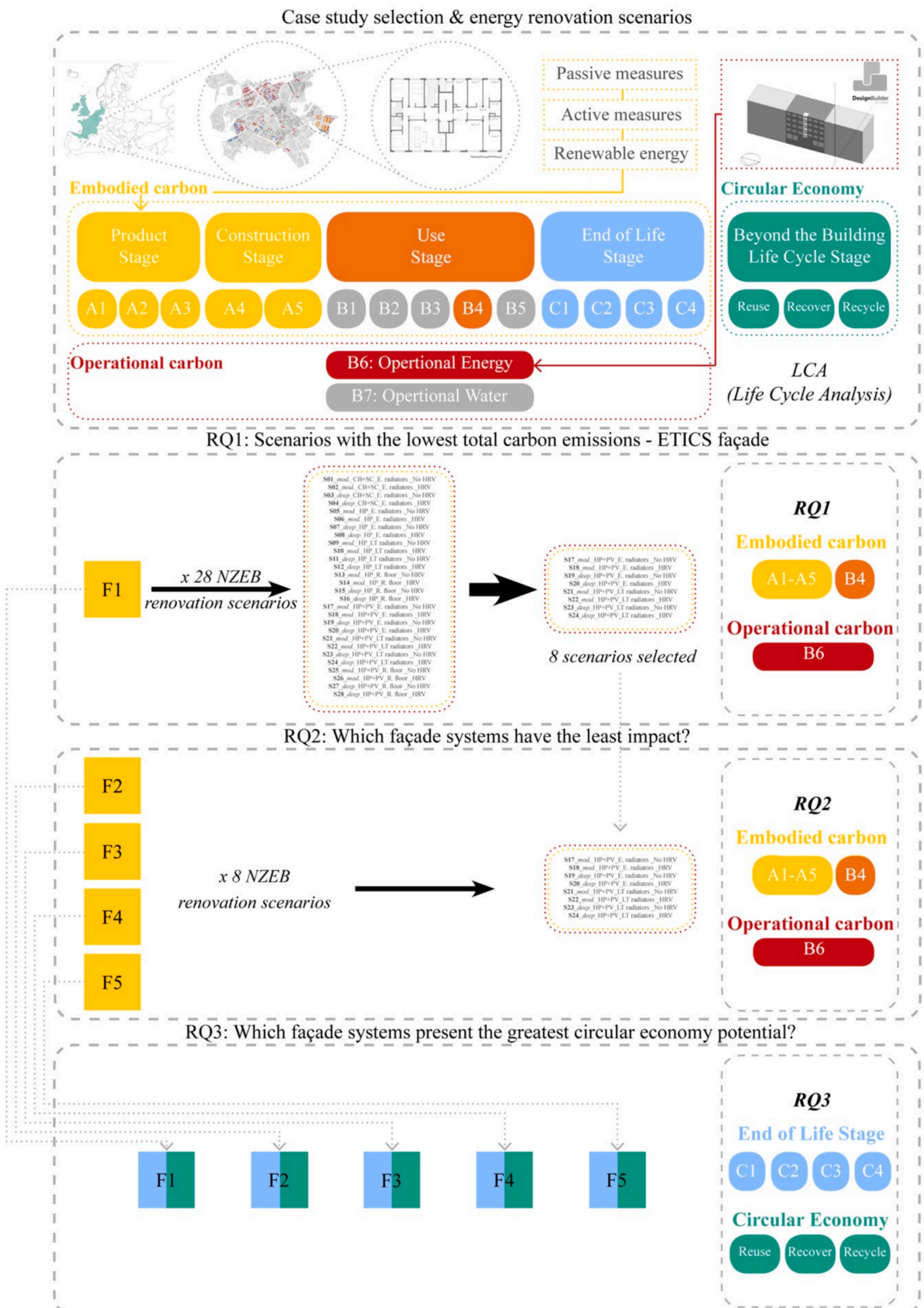


Fig. 1. Flow chart of the methodology developed in this research.

widespread. Specifically, there is insufficient research investigating the advantages and disadvantages of industrialised façades throughout their life cycle. Hence, this study aimed to compare conventional and industrialised façade systems for NZEB renovations using the LCA, as it is a widely adopted methodology encompassing all life stages. Herein, the term *industrialised* façade is employed according to the definition in Section 1.3, and a *pre-fabricated* façade system is construed as a subset of industrialised construction [12] that generally implies building components or full façade modules completely off-site, according to [12,75].

In the quest to demonstrate the potential application of industrialised solutions for NZEB renovations, the most representative building typology of a large sector in the current Spanish building stock was chosen as a case study. Concretely, it is a residential linear block built between the first energy regulation and implementation of EPBD 2002 (period in Spain: 1980–2006) in a temperate-climate (*Cfb)* city; a construction period that remains underexplored [76].

To meet the NZEB requirements, operational energy needs to diminish. Thus, different renovation scenarios (combining passive and active measures, as well as renewable systems) were studied under energy simulations, with the aim of knowing the amount of operational carbon savings each scenario could provide. However, if decarbonisation is the goal, the embodied energy throughout the whole life cycle must be considered to reduce total CO_2 emissions [77]. To conduct the comparison, different NZEB scenarios were investigated using the LCA to select the most appropriate, considering both operational and embodied carbon savings. On the basis of those NZEB scenarios, the following research questions are posed:

- RQ1: Which renovation scenarios present the lowest total carbon emissions when considering the conventional External Thermal Insulation Composite System (ETICS) system as the façade renovation system?
- RQ2: Which façade systems have the least impact when considering operational and embodied carbon?
- RQ3: Which façade systems present the greatest circular economy potential when the end-of-life stage is considered?

2. Methodology

In pursuit of decarbonising the built environment through NZEB renovation, the methodology outlined in Fig. 1 was developed and applied to a case study. First, a case study was chosen, and energy renovation scenarios were evaluated (Section 2.1). Subsequently, conventional and industrialised façade systems were defined (Section 2.2) and evaluated using the LCA methodology (Section 2.3). In addition, the carbon neutrality period was calculated (see Section 2.4). Finally, the end-of-life stage for each façade system was examined (Section 2.5).

2.1. Case study selection and energy renovation scenarios

As previously justified in the precedent publication [76], Pamplona, located in northern Spain, was selected as the study city. According to the Köppen–Geiger classification [78], its climate classification is *Cfb,* temperate without dry season, 'oceanic' type. Considering that nearly 45 % of the existing Spanish buildings [79] were constructed during the period between the first energy regulations (after the first oil crisis [80]) and the implementation of EPBD 2002 [33], the Spanish residential typologies of this period (1980 [81]–2006 [82]) were analysed. The linear block typology was detected as the most significant in the target period, representing 54 % in the studied city [76]. Therefore, this building typology was selected as the case study of this research. Its main characteristics were defined (Table A1, Appendix A). They were based on a representative sample of original projects (statistical confidence level: 99 %; sampling error: 2.5; dwellings consulted: 2,470) from the municipal archives in Navarra (name of the region to which Pamplona belongs).

Afterwards, to meet the NZEB standards in accordance with the current Spanish regulation [16], passive measures were proposed as *moderate* and *deep* renovations (Table A2, Appendix A). *Moderate* scenarios are those pursuing the thermal transmittance limit values, whereas *deep* scenarios follow the recommended thermal transmittance values. Combining these passive measures with different active measures, including various heating systems and emitters as well as hybrid and mechanical ventilation, energy renovation scenarios were defined (Table A3, Appendix A). Finally, to determine if the scenarios were valid or not for NZEB renovation, their energy consumption was obtained through energy simulations on Design Builder (7.0.0.102), based on Energy Plus (v.9.4). This tool was considered to be the most appropriate due to its detailed HVAC module possibilities. The results of these simulations were presented in the aforementioned publication [76].

2.2. Definition of conventional and industrialised façade systems

To procure the proposed passive measures, several building systems could be considered. The façade is identified as the most determinant building system in the whole envelope [56]. It has the greatest influence on the energy efficiency of residential buildings owing to its largest surface of thermal envelope. To distinguish the most appropriate system, a comparison between conventional and industrialised façade systems is developed. The most representative façade systems of each group have been selected. Table 1 presents all the façade systems contemplated for the current research.

On the one hand, the ETICS [83–85] is commonly used to renovate existing buildings. On the other hand, three design concepts were selected according to the classification based on the construction principles of industrialised renovation [12]: ventilated façade (which is also a commonly used renovation system nowadays [86–89]), timber-frame façade panels (not so often used in renovation), and modular façades (also referred to as unitised façades [90]). These are industrialised and pre-fabricated solutions, understanding pre-fabrication as defined in [12,72]: *building components or complete modules off-site (in the factory) before being transported to the site and become an integral part of the building.* Therefore, the industrialised systems explored in this study could be classified as pre-fabricated systems by small components (ventilated façade) or large modular panels (timber-frame façade panels and modular façade).

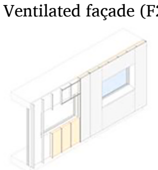
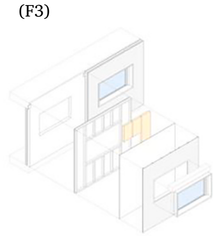
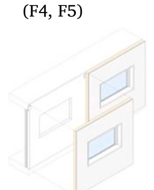
The insulation for all the systems is mineral wool [89,96]. For the ETICS façade, a common solution with different mortars was considered after browsing different manufacturer solutions [97–99]. Although a wide variety of different materials could be selected for the outer layer of the industrialised façades [56]; the same material is considered for all cases (timber-frame façade panels, ventilated and modular façade) to compare them equitably: phenolic panels, also known as high-pressure laminate plates. For the ventilated and modular façade, an aluminium substructure is selected, owing to its high durability and resistance [100]. The anchoring system of the timber-frame façade panels and the modular ones is made of steel. All renovation systems present the same quality for glass windows, depending on deep or moderate renovation, and carpentries are made of wood.

As regards timber-frame façade panels and modular façades (both industrialised building systems), they were designed as floor-to-floor height modules. In the first place, different projects were explored as guidelines. Then, the solutions were defined for the linear block building typology of the case study. Notably, for the modular façade, two possibilities were considered: without façade integrated photovoltaics (FIPV) and with FIPV on the south façade.

2.3. Life-cycle assessment

LCAs of the five types of façades (F1-F5 described in Table 1) and the rest of the passive and active measures proposed for NZEB renovation, were conducted in accordance with ISO 14040. SimaPro 9.5.0.1 was

Table 1
Conventional and industrialised façade systems contemplated for the current research. (Data based in [12] and available information on manufacturers commercial websites.)

Type of façade	Type of systems	Description	Construction	Work required*3	Windows	FIPV	Reference projects
ETICS (F1) 	• Conventional system • Not industrialised	Different mortar layers to cover the insulation. Different options for insulation materials*1.	Constructed on-site	🏭	Windows not incorporated in the framework	✗	Conventionalresidential projects [56,91]
Ventilated façade (F2) 	• Conventional system • Industrialised • Degree of industrialisation: prefabrication (small components), reproduction	Exterior cladding*2, air cavity, substructure and insulation layer*1.	Fabricated off-site, assembled on site	🏭 🏭	Windows not incorporated in the framework	✗	Conventionalresidential projects [56,92]
Timber-frame façade panels (F3) 	• Not conventional system • Industrialised • Degree of industrialisation: pre-fabrication (large modular panels), mechanisation	Load-bearing timber frame, sheathing boards*2, waterproofing and breathing membranes, and insulation*1 in between studs	Constructed off-site	🏭 🏭 🏭	Windows incorporated in the framework	✗	• MORE-CONNECT [70,93] • Energie Sprong [94]
Modular façade (F4, F5) 	• Not conventional system • Industrialised • Degree of industrialisation: pre-fabrication (large modular panels), reproduction	This façade is comprised of prefabricated modules with floor-to-floor height. They are fixed to the slab through an anchoring system. Each module is constituted by a secondary (metallic) substructure where insulation and exterior cladding are integrated. Exterior cladding could be, e.g., opaque materials or photovoltaic panels (PV)*5.	Constructed off-site	🏭 🏭 🏭	Windows incorporated in the framework	✓ *4	• ENSNARE [37,95] • AEGIR [50]

* ***Note (1):*** The insulation contemplated in this research for all systems is rock wool. ***Note (2):*** The outer layer considered in this research are phenolic panels, also known as high-pressure laminate (HPL) plates. The same material is considered for the ventilated façade, timber-frame façade panels and modular façade in order to facilitate the comparison between the proposed systems. ***Note (3):*** The symbol of the factory represents the time of work needed off-site (on the factory). It also should be noted, for the two first systems (ETICS and ventilated façade) a scaffolding will be needed. Conversely, the two last façade systems proposed could be placed on-site using cranes. Therefore, labour on-site will be reduced for these last systems: timber-frame panels and modular façades. ***Note (4):*** It is possible to create this kind of façade system with or without integrated PV. In this research, both possibilities will be considered: a modular façade without PV (F4) and a modular façade with PV placed on the south elevation (F5). ***Note (5):*** For further scenarios in this research, PV panels integrated in the façade are calculated for an ideal situation in which no shading of existing trees or elements at the street is affecting the area. It is assumed they will be only placed in the South elevation. When they are considered as part of the façade system, there will be no PV panels on the roof.
See Appendeces B, C and F for material specifications and construction processes for each façade system.

used to undertake the system modelling [101]. The system boundary (depicted in Fig. 2) covered stages A1–A3 (cradle to gate), A4-A5 (construction stage), B4 (replacement) and B6 (operational energy) according to EN 15978 [42]. In addition, categories C1–C4 (end-of-life) and D (circular economy) have been evaluated in terms of quality. The functional unit was established as the habitable floor area of a linear block throughout a service life of 30 years. It is considered to be an existing multi-family residence building that needs to be renovated (Section 2.1). The service life period was determined in accordance with Eurocode 1990, which specifies a design working life of 50 years for buildings [102]. Considering that the buildings from the studied period (post first-energy-regulation housing in Spain: 1980–2006) were already at least 18 years old, after the renovation a service life of 30 years was considered for the present study. The final impact results are given in units of impact/m^2 (kg of CO_2 equivalent per habitable floor area).

After defining the functional unit and system boundaries, the LCI was obtained throughout own drawings for each façade system. To calculate the exact weight of the materials, a document recognised by the Spanish regulation [103] as well as manufacturers' data were utilised. Then, the corresponding materials (see Appendix B for more detailed information) were all selected from the SimaPro library (Ecoivent 3 and Industry data 2.0). Life cycle impacts were evaluated using the European EN 15804 + A2 method. All environmental impacts were collected, although for this study, only the Global Warming Potential (GWP) has been employed as it was considered to be the most representative for the research objectives. The GWP provides summary of the impact of different pollutants affecting the same environmental processes. Up to this point, these results correspond to the cradle to gate analysis (A1-A3).

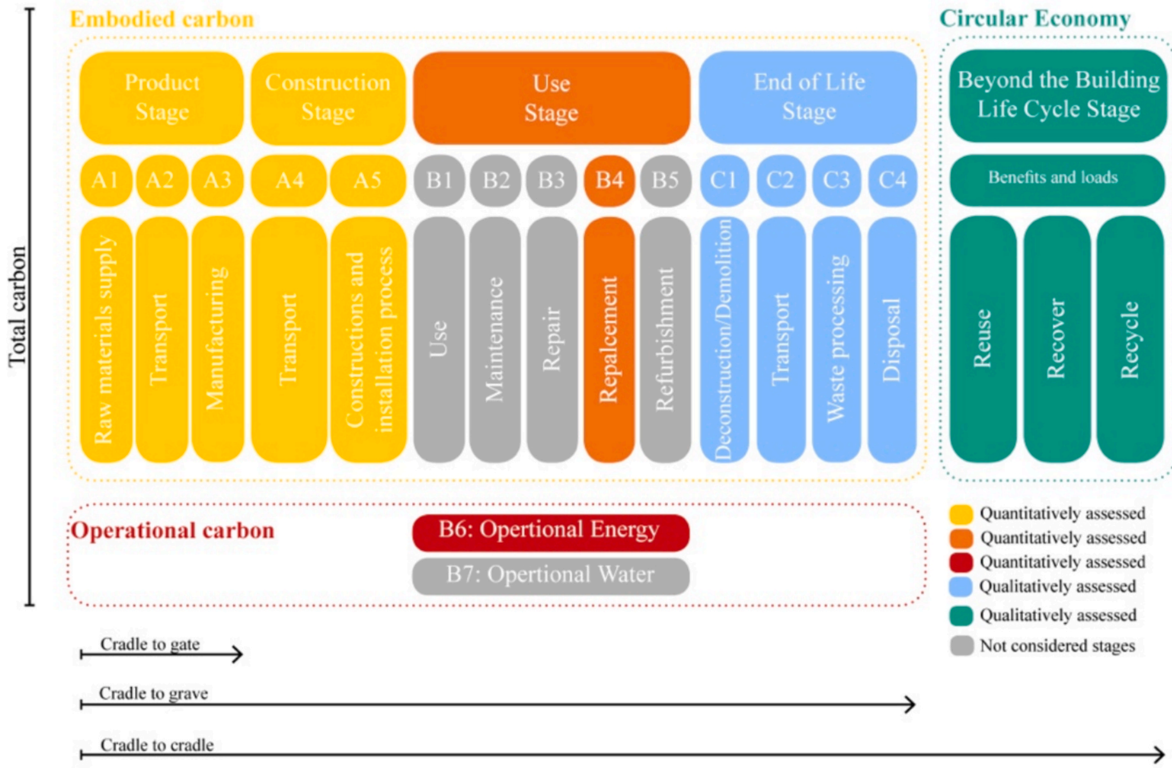


Fig. 2. LCA phases considered in this research (author's own elaboration based on EN 15978 [42]).

For the transport stage (A4), a fixed distance of 100 km, commonly assumed [104], was considered for both the route from the material factory to the worksite and the journey from the material factory to the industrialised façade systems factory. At present, there are no factories in Spain dedicated to producing industrialised systems for façade renovations; however, the major factory for industrialised building systems is located 300 km from the case study city (in a city between Madrid and Pamplona [105]). Therefore, this distance was considered for the route to the worksite. For the conventional façade systems, as well as for the roof renovation, a distance of 10 km was considered from the worksite to a nearby storage facility based on the current size of the city. Finally, for the disposal of existing materials, a distance of 20 km was assumed for transport to the nearest landfill. The results were also obtained using SimaPro. Table C1 in Appendix C outlines the specific assumptions for each system.

For the consideration of the construction and installation process (A5), a bill of quantities was developed for each scenario and proposed façade system, based on the CYPE database [106]. Table C2 (Appendix C) provides details of the specific equipment and machinery considered for each situation. Table C3 (Appendix C) specifies the lifespan assumed for the active systems, which was a key factor in calculating stage B4 (replacement).

The results of the energy renovations mentioned in Section 2.1 were transformed into kg CO_2 equivalents per year according to the document recognised by the Spanish Building Code [107]. (CO_2 equivalent refers to the total equivalent emissions of greenhouse gases). With the results, stage B6 was obtained for the service life. Finally, the results obtained from the sum of the embodied impact and operational impact [108] were analysed.

2.4. Carbon neutrality period

The carbon neutrality period in terms of kg of CO_2 equivalent was obtained for each scenario and façade system, with the aim of adding more information when selecting a solution. However, it is not a conclusive factor on its own. When comparing conventional and industrialised systems, it needs to be observed after the whole LCA result (GWP) [109].

First, to calculate the neutrality period, the operational carbon saved per year due to the renovation was collected in comparison with the annual current energy consumption. Second, the embodied carbon due to the renovation process was gathered. Lastly, the carbon neutrality period was calculated in years by dividing the embodied carbon (stages A1-A5, B4) by the operational carbon saved per year in comparison with the current state scenario (S0).

2.5. End-of-life assessment

An appropriate comparison between conventional and industrialised building systems needs to consider the whole life-cycle performance of carbon emissions [1]. However, there is a lack of information for some LCA phases, particularly regarding the end-of-life [110,111]. Therefore, the end-of-life has been evaluated using a qualitative methodology.

First, based on existing literature and professional architects' experience, an estimation for waste processing (C3) has been elaborated for each proposed system under two assumptions (PV panels fully recyclable or not). Second, end-of-life possibilities were evaluated for conventional and industrialised façade systems. Third, possible circular values were evaluated for each façade system. Lastly, some relevant conclusions were drawn. Notably, the figures are based on the embodied energy each material presents for the product stage to consider a numerical value. However, they are not the corresponding numbers of operational energy due to each waste processing. This is an original approach due to the lack of data regarding end-of-life assessment for industrialised façade systems, based on two existing methods: circular footprint formula from the product environmental footprint (EC 2017a) and the suggested formula for the CEN EN15804/EN15978 standards. More information on these specific methodologies is provided in [110].

3. Results

The results are organised under the three research questions established in Subsection 1.4.

3.1. (RQ1) total carbon emissions for NZEB renovations with the conventional façade system

To meet the NZEB standards in accordance with the current Spanish regulation [16] (Section 2.1), different energy scenarios were established by combining passive and active measures. Among other passive measures (Table A2, Appendix A), the ETICS system was used *a priori* for the façade renovation. The scenarios were evaluated via LCA to obtain their total carbon emissions due to their embodied (stages: A1-A5, B4) and operational (stage B6 for a service life of 30 years) carbon. The results, shown in Fig. 3, include the embodied energy for passive, active and renewable measures. Notably, scenario S0 has been included to consider the case in which the building is kept in its current state (CS) without proceeding with its renovation.

The operational emissions presented in Fig. 3 and Table D1, (see Appendix D for more detailed information) were based on energy simulations under the typical meteorological year, according to the Spanish Building Code. The results as well as the embodied and total carbon emissions were measured in kg of CO_2 equivalent per habitable floor area. In turn, the carbon neutrality period was calculated in terms of kg of CO_2 equivalent. This is the ratio between the embodied carbon (product, construction and replacement stages) and the annual savings in operational carbon (annual operational carbon from the current state scenario minus annual operational carbon from the renovation scenario).

Overall, *deep* renovations achieve significant reductions in operational carbon but not in embodied carbon. For renovation scenarios with the ETICS façade, *deep* renovations (S1–S16 in Fig. 3) offer greater carbon savings when both operational and embodied emissions are considered. However, when PV panels are added (S17-S24), the reduction in operational carbon becomes more pronounced, making embodied carbon more influential. In such cases, *moderate* renovations with PV panels result in greater reductions in kg of CO_2 equivalent than *deep* renovations.

Regarding the relationship between operational and embodied carbon: operational carbon decreases in all scenarios from the current state (S0 in Fig. 3) to 63 % (S1) and 100 % (S20 and S24). In contrast, embodied carbon increases in all scenarios, as expected, though there is no proportional relationship between operational and embodied carbon. For example, renovation scenarios with the lowest operational carbon (S20, S24) do not align with those showing the lowest embodied carbon (S1). Nevertheless, both values (operational and embodied carbon) are useful in selecting the best scenarios to promote decarbonisation, considering that the optimum scenarios are those presenting the lowest values on total carbon emissions.

Some interesting results should be noted regarding energy systems. Among all the proposed scenarios without PVs, condensing boilers present the greatest values for operational carbon emissions (S1–S3). Despite their low embodied carbon and fast carbon neutrality period, the results indicate that air-to-water heat pumps (HPs) are generally more suitable. It should be mentioned that there are noticeable variations when a particular heating emitter is used in combination with the energy system. In fact, depending on the heating emitter working with the air-to-water heat pump (HP), the total carbon emissions results can exceed the levels of condensing boiler (CB) scenarios (e.g. see S1 and S13 in Fig. 3).

The results of operational carbon indicate that low-temperature radiators are the most efficient emitters for reducing energy consumption, followed by existing radiators (E. radiators) at low temperatures (with HPs), and radiant floors, which exhibit the highest embodied and total carbon emissions. Differences between the total carbon emissions of scenarios with current and low-temperature radiators are not as high as those with radiant floors. The difference in total carbon emissions between low-temperature radiators (e.g., S24 in Fig. 3) and existing radiators working at low temperatures (S20) is 8.38 kg CO2 equivalent/m^2, corresponding to a 1.34 % reduction in total emissions compared to the current state (S0).

Regarding ventilation systems, the highest reduction in operational carbon is achieved by those scenarios with heat recovery ventilation (HRV) systems, and they present the highest values for embodied carbon. When studying total carbon values (operational plus embodied carbon), it is noteworthy that the presence of HRV can influence them differently. In the sense that scenarios with HRV are not always the best ones under the decarbonisation criteria (S23 and S24).

To conclude, all the proposed scenarios could promote decarbonisation as they will contribute to the reduction of total CO_2 emissions from the current state (CS, scenario S0) to 39 % (S14) and 59 % (S18). Nevertheless, the results in Fig. 3 indicate that the best scenarios, considering operational and embodied carbon emissions, are those with PV panels and HP for heating and domestic hot water (DHW), which present radiators (existing or low-temperature radiators) as heating emitters, namely, S17–S24 (Fig. 3). They are able to reduce operational carbon emissions from the current state (S0) to 96 % (S17) and 100 % (S20 and S24).

3.2. RQ2: Which façade systems have the least impact when considering operational and embodied carbon?

Fig. 4 compares the conventional ETICS system (F1) with the most common industrialised façade systems based on existing literature. Among them industrialised façades by small (F2) and big (F3, F4 and F5) components are considered, reflecting the shift towards industrialisation. The systems (presented in Table 1) proposed for the façade renovation are: ventilated façade (F2), industrialised façade with a timber-frame structure (F3), industrialised modular façade with a metallic

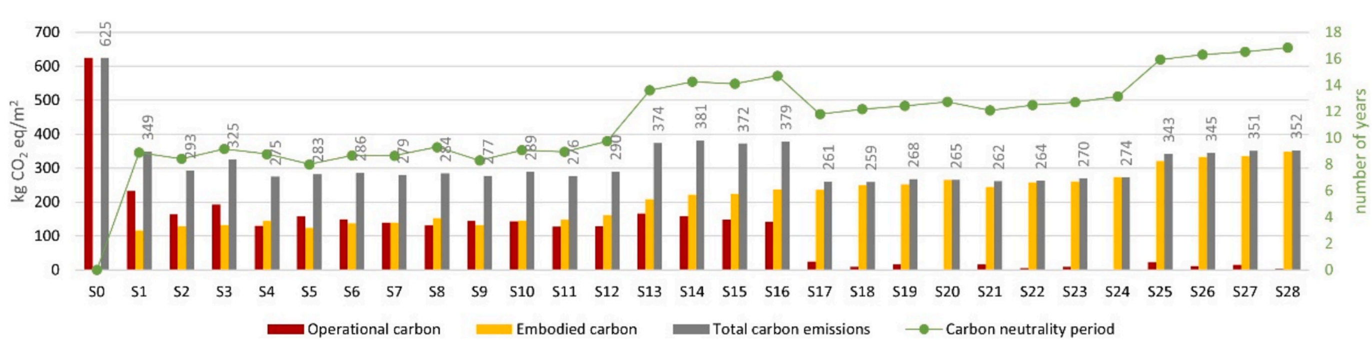


Fig. 3. Operational and embodied carbon of linear block typology after renovation. Scenarios for ETICS façade (F1 – conventional system) and other passive & active measures.

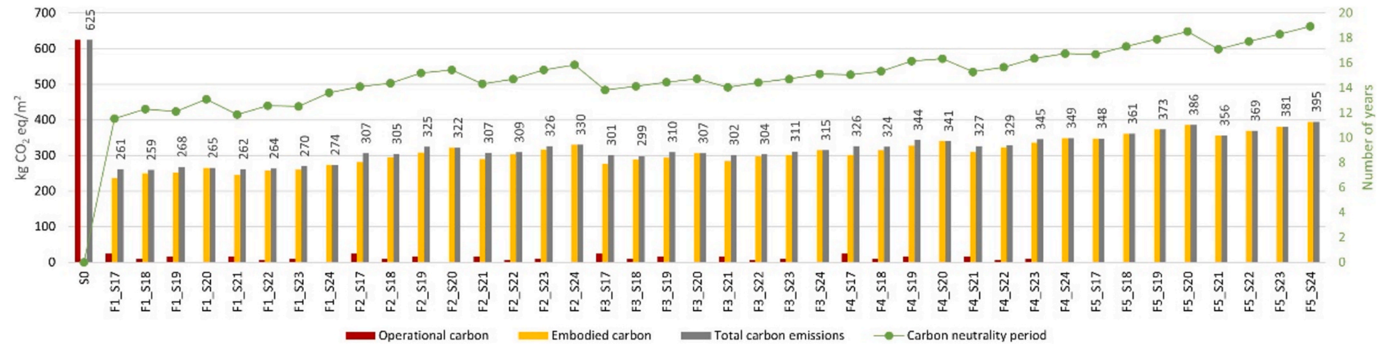


Fig. 4. Operational and embodied carbon of linear block typology after renovation. Scenarios for conventional and industrialised façade, for the most suitable active measures & renewable energies (PV).

structure (F4) and industrialised modular façade with a metallic structure and FIPV on the south elevation (F5).

After identifying the scenarios with the lowest total carbon (S17–S24 in Fig. 3), different renovation options were established by combining the aforementioned façade systems. Those façade systems, as well as the rest of the measures, were evaluated via LCA. Fig. 4, which follows the same parameters as those mentioned above (in Section 3.1), presents the results for all possible combinations. According to the results (see Table D2 in Annex D for more detailed information), *moderate* renovations (*vs. deep* renovations) in general are the ones that present the lowest values for the embodied carbon −due to reduced insulation- and greater reductions in terms of kg of CO_2 equivalent when using industrialised façades and PV panels (on the roof or façade integrated) for the NZEB renovation. Moreover, noticeable differences could be found among the different façade systems proposed.

The industrialised modular façade with FIPV (F5) offers the greatest savings in operational carbon, owing to the alignment between energy generation (vertical PV panels) and energy demand. As explained in Table 1, modular façade F5 is formed by separate pre-fabricated units with a metallic structure where exterior cladding or PV panels are attached. Conversely, from the point of view of embodied carbon, modular façade F5 has the highest impact among the systems, followed by industrialised modular façade with a metallic structure (F4), ventilated façade (F2), industrialised façade with a timber-frame structure (F3) and ETICS façade (F1). They could also be classified in the same order based on the total carbon results (see grey bars in Fig. 4). Notably, a considerable difference exists between the total carbon emissions of the renovation scenarios that employ industrialised modular systems with metallic substructures with FIPV (F5) and those without them (F4).

The scenarios with FIPV (F5) achieve zero operational emissions, but due to higher embodied carbon, they show a total carbon reduction of 37 % (F5-S24) and 44 % (F5-S17) compared to the current state (S0). In contrast, scenarios with the same industrialised modular façade system without FIPV (F4) achieve reductions of 45 % (F4-S24) and 48 % (F4-S18). Renovation scenarios with ventilated façades (F2) and timber-frame façades (F3) result in similar reductions, ranging from 48 % (F2-S24) to 52 % (F3-S18). The greatest reduction in total carbon emissions occurs with the ETICS façade system, especially in the F1-S18 scenario, which achieves a 58 % reduction from the current state (S0).

Notably, the results in Fig. 4 include their total carbon emissions due to their embodied carbon (A1-A5, B4) and operational carbon emissions (stage B6 for a service life of 30 years) because of passive, active and renewable measures. To deeply compare the façade systems, more stages of the LCA should be considered. This fact leads the study towards the following research question.

3.3. *RQ3: Which façade systems present the greatest circular economy potential when the end-of-life stage is considered?*

According to EN 15804, the end-of-life stage is divided into: deconstruction or demolition (C1), waste transport (C2), waste processing (C3) and disposal (C4). To evaluate them for the façade systems investigated in this study, the LCA model is used to estimate the environmental impacts of the end-of-life of buildings proposed in [112]. Fig. 5 presents the adapted model to the façade renovation process in general. Although each façade system will specify different activities. For instance, in the case that the façade renovation will be conducted by the ETICS system (F1) or the ventilated façade (F2), a scaffold might be built during the preparation phase to deconstruct them. Nevertheless, for the rest of the systems proposed (F3, F4 and F5), the deconstruction could be executed with cranes. This fact results in a reduction of construction waste and material use [12] when industrialised systems are chosen.

In accordance with [112], stages C3 and D (Fig. 2) demand the greatest attention to detail in LCA modelling. Tables 2 and 3 present the different end-of-life possibilities for each façade system based on the experience of professional architects and the existing literature. Notably, it was estimated that 70 % of the modules from the industrialised façades F3, F4, and F5 would remain in good condition for reuse. Therefore, this percentage was excluded from waste processing; however, transportation to a nearby storage facility for future reuse was included in the calculations.

The reuse and recycling of the façade components are considered to be positive possibilities towards circularity. Notably, for PV panels integrated into the last façade system proposed (F5), the service life considered in this study aligns with their conventional average lifetime of 30 years [113]. This fact prevents PV panels from being reused, whereas other waste treatments are considered. In this regard, two assumptions are presented: PV panels will be deposited on landfills, and PV panels could be fully recyclable. Tables 2 and 3 present the results for each situation, respectively. For those façade buildings without FIPV panels, PV panels on the rooftop (considered to be part of the renovation scenario) are counted to develop an egalitarian comparison. See Appendix E for a more detailed information. (The percentages indicated in Appendix E refer to the output values summarised in Appendix F).

To obtain the results presented in the following tables (Tables 2 and 3), the embodied energy of each material presented for the product stage is considered. As previously explained (Section 2.5), they are not the corresponding operational energy needed during waste processing. These numerical values are used to analyse the circular economy potential, which is understood as the possibility of being sorted, reused, recycled or used as backfill.

Based on EN 15804, the waste disposal stage was considered to be the sum of materials intended to be incinerated or deposited in landfills. Fig. 6 shows the waste disposal estimates for both assumptions. Furthermore, Fig. 7 depicts the potential for circular economy,

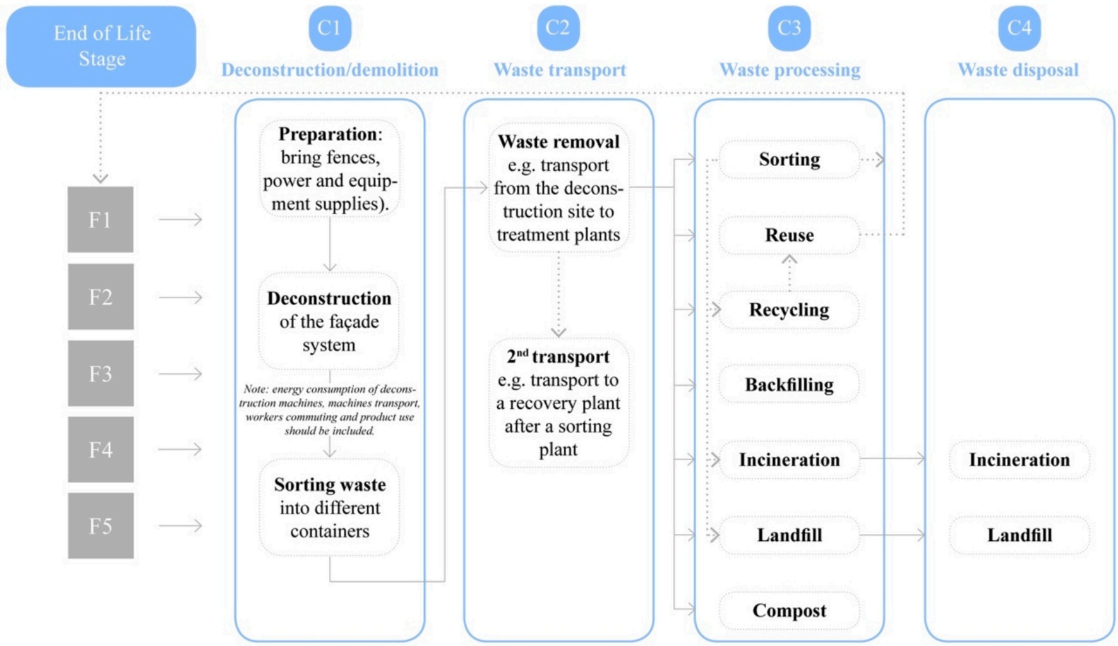


Fig. 5. End-of-life scheme.

Table 2
End-of-life possibilities for conventional and industrialised façade systems contemplated for the current research. Assumption A: PV panels will be deposited on landfills.

		Sorting	Reuse	Recycling	Backfilling	Incineration	Landfill
F1	ETICS	173	32	20	0	6	135
F2	Ventilated façade	242	76	40	0	6	131
F3	Timber frame façade panels	257	107	25	0	7	118
F4	Modular façade	296	139	33	0	6	118
F5	Modular façade + FIPV	340	130	33	0	6	171

Note: Data based in [112] and available information on manufacturers commercial websites [114]. Results in kg of CO_2 equivalent per façade surface.

Table 3
End-of-life possibilities for conventional and industrialised façade systems contemplated for the current research. Assumption B: PV panels will be fully recyclable.

		Sorting	Reuse	Recycling	Backfilling	Incineration	Landfill
F1	ETICS	173	32	134	0	6	21
F2	Ventilated façade	250	82	154	0	6	19
F3	Timber frame façade panels	257	107	139	0	7	4
F4	Modular façade	296	139	147	0	6	4
F5	Modular façade + FIPV	340	130	201	0	6	3

Note: Data based in [112] and available information on manufacturers commercial websites [114]. Results in kg of CO_2 equivalent per façade surface.

considering the estimated values for the rest of the waste-processing treatments (sorting, reuse, recycling, and backfilling). The results indicate that industrialised façade systems save more waste than ETICS systems (Fig. 6), as long as PV panels could be entirely recyclable. On that basis (Fig. 7), industrialised façade systems with pre-fabricated large modular panels (F5, F4 and F3) are the best façade systems in terms of circular economy and waste avoidance, followed by ventilated façades (F2).

To sum up, according to the total embodied results for each façade system proposed, when PV panels are fully recyclable (Fig. 8), it could be stated that industrialised systems, including the ventilated façade (F2) and particularly the modular ones (F3, F4 and F5), will likely provide the most savings in terms of embodied carbon owing to their possibilities towards circularity.

4. Discussion

The present research studies the potential impact that industrialised envelopes applied to NZEB renovations have on the decarbonisation of the built environment. The results indicated that if the proposed renovation of residential buildings were to take place, a main part of the 75 % of the built environment [8] (which is residential) could reduce its operational carbon emissions to 100 % (S20 and S24) in *Cfb* temperate climates. The industrialised modular façades proposed in this study, which were applied to the NZEB renovation in Spain, would be a great novelty, because nowadays, the building systems for renovating existing dwellings remain quite traditional and time-consuming, with unreasonably long periods of construction.

To analyse their suitability, LCA was employed to identify the optimal intervention in the built environment, aligning with similar studies [115–122]. However, when LCA is the main purpose, the input

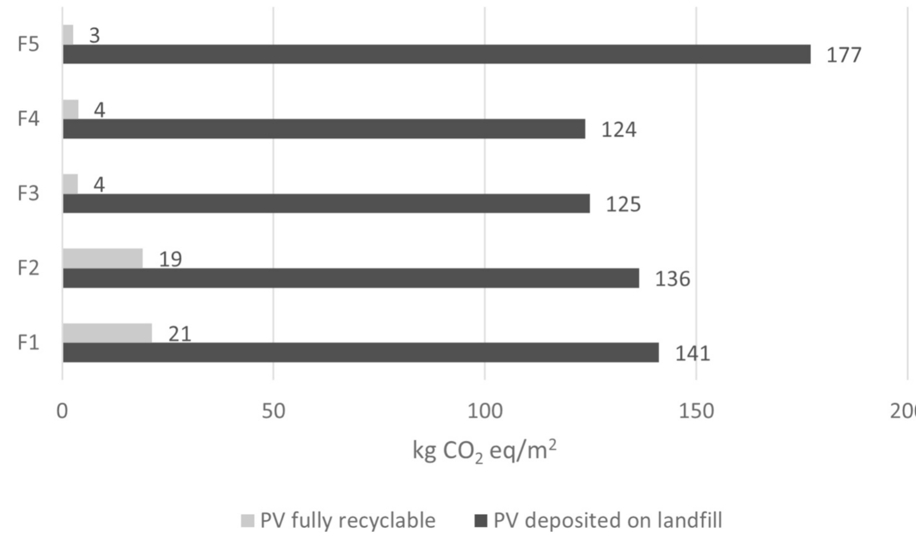


Fig. 6. Waste disposal (landfill + incineration) considering the recyclability of PV panels. (Results in kg of CO_2 equivalent per façade surface).

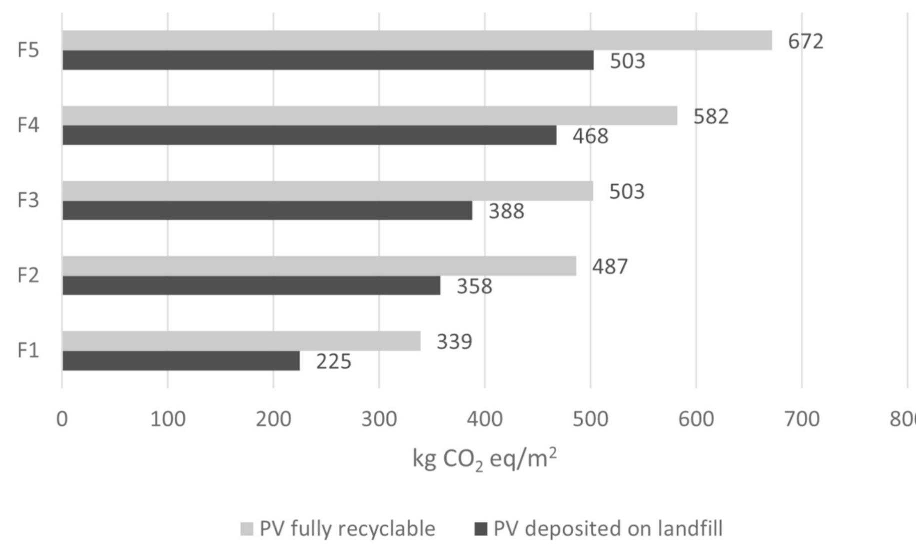


Fig. 7. Circular economy potential (sorting + reuse + recycling + backfilling) considering the recyclability of PV panels. (Results in kg of CO_2 equivalent per façade surface).

regarding active measures is sometimes less detailed. One of the main contributions of this study is the consideration of embodied carbon emissions for all renovation measures in the LCA, including passive, active and renewable measures (except for the end-of-life phase). To tackle this issue, the present study includes the embodied carbon of not only PV panels or solar collectors (SC) but also the energy systems (HP, CB) and heating emitters (E. radiators, LT radiators and radiant floor).

4.1. Evaluation of total carbon emissions in NZEB renovations

The results for RQ1 (Fig. 3), based on the NZEB renovation using the conventional ETICS façade, indicate the importance of considering both embodied and operational carbon. If only operational carbon emissions were measured, decision-making could be flawed. For instance, all scenarios with PV panels (S17-S28 in Fig. 3) seem desirable owing to their low values on phase B6 (see *Operational carbon* in Fig. 3). Nevertheless, as reported by similar studies [123], other scenarios without PV panels (S5–S12) would save more total carbon emissions as their embodied carbon is lower than those scenarios with radiant floor (RF, scenarios S25–S28). This is because installing radiant floors requires additional materials such as insulating panels, cement mortar, ceramic flooring [124,125], which increase embodied carbon, as explained by Gan et al [126].This suggests that embodied carbon values are important in the selection of the optimum scenario under the decarbonisation criteria.

Although this is not the only existing research in which different heat emitters are contemplated, it is noteworthy that in other studies focusing on heating system options (HPs, condensing boilers), heat emitters are only contemplated assuming different base cases [127]. Nevertheless, the current research contemplates the embodied carbon for different heating emitters as renovation scenarios, considering that the existing ones are original radiators (O. radiators). This study includes the embodied carbon of all the layers needed to install a radiant floor, as aforementioned, as well as the new low-temperature radiators.

To achieve carbon neutrality, the best scenarios for NZEB renovation using the conventional ETICS façade combine PV panels and HP as energy sources and radiators (existing or low-temperature radiators) as heating emitters. Although existing and low-temperature radiators have been recognised as the best heating emitters just by their operational consumption, the results of total carbon emissions (operational and

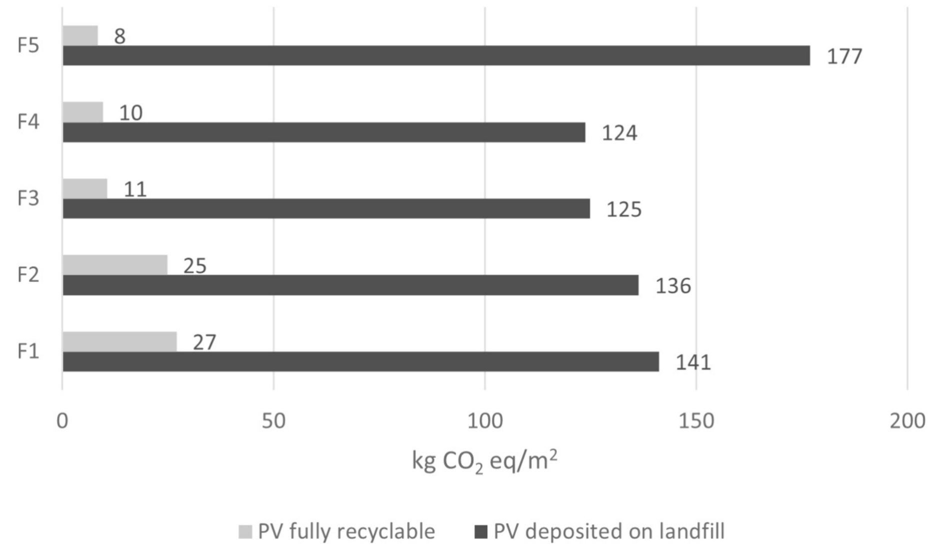


Fig. 8. Total embodied carbon results for each façade system proposed considering the recyclability of PV panels. (Results in kg of CO_2 equivalent per façade surface).

embodied emissions) in Fig. 3 reassure the use of PV panels. Fig. 3 also shows that these measures are recovered in terms of CO_2. It is worthy to mention the results are consistent with those of recent publications dealing with the same climate [128], such as the Vancouver case [129], which is also *Cfb* according to the Köppen–Geiger climate classification [78], as well as other existing studies [130–133]. Furthermore, as Hernandez and Kenny [134] observed, Fig. 3 shows some scenarios with low operational carbon (S18 or S22) perform better than self-sufficient scenarios (with nil results for operational carbon emissions) in life-cycle context (S20 or S24) [135].

LCA results presented in Fig. 3 show low carbon neutrality periods are not always aligned with the greater reduction in total carbon emissions. This fact is aligned with other studies that also consider the carbon neutrality period (or payback period). For instance, when analysing energy systems of residential buildings, D. Anastaselos et al. found that simpler options (e.g. condensing boiler with radiators) tend to have the most favourable carbon payback periods [136]. They explained this is because, although more complex systems demonstrate superior performance during the operational phase due to their higher efficiency, they also entail a greater environmental impact during production. As a result, their payback periods are extended.

Regarding whether *deep* or *moderate* renovations are better for carbon savings, results in Fig. 3 show the answer depends on the array of measures selected. Among scenarios without PV systems (S1-S16), *deep* renovations yield the best results for saving in total (operational and embodied) carbon emissions (see *Total carbon emissions* in Fig. 3). Contrarily, for those scenarios that include PV systems (S17-S28), *moderate* renovations are the ones warranting more carbon savings, considering total (operational and embodied) carbon emissions. While differences between *deep* and *moderate* renovations with ETICS façade are relatively small, results for the second research question (see the following section) suggest these differences increase with the industrialisation grade of the façade systems.

4.2. Comparison of different industrialised façade systems

Taking into account materials and construction are responsible for 11 % of global energy-related carbon emissions [37], assessing different industrialised façade systems for NZEB renovations seems timely. Section 3.2 analyses renovation scenarios conducted with four proposed façade systems, comparing them to the current state (S0) and the conventional ETICS façade solution. Fig. 4 illustrates that the higher level of industrialisation presented by the façade system (considering from most to least: F5, F4, F3 and F2), the bigger the impact of embodied carbon emissions. This seems logical, as increased industrialisation typically leads to greater complexity and higher material weight per square metre. These results are consistent with a prevailing project [95], where different industrialised façade options were compared with a conventional renovation system and the existing state but considering just the south façade as the aim of the research project [37].

As regards the conventional systems, it should be noted there is a concerning lack of highly skilled workers [28]. This is determinant as conventional systems require loads of labour, and the quality depends on their skills and the current state of the existing façade [12]. Contrarily, pre-fabricated systems are presented as high-efficiency solutions with magnificent manufacturing quality as their execution is controlled indoors, which reduces the possibility of unforeseen events [12]. Moreover, industrialised modular systems enable faster constructions and fewer inconveniences for occupants [12]. Consequently, industrialised façade systems provide more advantages during construction and replacement stages than ETICS systems.

Unlike other studies, this research considers only one type of cladding for industrialised façades to facilitate comparison. However, changing this layer can have a big impact on the final results of the LCA [100]. For instance, another study [85] reported that the two claddings proposed for the ventilated façade case exhibit considerable differences. In fact, the present results for the *moderate* scenario renovated with the ventilated façade (see Appendix F) indicate that the phenolic panels are the material with the second highest impact in the ventilated façade system, next to the façade substructure. Therefore, selecting façade cladding requires balancing durability, aesthetics, and environmental impact [137].

4.3. Towards circularity to decarbonise the built environment: beyond end-of-life

Transforming the built environment into low to zero-energy buildings requires considering the whole life CO_2 equivalent impact of renovations [138], including the end-of-life stage and circularity. Researchers advocate evaluating circularity in early design phases to prevent later design challenges [34]. However, developing a comprehensive LCA is time-intensive and complex [112], leading to calls for standardisation [139]. Sometimes, as in the present study, a quantitative assessment of phases C1–C4 and phase D is not possible (see reasons explained in Section 2.5). Nevertheless, a qualitative evaluation could also provide insight into the selection of a construction system [140], as indicated by the results of this study.

PV waste is projected to reach 1.7–8 million tonnes by 2030 and 60–78 million tonnes by 2050 [113,141]. On this basis, the first assumption for RQ3 was stated: PV panels will be deposited in landfills (Table 3). However, several studies have also emerged on the development of processes to recover PV materials (aluminium, glass, copper, silver, and silicon) [142–148] and reuse them in pre-fabricated building components (predalles slabs reusing PV glass) [146]. In fact, current EU regulations already mandate a minimum recyclability of 70–80 % for PV panels, and recent research demonstrates recycling rates of up to 82 % and material recovery rates of 94 % [149]. This is the reason why the second assumption was presented: in 30 years, PV panels could be entirely recyclable (Table 3). The feasibility of this hypothesis is supported by existing literature [150], the operation of Europe's first commercial PV module recycling facility since 2019 [151], and the recent opening of another recycling plant located in a Spanish city in proximity to Pamplona [152]. Results in Section 3.3 underscore the importance of recyclability in system selection.

As regards stage D (circular economy), no agreement has been reached as of yet on the strategies for circular assessment methods [34]. Nevertheless, according to EN 15804, the waste disposal stage includes only two processing treatments: incineration and landfill (Figs. 2 and 3). Hence, other waste-processing treatments introduced in phase C3 were considered to be activities that enhance circularity (Fig. 5). However, not all these treatments could foster a circular economy with equal force and effectiveness. Most studios consider *reuse* to be a better option than *recycling* [153]. Based on this statement, as long as reuse options are possible, circularity will increase [154,155] for those façade options with more components to be reused. Therefore, according to the results in this study, the modular façade with FIPV will be the most suitable façade system towards the circularity goal (Tables B6 and B7). This finding aligns with the results of the ENSNARE project outlined in [37], which also reported that the Global Warming Potential of the industrialised façade integrating photovoltaic panels is lower than that of the conventional renovation system or the baseline scenario in which the existing building remains unaltered. Furthermore, the project identified this industrialised façade as the renovation scenario with the lowest cycle-cost [37].

Overall, the findings related to the second research question (see Section 3.2) are consistent with those of Greer and Horvath [104], who examined the potential for carbon emission reductions in California if the state were to adopt factory-built modular housing. Their study concluded that emission reductions of between 1 % and 20 % could be achieved across all counties.

One of the major limitations of this study was the lack of quantitative data on end-of-life and waste treatments, which obstructs a numerical demonstration of prefabricated systems as a potential circularity solution. Some scholars argue for the development of automated circularity assessment technologies to address this gap [34]. Additionally, obtaining Environmental Product Declarations (EPD) for all products, especially for active systems, proved challenging, and in some cases, impossible [156,157]. Furthermore, selecting materials from existing libraries, such as Effinovatic for SimaPro, is also quite burdensome. Although initiatives to facilitate Life Cycle Assessment (LCA) via Building Information Modelling (BIM) have emerged [23,128,158,159], they are more useful for new projects than for renovation works that require a BIM model created specifically for the purpose.

Another major limitation concerns the lack of data regarding the construction stage for industrialised systems. Industrialised façade systems with large modular panels (F3, F4 and F5) are not widely used in Spain, and their application is even less frequent in the renovation sector. Therefore, data on the energy consumption required for assembling modules in the factory is unavailable. This had led to a shortage of information for comparing stage A4. Consequently, this publication also emphasises the need for manufacturers and construction companies to gather and freely provide these data to facilitate the selection of the most appropriate system for each case. As noted by Greer and Horvath in the context of California [104], a collaborative effort among general contractors, building designers and modular factory companies will also be required in Spain. Otherwise, the methodology followed in this research may be too burdensome to implement in practical projects. Nevertheless, this study offers a novel approach and contributes to a deeper understanding of industrialised and circular renovation, thereby supporting designers in the decision-making process when selecting façade systems for renovation.

Finally, it must be noted that the present study solely focused on the environmental impact of the proposed solutions and not on the existing building systems. Although cost reduction is one of the beneficial aspects entrusted to pre-fabricated systems [12], to achieve the energy transition, economical sustainability also needs to be ensured. One of the few existing studies comparing industrialised building systems with traditional methods indicates that both types of systems are broadly comparable in terms of investment costs, despite a cost variance ranging from approximately −7 % to + 16 % [160]. This study shows economic feasibility is a crucial factor in selecting the most appropriate façade system [160]. Future research should incorporate cost analysis and explore other building typologies, such as those developed for Atlanta [161], as well as conduct sensitivity analyses to address uncertainties related to the full recyclability of PV panels.

5. Conclusions

The present study highlights the role of industrialised façades applied in the NZEB renovations as a key factor to achieve carbon neutrality. They enable renovations on a large scale; at the same time, they would facilitate the circular economy owing to their possibilities for being easily deconstructed, reused and recycled. The main research goal of this study is to compare conventional and industrialised façade systems for NZEB renovations using the LCA methodology. In pursuit of this, the most representative building typology of a *Cfb* temperate climate was chosen as a case study: a residential linear block built between the first energy regulation and the implementation of EPBD 2002 in Pamplona (Spanish period: 1980–2006). The findings of the current study are as follows:

- Total carbon emissions, which consider both embodied and operational carbon, are decisive in selecting the optimum scenario under the decarbonisation criteria. For the case of NZEB renovations using the conventional ETICS façade, the scenarios combining PV panels, air-to-water heat pumps HPs and radiators (existing or low-temperature radiators) enable the most savings in total carbon emissions.
- *Deep* renovations (the lowest U values in Table A2) yield the best results in total carbon emissions for those scenarios without PV systems; however, when the scenarios include PV panels, *moderate* renovations (the highest U values in Table A2) enable more carbon savings.
- When considering embodied carbon emissions from the product (phases A1–A3), construction (phases A4-A5) and replacement (phase B4) stages, as well as operational carbon emissions (B6 stage), the façade system rank, from least to most total carbon emissions, as follows: ETICS façade (F1), timber-frame façade (F3), ventilated façade (F2, prefabrication system by small components), modular façade without FIPV (F4) and modular façade systems with FIPV (F5). Through the implementation of both active and passive renovation measures, façade system renovation reduces total carbon emissions from the current state to 44 % (F5-S17) and 58 % (F1-S18).
- The industrialised façade systems enable a greater reduction in construction waste and material use than the conventional ETICS façade when the end-of-life phase is considered, particularly the pre-

fabricated systems by large panels (F5, F4 and F3). Moreover, modular façade systems with FIPV (F5) could be the most advantageous façade system in terms of circular economy potential.

This study demonstrates that industrialised façades enable increased embodied carbon emissions during the product stage (A1–A3) compared with conventional renovation solutions. However, when the end-of-life stage (C3) is considered, industrialised façades can offer significant reductions in embodied carbon owing to their potential for circularity, particularly those with pre-fabricated large modules (F3, F4 and F5), provided that PV panels are fully recyclable.

The industrialised modular façades proposed in this study represent a significant innovation for NZEB renovations in Spain, addressing the shortage of available labour and the lengthy construction periods associated with conventional methods. Industrialised systems enable faster completion times while ensuring high quality construction and facilitating disassembly. These advantages are crucial for achieving NZEB renovations on a large scale and contributing to carbon neutrality across Europe.

Nevertheless, the lack of information on the construction stage (A4-A5) for industrialised systems in Spain presents a limitation in this study. Therefore, one of the objectives of this publication was to promote the need for Spanish manufacturers and construction companies to collect and freely share these data to encourage the adoption of industrialised systems. Future research should also incorporate cost analysis to evaluate economic sustainability.

CRediT authorship contribution statement

Lourdes Beneito: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Thaleia Konstantinou:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Joaquín Torres-Ramo:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Ana Sánchez-Ostiz:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Main features of the building typology – Current State.

Type	Linear block
Use	Residential building
Ground floor	Retail space without current use
Number of floors	4
Number of dwellings per floor	2
Total area per dwelling (m^2)	92
Façade	Face brick with light insulation
Roof	Flat roof with light insulation
Windows	Double glazed (4/6/4) windows with aluminium carpentry
Current active systems	Individual natural gas boiler for heating and DHW; water radiators; no cooling systems; natural ventilation

Table A2
Summary of the main input data considered in energy simulations.

Passive measures	Current state (CS)	*Moderate* renovation	*Deep* renovation
U regular façade (W/m^2K)	0.81	0.38	0.25
U façade with thermal bridges (W/m^2K)	1.39	0.41	0.37
U roof (W/m^2K)	0.48	0.30	0.21
U glass (W/m^2K)	3.15	1.27*1	1.60
U frame (W/m^2K)	5.88	1.10	1.10
Increased façade insulation (cm)	-	+5	+10
Increased roof insulation (cm)	-	+4	+10
Envelope's heat transfer coefficient (K_{limit}) *2 (W/m^2K)	1,85	0,69	0,67
Solar shading system	Blinds	Blinds with insulated slats	Blinds with insulated slats
Infiltration (50 Pa)*3	7	5	3
Ventilation rate (1/h) – all year	4(Only 30' in the morning)	0.51	0.51
Ventilation rate (1/h) – summer nights	4	4	4

Note: All values considered for *Moderate* renovation meet the threshold described by [16] in table 3.1.1.a – HE1; the ones considered for *Deep* renovation follow values in table a-Annex E of the same document [16]. For renovation scenarios slabs, staircase shafts and partition walls are kept in the original state.

Note (1): 1.73 is the minimum value accepted by [16]. However, in order to meet K_{limit} it was changed to 1.27.

Note (2): K_{limit} is a term used in [16]. It refers to the heat transfer coefficient for the overall thermal envelope of the building.

Note (3): The data collected in the research project INFILES [162] was used as a basis for the energy simulation values regarding airtightness in the current state, as well as improvements in airtightness for the NZEB scenarios.

Table A3
Scenarios, combining passive & active measures, considered for energy simulations of the linear block typology (1980–2006).

Renovation scenario	Passive measures	Energy system H&DHW*1	Heating emitter*2	Ventilationsystem*3
S0	*CS*	OB	O. radiators	N. vent.
S1	*mod.*	CB+SC	E. radiators	No HRV
S2	*mod.*	CB+SC	E. radiators	HRV
S3	*deep*	CB+SC	E. radiators	No HRV
S4	*deep*	CB+SC	E. radiators	HRV
S5	*mod.*	HP	E. radiators	No HRV
S6	*mod.*	HP	E. radiators	HRV
S7	*deep*	HP	E. radiators	No HRV
S8	*deep*	HP	E. radiators	HRV
S9	*mod.*	HP	LT radiators	No HRV
S10	*mod.*	HP	LT radiators	HRV
S11	*deep*	HP	LT radiators	No HRV
S12	*deep*	HP	LT radiators	HRV
S13	*mod.*	HP	R. floor	No HRV
S14	*mod.*	HP	R. floor	HRV
S15	*deep*	HP	R. floor	No HRV
S16	*deep*	HP	R. floor	HRV
S17	*mod.*	HP+PV	E. radiators	No HRV
S18	*mod.*	HP+PV	E. radiators	HRV
S19	*deep*	HP+PV	E. radiators	No HRV
S20	*deep*	HP+PV	E. radiators	HRV
S21	*mod.*	HP+PV	LT radiators	No HRV
S22	*mod.*	HP+PV	LT radiators	HRV
S23	*deep*	HP+PV	LT radiators	No HRV
S24	*deep*	HP+PV	LT radiators	HRV
S25	*mod.*	HP+PV	R. floor	No HRV
S26	*mod.*	HP+PV	R. floor	HRV
S27	*deep*	HP+PV	R. floor	No HRV
S28	*deep*	HP+PV	R. floor	HRV

This table was previously published in the authors' earlier work [76].

* *Note (1):* H&DHW (Heating & Domestic Hot Water). OB (Original boiler) refers to the existing natural gas boiler (individual dwelling units) of the *CS* (Current State). CB+SC refers to renovation scenarios that combine CB (Condensing boiler) as individual dwelling units with SC (Solar collectors). HP (air-to-water heat pump) are individual dwelling units too. HP+PV refers to renovation scenarios where HP are combined with PV (photovoltaic panels) placed on the roof. In detail, for PV panels placed on roof the following data was considered: 51 (number of panels to avoid possible shading), 102 m^2 (PV total area), 22.5% (PV module efficiency).

Note (2): O. radiators (Original radiators) are water radiators whose water supply temperature (WST) is 80°C. All heating emitters proposed for the renovation scenarios are low-temperature heating emitters. E. radiators (existing radiators) refers to the original water radiators working at low-temperature (WST: 50 °C). LT radiators refers to the new low-temperature radiators (WST: 45 °C) that will replace the original ones. R. floor refers to a new radiant floor system (WST: 40 °C).

Note (3): N. vent (Natural ventilation) refers to the lack of mechanical ventilation system at the *CS*. No HRV: hybrid ventilation without heat recovery system. HRV: mechanical ventilation with heat recovery system. The efficiency considered for the HRV is 75%.

** It must be noted that the initially proposed NZEB renovations (S1–S4) maintain existing radiators and natural gas as energy sources but replace the original boilers with condensing ones, which are more energy efficient. Although extra renewable energy is included in those scenarios (solar collectors) to satisfy the renewable threshold value for Domestic Hot Water (DHW, as established in [82]), such scenarios should not be considered totally fossil fuel free. Nevertheless, condensing boilers were defined as a first step because, a priori, that could be the most affordable scenario to achieve.

Note: The remaining appendices are provided in the **Supplementary section**.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115885.

Data availability

Data will be made available on request. See Appendices A, B, C, D, E and F for more detailed information.

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