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Definition and design of a prefabricated and modular façade system to incorporate solar harvesting technologies

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Abstract

The current research presents the design and development of a prefabricated modular façade solution for renovating residential buildings. The system is conceived as an industrialised solution that incorporates solar harvesting technologies, contributing to reducing energy consumption by employing an "active façade" concept.

One of the main challenges was to achieve a highly flexible solution both in terms of geometry and enabling the incorporation of different solar-capturing devices (photovoltaic, thermal, and hybrid). Therefore, to be able to provide alternative customised configurations that can be fitted to various building renovation scenarios. Guided by the requirements and specifications, the design was defined after an iterative process, concluding with a final system design validated and adopted as viable for the intended purpose.

A dimensional study for interconnecting all the technologies composing the system was carried out. Potential alternative configurations were assessed under the modularity and versatility perspective, resulting in a set of alternative combinations that better fit the established requirements. Complementarily, the system also integrates an active window solution a component that incorporates an autonomous energy recovery system through ventilation.

The main outcome is explicated in a highly versatile modular façade system, which gives existing buildings the possibility to achieve Nearly Zero Energy Building requirements.

Keywords

multifunctional prefabricated façade, industrialisation, renewable integration, façade renovation

DOI

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1 INTRODUCTION

1.1 CONTEXT

The existing building stock plays a vital role in the energy transition and achieving carbon neutrality in the built environment, accounting for nearly 40% of energy consumption in Europe (Tsemekidi-Tzeiranaki et al., 2020). The European Union's building stock comprises over 220 million units, with approximately 85% built before 2001. It is projected that 85-95% of the current buildings will still be standing in 2050 (European Commission, 2020). In line with this, the Energy Performance of Buildings Directive (EPBD) mandates that all existing buildings must be converted into zero-emission buildings by 2050. Deep renovation, with savings of at least 60% of the current energy consumption, is needed to achieve the decarbonisation goals and additional benefits, job creation, and elimination of energy poverty. Presently, around 75% of the building stock is energy inefficient, and only about 1% undergoes renovation annually, with deep renovation only in 0.2% of the building stock per year (European Commission, 2020).

Recognising this challenge, the European Commission launched the Renovation Wave in 2020 as part of the European Green Deal. This initiative includes an action plan outlining specific regulatory, financial, and supportive measures to promote building renovation and double the current rate of annual energy renovation by 2030 while encouraging comprehensive renovation (European Commission, 2019, 2020). The "fit for 55" package also recognises buildings as one of the key sectors to cut down emissions and supports the renovation and the increase of the renewable energy sources application (European Commission, 2021).

Given the urgency, the EU must prioritise strategies that improve energy efficiency, reduce carbon emissions, and promote sustainability throughout a building's lifespan (European Commission, 2023).

Consequently, stakeholders such as policymakers, social housing corporations, institutional real estate owners, financial organisations, and end-users are increasingly focusing on the potential of renovating the existing building stock to achieve energy-neutral standards. To accomplish this, it is crucial to enhance the process of building renovation by increasing both the rate and depth of renovation (Artola, Rademaekers, Williams, & Yearwood, 2016; Economidou et al., 2011; Jensen, Maslesa, Berg, & Thuesen, 2018).

Currently, the annual renovation rate of the building stock varies between 0.4% and 1.2% across EU Member States, falling short of meeting emission targets (Broers, Vasseur, Kemp, Abujidi, & Vroon, 2019; European Commission, 2020). To align with policy objectives, this rate needs to increase to approximately 2.5-3% of the housing stock per year (Sandberg et al., 2016; Wilson, Pettifor, & Chryssochoidis, 2018). Additionally, most improvements in residential buildings are limited to basic maintenance and shallow renovation, necessitating broader and deeper energy renovation measures. While shallow renovation, such as standard thermal wall insulation and insulated glazed components, offers lower initial costs, it fails to provide a sufficient return on investment in financial terms (Filippidou, Nieboer, & Visscher, 2016; Semprini, Gulli, & Ferrante, 2017).

Furthermore, in response to the energy crisis, the issue can be addressed by incorporating renewable energy sources (RES) into the building structure. This can be achieved by utilising specific installation methods within a modular framework, resulting in the creation of a multifunctional façade module (MFM). In this scenario, the innovative building façade serves various purposes, such as providing protection, harnessing energy, and converting it into usable forms (Li & Chen, 2022).

1.2 SOA IN ENERGY RETROFITTING THROUGH THE FAÇADE

Deep renovation interventions are based on applying different technologies to buildings, considering façades, roofs, windows, heat and cooling production, ventilation or renewables (Streicher et al., 2020; Moran et al., 2020). When combining such technologies, alternative packages can be compiled to achieve different impact levels after the intervention, typically considering an upgrade of the envelope.

To increase energy performance, ventilated façades are widely used in renovation (Colinart et al., 2019; De Gracia et al., 2013). This system increases the thermal resistance to heat flow of the existing wall by means of adding thermal insulation (*Gagliano & Aneli, 2020)*. This results in a reduction of the energy demand, mainly for heating during cold periods of the year. The systems usually comprise the elements substructure, insulation, waterproof membrane, and cladding panels. It is a dry solution, which is installed on an existing wall by fully assembling all the elements on-site, and some experiences with prefabrication variations have also been considered in the past (Avesani et al., 2020).

However, the evolution of envelope systems is moving towards increasingly industrialised solutions (Wasim et al. 2020; Ferdous et al. 2019; Navaratnam et al. 2019; *D'Oca et al. 2018*), manufactured off-site under controlled conditions by specialised workers. This approach provides the opportunity to incorporate energy-related technologies into the envelope components (Van Roosmalen, Herrmann, & Kumar, 2021). Industrialisation gives more reliability to guarantee higher product quality and minimises on-site activities, where uncertainty about the correct execution grows exponentially. At the same time, the interest in prefabricated solutions is currently growing due to the lack of specialised labour in the construction sector.

Modular curtain walling is also an increasingly widespread example of industrialised envelope systems but is applied mostly for new buildings rather than for renovation activities. These solutions are made up of modules formed by a self-supporting frame that contains the different layers together with the elements of the enclosure. These modules are manufactured entirely in the factory, and the on-site intervention is limited to the positioning and fixing of the modules on the building. Many of the performance requirements for these systems are guaranteed through standardised tests in approved laboratories. However, modular solutions have so far not penetrated the retrofitting market to any significant extent. Mainly because a solution flexible enough to adapt to the built environment has not been achieved and because they are substantially more expensive than other in-situ assembly systems, theoretically offering similar performance. It is common for curtain walling systems to be conceived as a new-build solution, so their application to the built environment is not obvious.

A relevant aspect that ventilated façades and curtain walling have in common is the widespread use of aluminium profiles as a framing element. Its strength, lightness, and durability against external agents make it an ideal material for this use. Different aluminium alloys provide alternative profiles with different properties, while the possibility to recycle this material indefinitely also contributes to reducing construction waste. On the other hand, the production of aluminium from raw materials requires a rather high amount of energy (Efthymiou, Cöcen, & Ermolli, 2010).

In the most innovative areas, new envelope systems with integrated renewables are being developed to meet the EU's decarbonisation targets for the building stock (*Du, Huang & Jones, 2019; D'Oca et al., 2018).* Many of these developments (Bonato et al., 2019) are part of solutions conceived under a modular concept which considers the integration of solar technologies for use inside the building (Elguezabal & Arregi, 2018). Nevertheless, although there have been some research approaches towards solutions for the decarbonisation of the building stock in recent years (Van Roosmalen, Herrmann, & Kumar, 2021; Streicher et al., 2020; Navaratnam et al., 2019; Du, Huang & Jones, 2019; D'Oca et al. 2018), it has become apparent that these experiences are not yet sufficiently developed in aspects such as the industrialisation of the system, flexibility in terms of modularity, interchangeability and customisation of solar collection technologies to provide an ad-hoc response to the demands of each building and the accessibility for maintenance and replacement that these active envelope systems may require.

In this context, a need has been identified to develop new façade systems for the retrofitting sector that integrate solar capture technologies. These solutions will reduce the building's fossil energy consumption and are conceived from a prefabricated and industrialised perspective under a systemic approach, aiming to minimise on-site operations and offer maximum performance guarantees.

The purpose of this paper is to explain the process followed for the definition and design of prefabricated and modular façade systems to incorporate solar and renewable technologies. It is a modular and industrialised façade system capable of integrating different solar collection technologies under different configurations, enabling the possibility to meet different needs for alternative buildings. The designed active façade gets a new functionality, namely solar harvesting, enabling this component to be employed in multiple ways in conventional solar systems in residential buildings. The large-scale objective is to achieve a solution that meets the decarbonisation needs of the building stock to achieve the EU's 2050 targets. The main defining characteristics of this system are:

- Versatility in terms of construction and energy. It is a system aimed at the refurbishment sector, adaptable to different building scenarios. It offers the integration of different technologies for collecting solar energy depending on the specific energy needs. These components are also interchangeable, using a plug-and-play mechanical fixing system.
- Integration of the service network of the solar technology in the same modular solution. From a modular perspective, the system contemplates the possibility of interconnecting the solar panels between modules, generating the necessary network on the same façade plane, making it fully accessible for installation and maintenance.
- Modular design under the premises of industrialisation to achieve a system that offers guarantees in terms of anticipating the expected performance, especially in this case where it is not only necessary to guarantee the functionalities as a construction product but also as a renewable energy collector element, functionally active throughout its useful life.

2 METHODOLOGY

The methodology carried out to achieve a solution with the aforementioned characteristics can be summarised as follows:

A Definition of the industrialised façade panel design concept
The main premises to define the conceptual design of the system are: (1) to develop an industrialised system, (2) to conceive it for implementation in the envelope refurbishment sector, and (3) to integrate different solar collecting technologies. Taking these conditions into account, the concept design of the developed system has been based on the characteristics of ventilated façade systems, which are solutions mechanically fixed on an existing wall and modular curtain walling solutions that have a high degree of industrialisation.

B Analysis and definition of the dimensional and technical specifications to be considered in the design phase of the façade system:

- To have great flexibility to be adapted to the wide range of construction typologies that constitute the European building stock. Parameters such as distance between floors, distance between windows and dimensions, overhangs and irregularities, etc., have been considered. An analysis of the dimensional limitations imposed by the transport of the façade modules has also been carried out.
- To have the appropriate versatility from the energy point of view so that the façade system can integrate different solar collecting technologies that meet the specific demand of each building. The modularity and restrictions of each solar technology and alternative combinations have been considered for their integration into a façade module, fulfilling the specifications defined in the previous point. Likewise, the integration of active windows with a heat recovery system has also been considered. This provides the façade system with an energy-efficient solution for the opening elements.
- To ensure that the infrastructure associated with solar technologies is fully accessible for connection and maintenance during all phases of the façade system's operational life and decommissioning. To this end, a specific space has been defined within the modular system, named access zone. Its dimensions are variable depending on the needs of the technologies integrated into the façade system.

C Analysis and definition of the regulatory requirements that the façade system must comply with the Construction Product perspective (EU Parliament, 2011). As there is no specific standard for this innovative system, the essential characteristics (performance) that will be required of this system have been defined based on the following product standards:

- EAD 090062-00-0404: Kits for external claddings mechanically fixed (EOTA, 2018)
- EN 13830: Curtain walling. Product standard (CEN, 2020)
- EN 50583: Photovoltaics in buildings

The selection of the first standard as a reference for the design is based on the premise of developing an envelope solution oriented towards the renovation sector; thus, it will be installed and fixed on an existing wall. Likewise, as a priority objective, it is established that this solution should have a high degree of industrialisation so that on-site activities are reduced as much as possible. Hence, the product standard for curtain walling is set as the second reference standard. Finally, the standard that contemplates the integration of photovoltaic technology in buildings has been considered, as the façade system comprises, among others, this solar energy collection technology.

D Detailed definition of the façade system based on the established requirements and specifications and design principles towards an industrialised solution (Lessing, 2006; Viana, Tommelein, & Formoso, 2017). Modularity of the technologies, the connection and interchangeability through plug-and-play systems have been part of the design guidelines.

E Evaluation of the performance of the façade system as a Construction Product. The most critical performances have been selected. These performances are those with the highest level of uncertainty, and the verification of these is made either by simulations, during the design phase, or laboratory tests once the detailed design has been defined. The manufacture of full-scale prototypes for laboratory tests has also allowed to validate the production and assembly process, as well as the suitability of the different elements composing the complete façade. The achievement of each of the evaluation phases has led to an iterative review of the construction design.

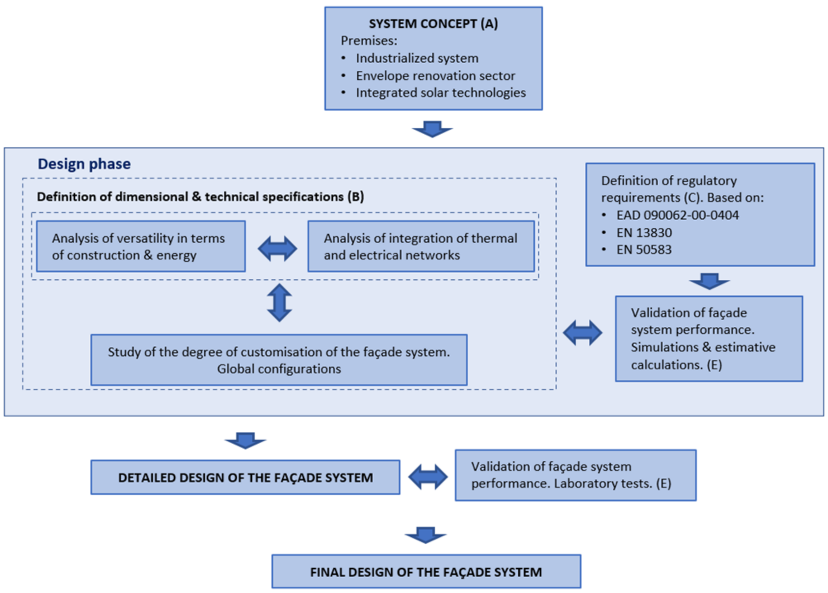

FIG. 1 Methodology followed for the development of the innovative façade system.

3 RESULTS

3.1 DESCRIPTION OF THE SYSTEM

This initial section in Chapter 3 provides a general description of the façade system developed with its main characteristics. Sections 3.2, 3.3, and 3.4 describe each of the system's components and the research conducted to define them.

The modular system consists of two independent layers: the inner layer and the outer layer. These layers are joined together through a mechanical fastening system.

The developed façade system has significative similarities with ventilated façades, as it is defined as a solution mechanically fixed to a supporting wall, but also with curtain walls as the system is conceived as a fully modular concept. From the energy performance perspective, it provides improved thermal insulation to the façade as well as the generation of energy (electrical and thermal) thanks to the solar collecting technologies incorporated. The flexibility of the modular system allows the external active skin to be customised according to the different energy requirements of each building. An aluminium supporting mesh gives the system the required modularity and flexibility.

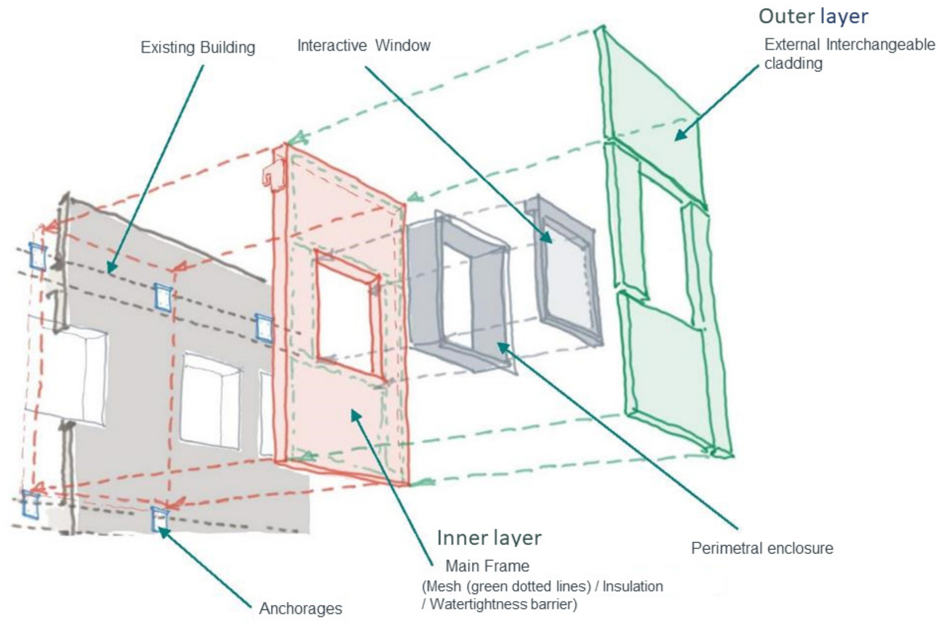

FIG. 2 Modular façade system concept.

The inner layer covers structural, thermal insulation, air and watertightness. The outer layer incorporates different solar harvesting technologies and the access zones through which the infrastructure associated with these technologies runs on the façade plane.

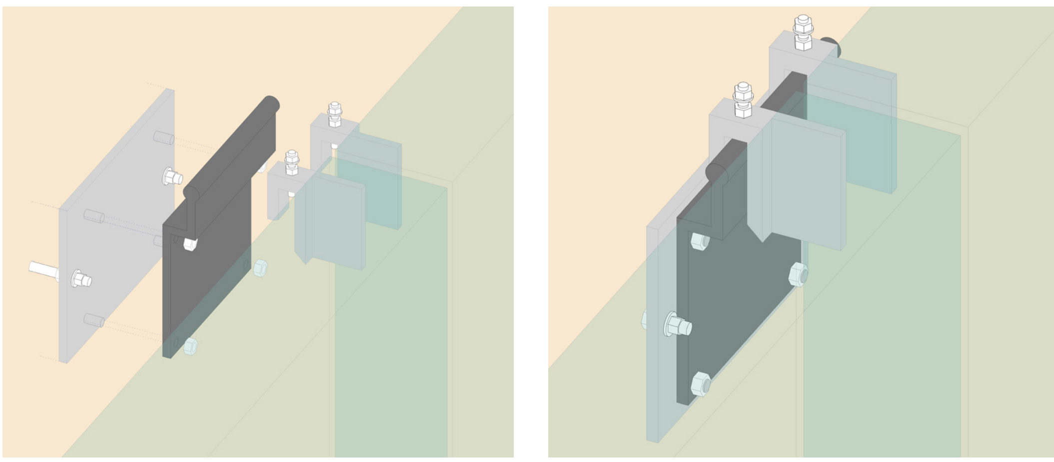

FIG. 3 Anchoring system designed by ENAR. Exploded view (left). Assembly (right)

The inner layer consists of a structural aluminium main frame containing thermal insulation and a breathable membrane. The membrane defines the watertight plane of the system. Constructively, the mainframe works as a modular tongue and groove curtain wall system. The anchoring system consists of a set of two support plates fixed to the slab of the building and two hanging elements at the top of the mainframe. This concept is similar to those used for anchoring modular curtain wall solutions.

One of the plates (grey in FIG 3.) is fixed to the slab of the building, and the other plate, which is placed in the front (black in FIG 3.), allows the adjustment in the perpendicular direction of the façade. The top hanging elements are placed on the outer plate. The position of the modules is adjusted by means of the levelling screws located on the hanging elements. This assembly has three degrees of freedom, allowing the façade module to be positioned and adjusted in all three axes. This design involves a bottom-up assembly process that allows access to the anchoring elements during the installation process. Finally, on the back of the mainframe, covering the whole surface, a continuous low-density insulation layer is deployed. This insulation layer absorbs the vertical misalignment of the existing wall and fills in the space generated between the modules and the façade. This element is an essential component of the modular façade system to guarantee that no air cavity is generated between the module and the existing façade.

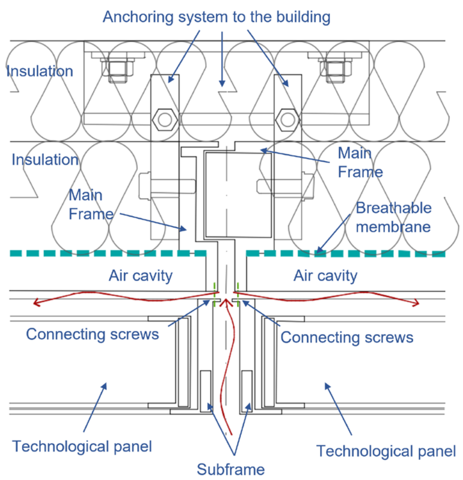

FIG. 4 Schematic horizontal section of the modular façade system. The red arrows indicate the air path from the outside into the air cavity through the perimetral joint between the subframe and the mainframe.

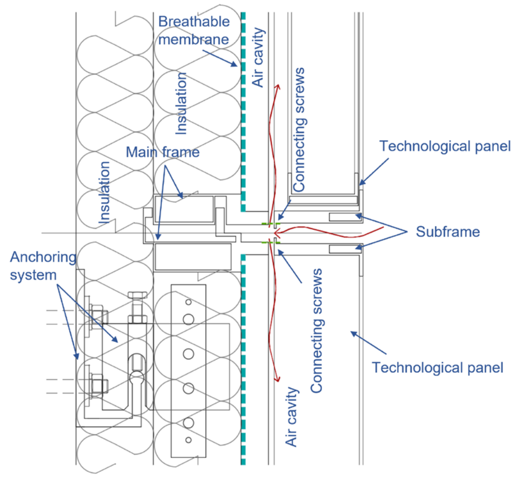

FIG. 5 Schematic vertical section of the modular façade system. The red arrows indicate the air path from the outside into the air cavity through the perimetral joint between the subframe and the mainframe.

The outer layer is composed of different solar collecting technologies combined with the access zones in which the energetic network associated with these active elements is arranged. Technological panels are formed, integrating every solar technology in a subframe. These technological panels are fixed to the mainframe with a mechanical plug & play connection. A screw is mechanically fixed every 30 centimetres to a specifically designed channel that is located in the mainframe. These fixings are placed around the entire perimeter of the technology panel and can be removed and replaced multiple times. This fixing system makes it easy to replace the panels independently in case the panel is broken or damaged. It turns this outer layer into an easily interchangeable enclosure, while the mainframe does not require to be replaced. Moreover, the connection system between the internal and external layers generates a perimetral opened joint that allows the ventilation of the air cavity between the two layers. This guarantees the correct hygrothermal behaviour of the façade and, at the same time, benefits the efficiency of the photovoltaic technologies. From a constructive point of view, this configuration can be integrated into cladding systems that are mechanically fixed to a supporting wall, such as ventilated façade systems.

The main features of each of the active technologies that are integrated into the outer layer can be summarised as follows:

- Thermal solar panel for thermal energy generation. It captures solar energy through an aluminium absorber and transfers the energy to a hydraulic circuit.
- Photovoltaic panels with aluminium and synthetic stone substrates to transform irradiation into electricity, an energy that is then distributed through electric circuits.
- Hybrid panel for the generation of thermal and electrical energy. It combines photovoltaic and solar thermal technologies.

The connection between the technology panels and the layout of the infrastructure in the façade plane requires an accessible space next to the solar technologies. The solution to this need is solved through the so-called access zones that are also located in the exterior layer; a chamber that is generated as part of that layer. They follow the same aesthetics and fixing system as the technological panels and have a phenolic panel cladding as closure. They are fully registrable, generating a continuous track to interconnect the technological panels and can be arranged vertically or horizontally depending on the configuration of the technological layer and the energy networks required depending on the case. Access to the infrastructure for maintenance throughout its service life is possible thanks to the hinge system incorporated in the cladding of the access zones, allowing the cladding to be opened 180°.

Finally, the façade system responds to the glazing elements of the buildings by incorporating active windows with an intelligent ventilation and heat recovery system. This component substantially improves the management of the building's ventilation from the perspective of comfort and energy efficiency. An autonomous control system manages air renewal considering the results of the monitoring of the indoor conditions. The active window is located in the same plane as the insulation layer of the system to guarantee its continuity.

Therefore, this industrialised envelope system allows a fast and accessible connection between all its components in all phases of its service life and even during the decommissioning phase. Since the façade system is installed from the outside very quickly, the impact on the building's activity is very low or even negligible. It is designed to allow for the replacement of the outer layer panels for maintenance purposes. The system also ensures a high degree of flexibility to be adapted to different building typologies that are present in the building stock, guaranteeing fast and efficient manufacturing and installation processes. The system allows the combination of different solar harvesting technologies, aiming to incorporate a significant number of interconnected active panels and, therefore, enabling the adoption of large-scale renewable energy solutions as part of façade energy refurbishment interventions.

3.2 ANALYSIS OF CONSTRUCTION AND ENERGY VERSATILITY

In the design phase, the first analysis focused on the dimensional definition of the façade modules and their flexibility in both width and height. Afterwards, the solar technologies were analysed to define a wide variety of interchangeable technological panels, taking into account optimum energy performance.

3.2.1 Architectural modularity of the façade system

The developed modular façade system is designed to be adaptable to a broad typology of existing buildings. The general dimensions (width and height) of the façade module have been defined considering the following aspects:

- Constructive characteristics of the residential building stock. The distance between floors in the building stock varies greatly. Residential buildings less than 40 years old have distances of 2.75 m between axes. However, older buildings have greater distances between 3 and 3.2 m in height. Windows also vary greatly in size, but a width of 0.70 m to 1.10 m can be taken as a reference for single-leave windows, and double-leave windows range from 1 m to 1.6 m. The height is usually between 1.30 m and 1.70 m.
- Maximum weight allowed of the module on the existing structure. The self-weight of the modular façade, as well as the wind load on the façade, will be transmitted directly to the floor slabs of the building as point loads through the anchoring system between the façade module and the existing wall. Therefore, the permissible maximum weight of the modules will depend on the load-bearing capacity of the building structure. This parameter must be verified in each project. However, as a design parameter, a target of 100 kg/m^2 has been established for the modular façade. It is higher than conventional curtain walls, whose weight is around 40-70 kg/m^2. Regarding the load limitation of the auxiliary means required in the installation phase, conventional cranes have a peak load limitation of 2000 kg.
- Optimisation of transport to avoid exorbitant costs (MITMA, 2023). The standard dimensions of the trucks have been considered to establish the modularity of the system.

After analysing these aspects, a 2.2x3.40 m module was defined as the maximum size that would adequately cover the established main requirements of flexibility, lightness, easy transport, and installation. On the other hand, the total thickness of the modular system is variable and adaptable. The inner layer and the outer layer have an established thickness of 133 mm and 103 mm, respectively. The perimetral opened joint between them is 4 mm thick. However, the insulation layer behind the mainframe has a variable thickness, depending on the case. This dimension will be defined taking into account the lack of vertical alignment of the existing façade and the cavity generated between the module and the existing wall that needs to be filled with insulation. At least 40 mm of insulation will be needed. Therefore, the total thickness of the modular system will be at least 280 mm.

3.2.2 Technological panel modularity

A fundamental aspect to be analysed during the design of the modular system is the dimensional flexibility of the technological panels to be integrated into the outer layer. To this end, the requirements and limitations of each of the technologies and the restrictions imposed by their integration have been identified. Based on this study, a technology database has been created, offering all the possibilities for technological panels and their different combinations within a façade module.

Common requirements for all the technologies have also been established:

- The maximum weight of the technological panels is set at 50 kg (INSST, 2011). This condition is imposed to facilitate the handling by two operators during the assembly phase of the façade in the workshop manufacturing process and to facilitate maintenance and replacement processes during their lifetime.
- All the technologies are integrated into an aluminium subframe. The subframe, combined with the technologies, forms the technological panel. This subframe is mechanically fixed to the mainframe of the inner layer. This allows the standardisation of the connection between the two layers, regardless of the technologies selected for the outer layer. The geometry of the subframe allows a quick and removable connection to the main frame.

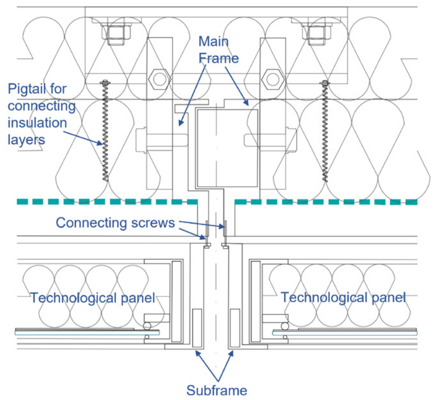

FIG. 6 Schematic horizontal section of the connection between the technological panels and the mainframe via the subframe.

The analysis and results on the modularity obtained for each technology are summarised below: solar thermal (ST), photovoltaic (PV), and hybrid technology (PVT).

Solar Thermal panel (ST)

The ST technology consists of an external glass, an aluminium absorber with integrated hydraulic channels, an airtight air chamber between these two elements, and rock wool insulation on the back of the absorber. One inlet and one outlet hydraulic pipe to interconnect multiple ST panels are also part of these panels. An aluminium frame closes all the elements so that this assembly is integrated into the subframe. The limiting element to determine the size of the ST panel is the geometry of the absorber. The dimensions of this collector have been established considering the following conditions:

- The manufacturing process of the absorber limits the maximum dimensions of the collector to 510x1660 mm.
- This collector, which is also the basis of the hybrid panel (PVT), must have compatible dimensions to be able to attach the photovoltaic technology with an adequate distribution of cells. In other words, the absorber must be valid both for ST and for PVT technologies.
- Offer at least three configuration alternatives that can be installed vertically and horizontally.

As a balanced solution meeting all these requirements, an absorber of 485x1660 mm was selected.

The image below shows the modularity exercise carried out for ST. The combination of one, two or three absorbers (ST1, ST23, and ST34) offers the possibility of positioning the panels vertically (V) or horizontally (H). The hydraulic connections are arranged on the side (L) or in the upper area (U). A single absorber solar thermal panel is also feasible.

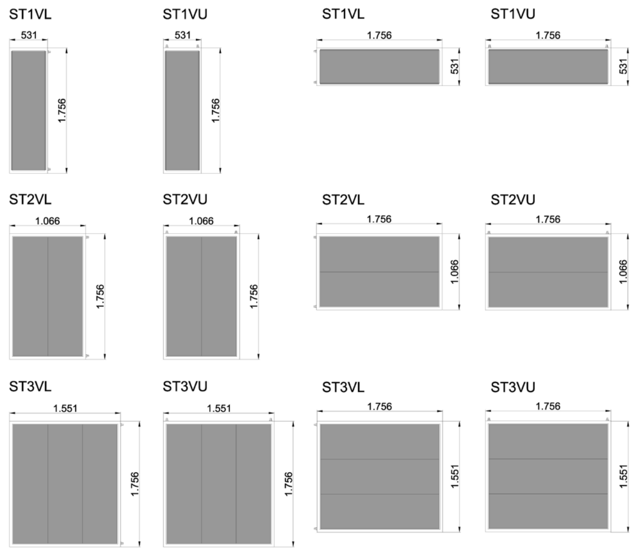

FIG. 7 Modularity analysis of solar thermal technology.

The following table shows the dimensions of the technological panel in all its combinations.

TABLE 1 Modularity of solar thermal panel (ST)

	CODE NAME	ST PANEL DIMENSION	ST PANEL DIMENSION
TECHNOLOGY		(width) [mm]	(height) [mm]
ST PANELS	ST1VL	571	1756
	ST1VU	531	1796
	ST1HL	1796	531
	ST1HU	1756	571
	ST2VL	1106	1756
	ST2VU	1066	1796
	ST2HL	1796	1086
	ST2HU	1756	1126
	ST3VL	1591	1756
	ST3VU	1551	1796
	ST3HL	1796	1551
	ST3HU	1756	1591
	ST4VL	2076	1756
	ST4VU	2036	1796
	ST4HL	1796	2056
	ST4HU	1756	2096

Hybrid panel (PVT)

This technology incorporates the same absorber as the ST panel. A photovoltaic panel is attached to the front surface of the absorber, while an insulation layer is adhered to the back. The hybrid technological panel is generated once these components are integrated into the subframe.

The density of cells in PVT panels is dependent on the number of absorbers. For example, a PVT panel with one absorber can accommodate 20 photovoltaic cells, but a PVT panel with two absorbers integrates up to 60 cells.

Under the same conditions as in the case of ST panels, an analogous modularity study is carried out for hybrid technology, obtaining 32 types of PVT panels. These panels contain 1, 2, 3 or 4 absorbers. The data is included in Table 7 in the Appendix.

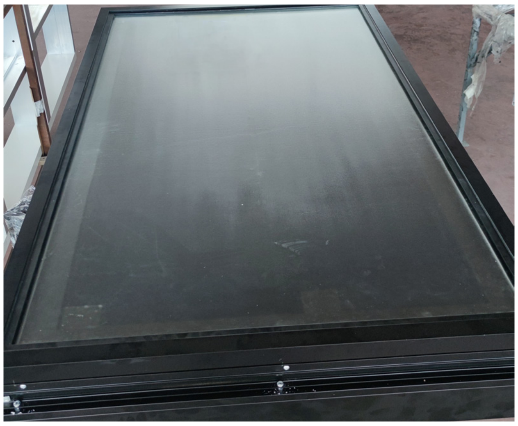

FIG. 8 Prototype of ST panel combining RIVENTI's and KAMEL's technologies.

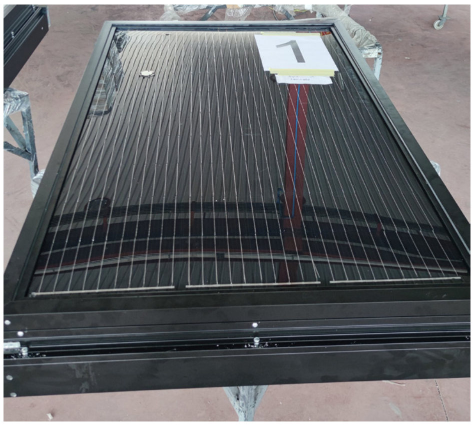

FIG. 9 PVT panel, scaled prototype, combining RIVENTI's, TECNALIA's, ONYX's and KAMEL's technologies.

Photovoltaic panels (PV) with different substrates

The modular façade can accommodate two types of substrates for the lamination of photovoltaic technology; aluminium (PV+AL) and synthetic stone panel (PV+SS). As for the rest of the technologies, these are integrated into the subframe, generating the photovoltaic technological panel. The requirements that have guided the analysis and dimensional design of the photovoltaic panels are:

- Standard supply dimensions of the aluminium and synthetic stone panel are adopted as baseline.
- Limit the waste of substrate generated in the production process to less than 15%.
- Achieve dimensions compatible with ST and PVT technologies to facilitate the combination of all three technologies in the same façade module. This is achieved when the dimension of one side of the PV technology matches the dimension of one side of the ST and PVT technologies.
- Offer a variable density of cells in such a way that the substrate is visible to a greater or lesser extent. Both aluminium and synthetic stone have an aesthetic value, and the visibility of the substrate affects the design of the envelope. The possibility of generating panels with variable cell density provides a great variety of alternatives from an aesthetic point of view.

The dimensions of the optimised panels are available in Table 8 in the Appendix. The figure below shows the different phases of the study.

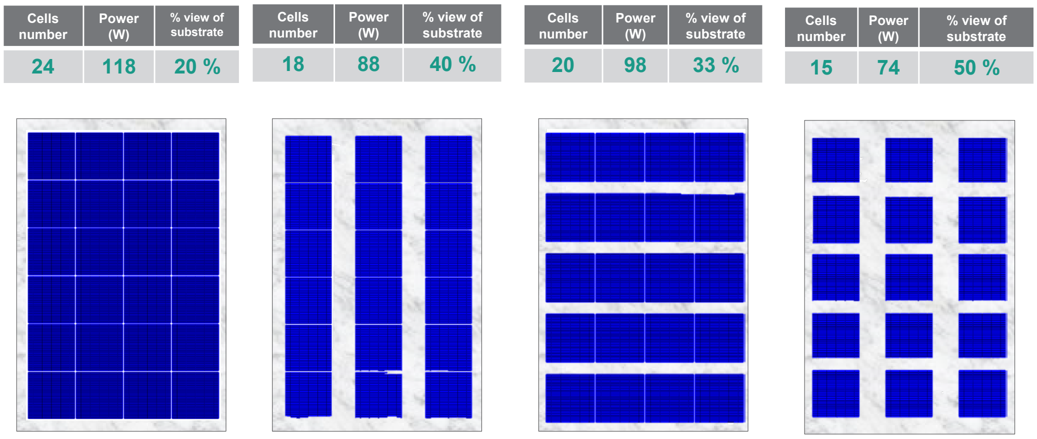

FIG. 10 Study on different cell densities in a 1060x710 mm PV+SS panel. This exercise was carried out for all the dimensions considered. Source: ONYX.

The following table shows the dimensions of PV+AL and PV+SS that are compatible with PVT and ST technologies. This means that they can be easily combined in the same façade module. These dimensions are indicated in bold.

TABLE 2 Dimensions of PV+AL and PV+SS technological panels compatible with PVT and ST technologies.

	PV PANEL DIMENSION	PV PANEL DIMENSION
TECHNOLOGY	(width) [mm]	(height) [mm]
PV+AL	1106	756
	571	766
	571	1476
	756	1591
PV+SS	1106	756
	571	766
	1106	1476
	571	1476
	756	1591

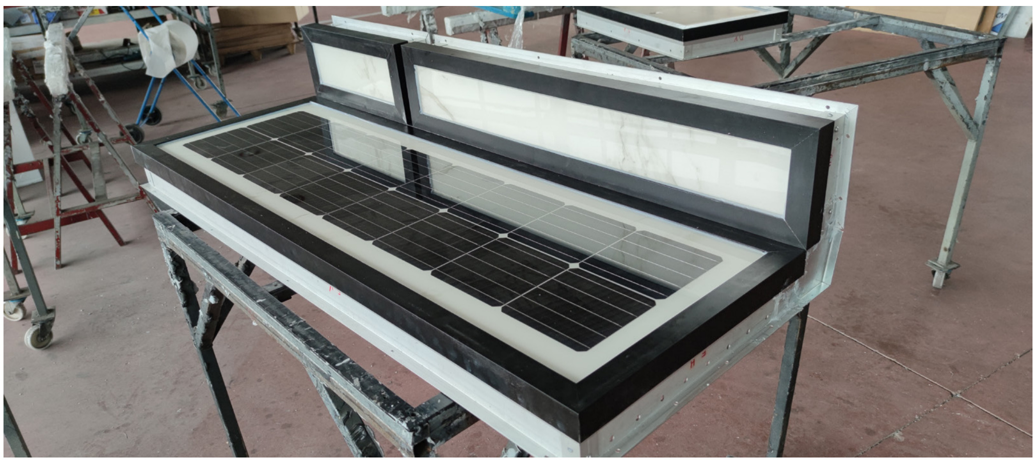

FIG. 11 PV+SS panel, scaled prototype, combining RIVENTI's and ONYX's technologies.

3.2.3 Active window

The active window incorporates an intelligent decentralised ventilation system with heat recovery integrating a heat exchanger that takes benefit of the thermal differences between the supply and exhaust air. The air renewal control is activated according to a series of parameters monitored inside the room, mainly humidity, CO_2, and temperature.

From a constructive point of view, the active window is fixed to the mainframe of the inner layer. This element is positioned aligned with the waterproof membrane and the insulation layer to guarantee the airtightness, watertightness, and correct thermal behaviour of the assembly. The interface between the window and the outer layer of the façade system is solved through the subframe profile. The ventilation box is integrated into the lintel and includes a thermal bridge break that is aligned with the one for the window. The back of the ventilation box must be accessible from inside the building to ensure proper air renewal and to facilitate possible maintenance works. Likewise, the wiring required for the power supply of the ventilation system and for the control system is in an area accessible from inside the building.

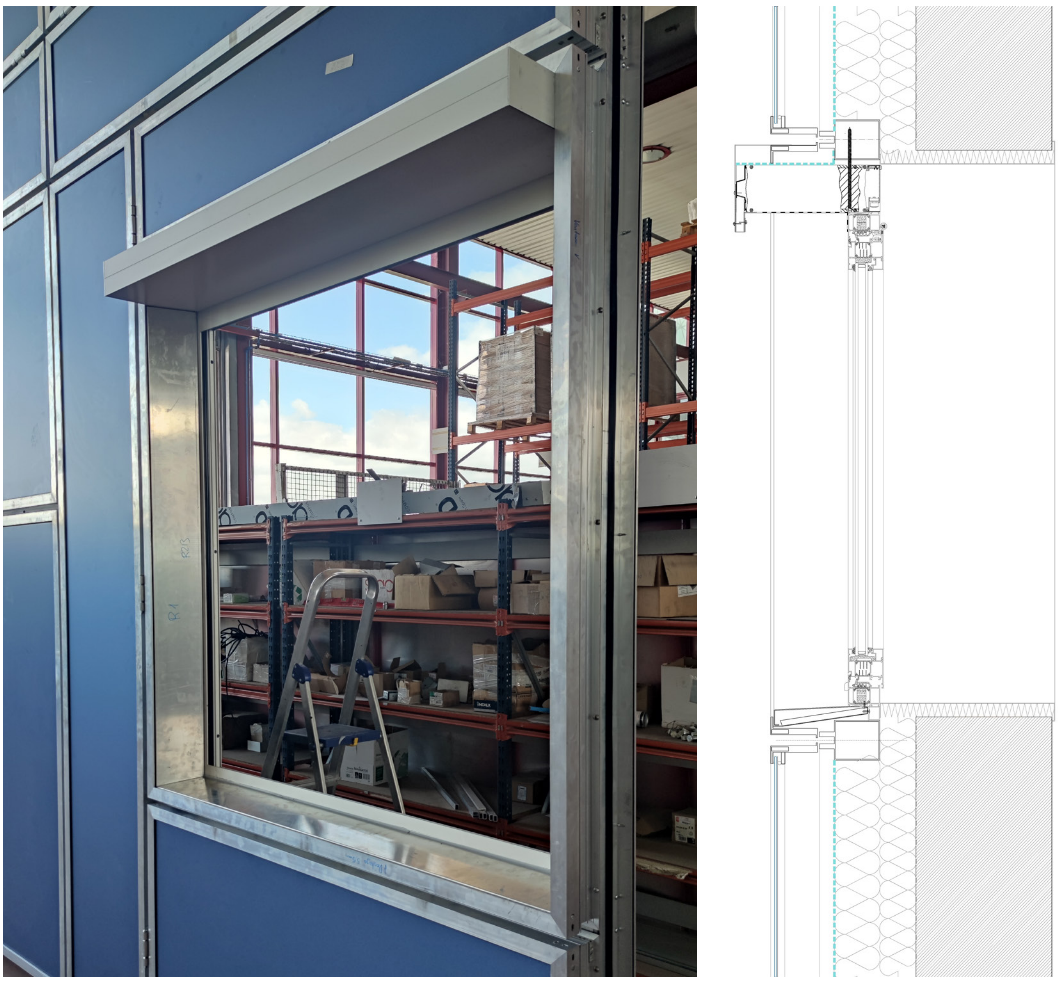

FIG. 12 Integration of the active window in a full-scale prototype of the façade system, combining RIVENTI's and TRESPA's technologies (left). Vertical section (right).

To avoid problems of interferences between the aerator box and the existing façade in the on-site installation phase, some minimum distances between these elements must be considered. Specifically, 10 mm separation between the rear face of the aerator and the existing façade and 20 mm to the horizontal plane of the existing window opening. Thus, the position of the ventilation system in the façade module must be verified in each project according to the characteristics of each building.

All these distances allow the absorption of small deviations in the dimensions of the window opening as well as the incorporation of the finishing elements in the transition area between the new window and the old window for renovations that involve removing the old window. This area is covered with aluminium composite perimeter elements that are installed once the modular façade system that incorporates the new window is in place.

3.3 ANALYSIS OF INTEGRATION OF THE ELECTRICAL AND THERMAL NETWORKS IN THE MODULAR FAÇADE SYSTEM

Another innovative aspect of the façade system is the integration of a specific space to interconnect the solar technologies from different modules and to generate an infrastructure network, hydraulic and electrical, on the façade plane that is fully accessible for installation and maintenance.

The layout of the access zones on the façade is defined according to the integrated solar technologies and the connection between them. The access zones must ensure a continuous network on the exterior layer of the façade system. For this purpose, they can be positioned horizontally and vertically.

The access zones are configured by a phenolic panel as a cladding layer, the subframe common to all the technologies of the outer layer of the façade system and a hinge system that allows a 180° opening of the cladding. This opening guarantees full access to the space destined to integrate the installation network.

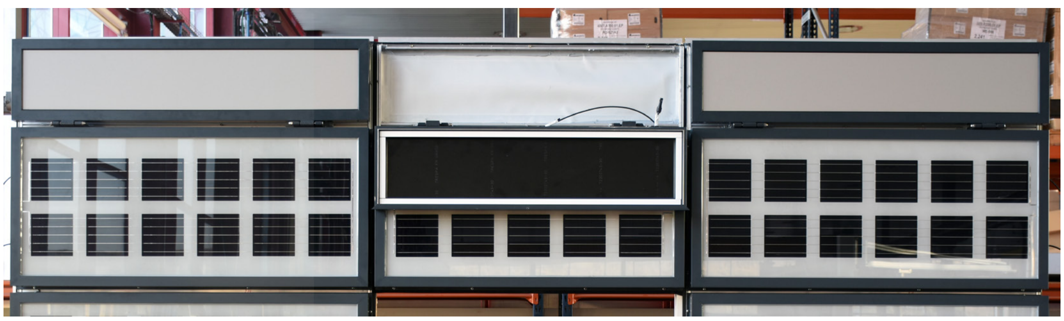

FIG. 13 Full-scale prototype, combining RIVENTI's and ONYX's technologies. 3 access zones can be seen at the top of the sample. The central access zone is opened, and the lateral ones are closed.

The minimum dimensions of the access zones are defined by the space required by all the components of the integrated network. The hydraulic network requires more space than the electrical one. Valves, air purges, elbows, etc., are elements that must necessarily be placed in these spaces. Therefore, the minimum width in the case of vertical access zones will be 300 mm if the panels with solar thermal technology are located on the same side of the access zone and 400 mm if they are on both sides of the access zone. In the case of horizontal access zones, these are connected to the solar thermal technologies located below them to ensure proper hydraulic operation. Given this premise, the minimum height required for horizontal access zones is 300 mm. In addition, to define these minimum dimensions, the requirements for supporting elements for piping and electrical wiring have also been considered.

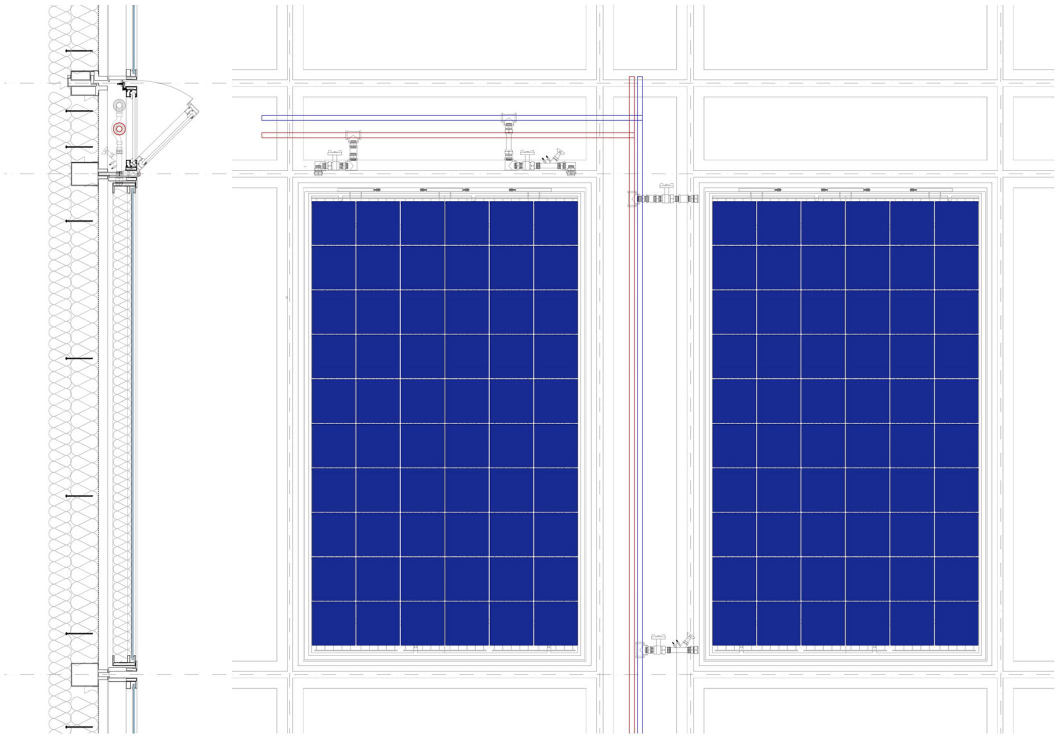

FIG. 14 Distribution of hydraulic infrastructure, connecting PVT panels in vertical and horizontal access zones. Elevation view (right) and vertical section (left).

The access zone can be sized to include services that run along the façade of the building before the renovation, such as drainpipes, gas pipes or cables, also making them accessible. This might require a slight adaptation of their tracks to place them into the outer layer of the modular system.

3.4 GLOBAL CONFIGURATION OF THE MODULAR FAÇADE SYSTEM

The modular façade tends to be configured using large modules. The larger the modules, the cheaper they are to manufacture and the quicker the installation of the complete façade system on the building will be. However, it is possible to manufacture smaller modules to suit the needs of every building. Each module can have multiple configurations depending on the type of panels placed on the outer layer and their relative position in the module. The ST and PVT panels are the most limiting ones from a dimensional perspective, as their sizes are fixed by the number of absorbers that they comprise.

Based on the results obtained in the modularity analyses described in the previous sections, the possible combinations of technological panels that a façade module can offer are studied.

Initially, the number of ST or PVT panels was quantified by combining the number of absorbers per panel, their orientation (vertical or horizontal), and the position of the connections (top, right-hand side and left-hand side) with the general network in the access zone (horizontal or vertical). As a result of this analysis, 48 panel alternatives for ST and PVT were obtained.

TABLE 3 ST and PVT combinations depending on the number of absorbers, their orientation and the connection with the access zone.

	N° ABSORBERS	1		2		3		4	
ABSORBER'S POSITION	Access zones	PVT	ST	PVT	ST	PVT	ST	PVT	ST
VERTICAL	LATERAL left or right	$PVT1VL_L$ $PVT1VL_R$	$ST1VL_L$ $ST1VL_R$	$PVT2VL_L$ $PVT2VL_R$	$ST2VL_L$ $ST2VL_R$	$PVT3VL_L$ $PVT3VL_R$	$ST3VL_L$ $ST3VL_R$	$PVT4VL_L$ $PVT4VL_R$	$ST4VL_L$ $ST4VL_R$
	UPPER	PVT1VU	ST1VU	PVT2VU	ST2VU	PVT3VU	ST3VU	PVT4VU	ST4VU
HORIZONTAL	LATERAL left or right	$PVT1HL_L$ $PVT1HL_R$	$ST1HL_L$ $ST1HL_R$	$PVT2HL_L$ $PVT2HL_R$	$ST2HL_L$ $ST2HL_R$	$PVT3HL_L$ $PVT3HL_R$	$ST3HL_L$ $ST3HL_R$	$PVT4HL_L$ $PVT4HL_R$	$ST4HL_L$ $ST4HL_R$
	UPPER	PVT1HU	ST1HU	PVT2HU	ST2HU	PVT3HU	ST3HU	PVT4HU	ST4HU

Secondly, the relative position of these panels within the module has been considered. The module is divided into upper zone (U), middle zone (I), and lower zone (L). This iteration results in 48 possible configurations for the module, considering ST and PVT panels with 1, 2, 3 or 4 absorbers.

TABLE 4 Alternative combinations depending on the type of PVT or ST panels (number of absorbers, 2, 3 and 4), their orientation and the positioning of the active panel inside the module.

	N° ABSORBERS		
COMBINATIONS	2	3	4
HAAZ Horizontal absorbers + access zone	HAAZ2U	HAAZ3U	HAAZ4U
	HAAZ2I	HAAZ3I	HAAZ4I
	HAAZ2L	HAAZ3L	HAAZ4L
VAAZ Vertical absorbers + access zone	VAAZ2U	VAAZ3U	VAAZ4U
	VAAZ2I	VAAZ3I	VAAZ4I
	VAAZ2L	VAAZ3L	VAAZ4L
HVAZ Horizontal absorbers + vertical access zone	HVAZ2U	HVAZ3U	HVAZ4U
	HVAZ2I	HVAZ3I	HVAZ4I
	HVAZ2L	HVAZ3L	HVAZ4L
VHAZ Vertical absorbers + horizontal access zone	VHAZ2U	VHAZ3U	VHAZ4U
	VHAZ2I	VHAZ3I	VHAZ4I
	VHAZ2L	VHAZ3L	VHAZ4L

As an example, nine possible module configurations are graphically presented below. In this case, the access zone is horizontal with a vertical PVT panel with 2, 3, and 4 absorbers. The white areas are photovoltaic technology, PV+Al or PV+SS.

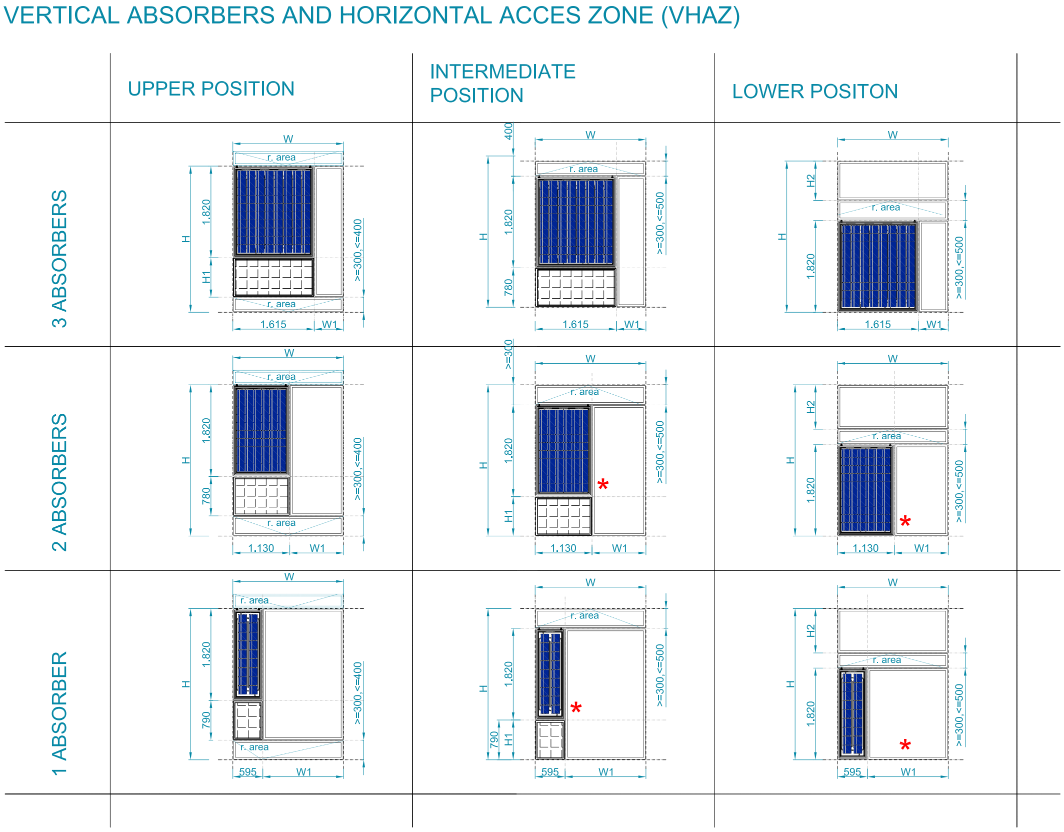

FIG. 15 Graphical representation of nine possible configurations when the access zone is placed horizontally and when the absorber is in the vertical direction (VHAZ)

Finally, after thoroughly defining the system design, all possible combinations of technological panels have been analysed, and an assessment was conducted to quantify the system's weight. Firstly, the weight per square metre of the different components that comprise the modular façade was calculated. This information is presented in the following table.

TABLE 5 Weight values per surface area of the components of the modular façade system.

Layer	Components	Kg/m²
Inner	Aluminium profiles Insulation panels Waterproof Membrane	20
Outer	Access zone	18
	ST	32
	PVT	43
	PV+Al	26
	PV+SS	30

Therefore, the weight range per square metre of the modular system varies between 38 and 63 kg/m2.

A representative module of 1.13x3.32 m configurated by a PVT panel with two absorbers (1.13x1.82 m), a PV+Al (1.13x1 m), and an access zone (1.13x0.5 m) would reach a total weight of 203 kg.

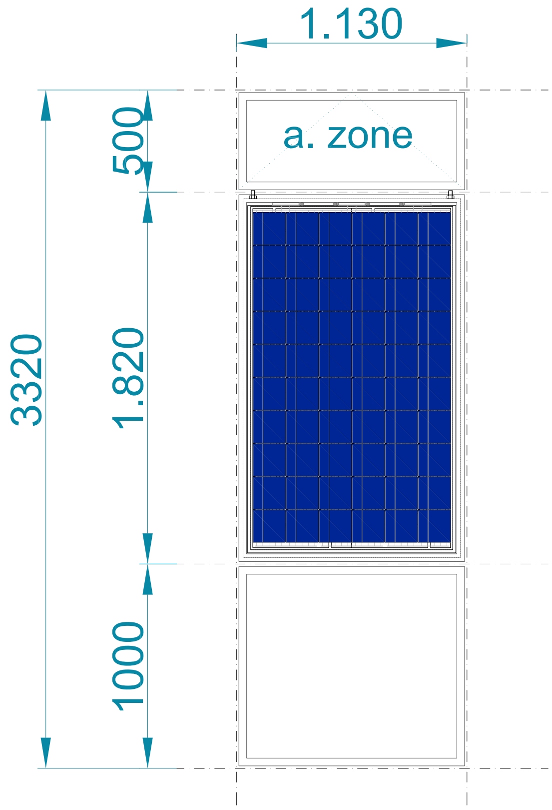

FIG. 16 Representative module

3.5 VALIDATION OF SYSTEM PERFORMANCE

As indicated in the Methodology section, reference standards for evaluating the system performance are EAD 090062-00-0404, EN 13830, and EN 50583. As the inner layer is assimilated to a modular curtain wall solution, the assessment of the essential characteristics related to this element will be carried out under Product Standard EN 13830. However, the exterior layer is assimilated in many aspects as an external cladding mechanically fixed, and for that reason, the essential characteristics associated with this element will be evaluated under the standard EAD 090062-00-0404. EN 50583 standard for the assessment of photovoltaic panels as construction products, when installed on buildings, compiles, among others, the above two references depending on whether the photovoltaic technology is integrated into a façade system or is part of the cladding of the building and mechanically fixed to a supporting wall.

The following table shows the priority essential characteristics identified for the new façade system as well as their target value. The reference standards considered to define the target value are also indicated.

These are the main requirements considered critical for the design and validation phase of the innovative façade system. In later development stages towards the commercialisation of the solution, an analysis of other additional requirements may be necessary depending on the application scenario. This is the case of seismic behaviour, a parameter that has not been evaluated yet but that could imply some adaptation of the system to comply with such requirements.

TABLE 6 Priority essential characteristics of new façade system.

No	Essential characteristic	Assessment method	Type of expression of product performance	Target value
Basic Works Requirement 2: Safety in case of fire				
1	Reaction to fire	SBI TEST EN 13501-1, based on EAD	Class	([1]) B-s3, d0 (required class) B-s2, d0 (desired class)
Basic Works Requirement 4: Safety and accessibility in use				
2	Wind load resistance	Simulations	Level	([2]) Qw = 2-3 kN/m^2
3	Weight resistance	Simulation, based on EN 13830	Level	
Basic Works Requirement 6: Energy economy and heat retention				
4	Thermal resistance	Simulation	Level	([3]) 0.2 W/m^2·K (Overall value of the façade)
Durability				
5	Hygrothermal behaviour	Analysis	Description	Not applicable

Two typologies of analysis have been considered for assessing compliance with the priority essential characteristics:

- Validation through simulations and/or estimative calculation. These are related to structural, thermal and hygrothermal performance.
- Validation through tests. This affects mainly the protection against fire performance. Ensuring that the façade system meets the regulatory requirements for fire performance is essential to validate the developed solution.

The evaluation of structural, thermal, and hygrothermal performance was carried out during the design phase. These analyses have allowed us to define in detail the sections of the profiles, the layers of the system, their characteristics and their relative position. As a result of the verification of these essential characteristics together with the modularity exercise described, the detailed solution of the façade system was defined.

Then, the fire reaction was validated through a laboratory test once the design phase was completed. The heterogeneity of the system, configured by the connection of numerous elements, layers and materials, implied a significant uncertainty in this respect.

1 Depending on the building type, the height, and the EU Member State, fire safety requirements vary. The preliminary fire reaction classification of B-s2, d0 should be aimed for, though other classifications such as the B-s3, d0 are valid for façades in many Member States. In the case of the Spanish standard, CTE DB-SI, the maximum classification required is B-s3, d0, for façade elements that occupy more than 10% of the surface area in buildings with a height of more than 18 metres. This class is also required for insulation systems located in ventilated air chambers in buildings with a height of less than 28 metres.

2 Ref Standard CTE DB SE AE. Section 3.3. (CTE DB-SE-AE, 2009)

3 Ref Standard CTE DB HE. (CTE DB-HE, 2022)

REACTION TO FIRE – SBI TEST

This test evaluates the potential contribution of a product to the development of a fire under a fire situation, simulating a single burning item in a room corner near that product. In the specific case of the new façade system, the outer technological layer, including all the fixing systems, was tested. One test per each of the five technologies considered for these panels was performed, obtaining a preliminary fire reaction classification:

- 1 phenolic sample representing the access zones of the system
- 1 thermal solar sample (ST)
- 1 hybrid sample (PVT)
- 1 photovoltaic sample with aluminium substrate (PV+AL)
- 1 photovoltaic sample with synthetic stone substrate (PV+SS)

The configuration and the dimensions are detailed in the figure below.

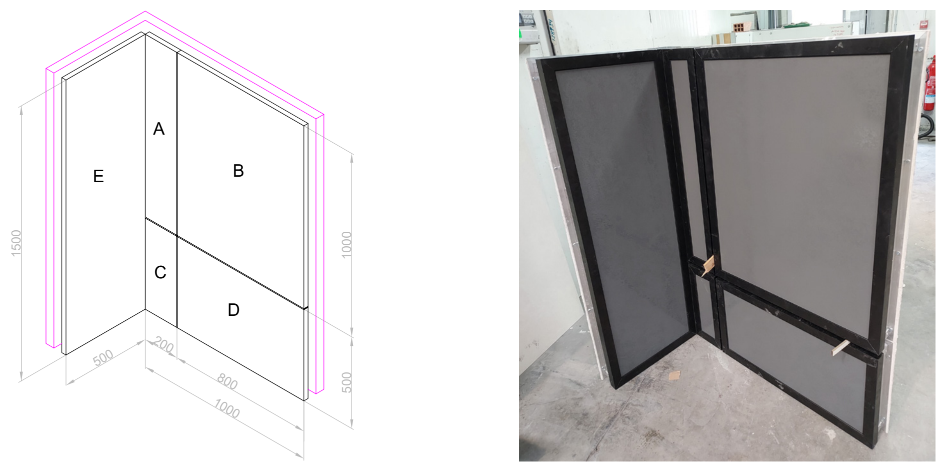

FIG. 17 Configuration and dimensions of the SBI test sample (left). Phenolic sample combining RIVENTI's and TRESPA's technologies (right)

The same result was achieved for all five tests–pictures are included below–concluding with a preliminary reaction to fire classification of B-s1,d0.

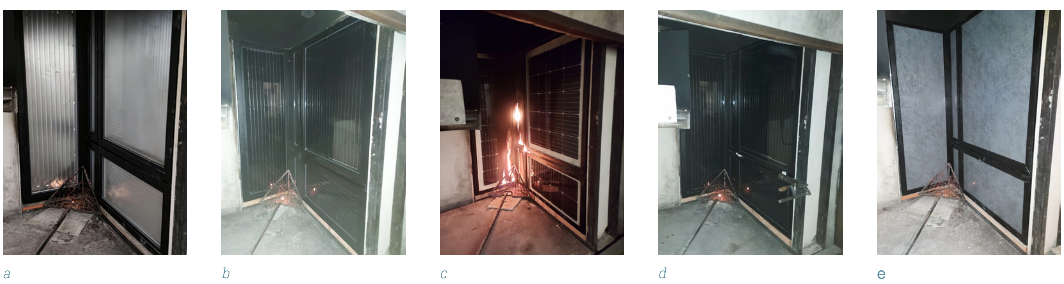

FIG. 18 a: sample of ST panels (without selective coating), b: PVT panels sample, c: PV+SS sample, d: PV+AL sample and e: phenolic panels sample. RIVENTI's, TECNALIA's, ONYX's, KAMEL's and TRESPA's technologies were adopted.

4 DISCUSSION AND CONCLUSIONS

This paper presents the development process of a prefabricated modular system for renovating residential buildings. The system consists of an industrialised solution that incorporates solar harvesting technologies. One of the main challenges was to achieve a highly flexible solution both in terms of geometry and to enable the incorporation of different solar-capturing devices. The ultimate goal was to achieve a façade system for the renovation sector that is constructively adaptable to a wide range of residential buildings and that provides renewable solar energy, thermal or electrical, depending on the demand of the building. This solution offers existing buildings the possibility to fulfil Nearly Zero Energy Buildings requirements.

The following conclusions have been drawn from the process of developing this modular façade system.

- From a constructive flexibility and architectural adaptability perspective, the solution is adaptable to any distribution and size of windows in the building, whether regular or irregular. However, this system is more suitable for flat façades than for those with balconies. The thickness of the modular façade system is significant, therefore reducing the useful surface area of these elements. Its design allows different thermal insulation levels to be met, as the thickness of the insulation layer is adaptable. Ensuring contact between the insulation layer of the modular system and the existing wall of the building was identified as a complex challenge in the design phase due to the multiple irregular alignments on the vertical plane that commonly appear in buildings. The mainframe of the modular system cannot be adapted to these irregularities. Therefore, to avoid generating an air gap between the façade module and the existing wall, a layer of low-density insulation covering the whole surface was incorporated on the back of the mainframe. As a consequence, this insulation layer limits the contact of the aluminium mainframe with the existing wall, limiting the thermal bridges just to the specific area of the anchorages.
- In terms of the ability to customise the outer layer of the façade system from an energy point of view, offering the possibility to combine different solar technologies. The method that allows obtaining the maximum variety of sizes and combinations has been identified: 1) to analyse the dimensional flexibility of each technology considering aspects such as: size restrictions and % waste limitations at the manufacturing phase of the technological panels and 2) to define the potential sizes of the technological panels (façade element) of the most constraining technology. The energy efficiency of those integrated technologies and the handling during the assembly in the workshop (off-site) needs to be considered, 3) to identify which panel sizes of the technologies with greater dimensional flexibility are compatible with the previous ones, taking into account the energetic performance, 4) to compose all the combinations of panels in the façade module incorporating the access zones. During this study phase, ST and PVT panels with four absorbers were discarded due to the difficulty of handling them, given their dimensions and weight. The maximum dimensions of the PV+Al panels have been limited to 1300x1060 mm due to the restrictions of the lamination process of the photovoltaic cells on the substrate. The maximum surface area of the PV+SS panels has been restricted to 1.7 $m^{2,}$ not to exceed the maximum weight for their manipulation.
- From the performance point of view. The results of the reaction to the fire test predict a B-s1,d0 classification, higher than the target value established. This highlights the potential of the façade system developed as a solution for the renovation market.

In conclusion, a prefabricated and modular façade solution with the integration of solar technologies to meet the decarbonisation objectives of the EU building stock was developed. The objective of versatility from the constructive and energetic aspect has been achieved in such a way that this system not only adapts to the physiognomy of existing buildings but also to their energy demands.

However, future research is planned in the area of fire performance and propagation assessment of the system in order to ensure that this façade solution can meet the highest regulatory requirements currently applied in certain countries, such as the United Kingdom. Although it is not yet mandatory in many EU countries for façade systems to be certified for their fire performance concerning the spread through the façade, this performance is essential to ensure the safety of users, especially in high-rise buildings.

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References

Artola, I., Rademaekers, K., Williams, R., & Yearwood, J. (2016). *Boosting Building Renovation: What Potential and Value for Europe?: Study*: European Parliament.

Avesani, S., Andaloro, A., Ilardi, S., Orlandi, M., Terletti, S., & Fedrizzi, R. (2020). Development of an Off-site Prefabricated Rainscreen Façade System for Building Energy Retrofitting. *Journal of Façade Design and Engineering, 8(2)*, 39–58. https://doi.org/10.7480/jfde.2020.2.4830

Bonato, P., Fedrizzi, R., D'Antoni, M., Meir, M., (editors) (2019). *State-of-the-art and SWOT analysis of building integrated solar envelope systems*: IEA SHC Task 46, Deliverables A1 and A2. Retrieved from https://task56.iea-shc.org/publications

Broers, W., Vasseur, V., Kemp, R., Abujidi, N., & Vroon, Z. (2019). Decided or divided? An empirical analysis of the decision-making process of Dutch homeowners for energy renovation measures. *Energy Research & Social Science, 58*, 101284.

CEN - European Committee for Standardization, (2020). EN 13830:2015+A1:2020, Curtain walling – Product standard

CEN - European Committee for Standardization, (2016). EN 50583: Photovoltaics in buildings

Colinart, T., Bendouma, M., & Glouannec, P. (2019). Building renovation with prefabricated ventilated façade element: A case study. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2019.01.033

CTE DB-HE - Technical building code, basic document *Energy Saving*, Spanish government (2022). https://www.codigotecnico.org/DocumentosCTE/AhorroEnergia.html

CTE DB-SE-AE- Technical building code, basic document *Loads on the buildings*, Spanish government (2009). https://www.codigotecnico.org/DocumentosCTE/SeguridadEstructural.html

DIRECTIVE. (2018/844/EU). *on the energy performance of building*. Brussels: THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Retrieved from http://data.europa.eu/eli/dir/2018/844/oj

DIRECTIVE. (P9_TA(2023)0068). *on the energy performance of building (recast)*. Brussels: THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Retrieved from https://www.europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.html#title1

de Gracia, A., Castell, A., Navarro, L., Oró, E., & Cabeza, L. F. (2013). Numerical modelling of ventilated façades: A review. *Renewable and Sustainable Energy Reviews, 22*, 539–549.https://doi.org/10.1016/j.rser.2013.02.029

D'Oca, S., Ferrante, A., Ferrer, C., Pernetti, R., Gralka, A., Sebastian, R., & Op 't Veld, P. (2018). Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects. *Buildings, 8(12)*, 174. https://doi.org/10.3390/buildings8120174

Du, H., Huang, P., & Jones, P. (2019). Modular façade retrofit with renewable energy technologies: The definition and current status in Europe. *Energy and Buildings, 205*, 109543. https://doi.org/10.1016/j.enbuild.2019.109543

Economidou, M., Atanasiu, B., Despret, C., Maio, J., Nolte, I., Rapf, O., . . . Strong, D. (2011). Europe's Buildings Under the Microscope; 2011. *Buildings Performance Institute Europe (BPIE)*.

Elguezabal, P., & Arregi, B. (2018). An analysis of the potential of envelope-integrated solar heating and cooling technologies for reducing energy consumption in European climates. *Journal of Facade Design and Engineering, 6(2)*, 085–094. https://doi.org/10.7480/jfde.2018.2.2102

Efthymiou, E., Cöcen, O. N., & Ermolli, S. R. (2010). Sustainable aluminium systems. *Sustainability, 2(9)*, 3100–3109. https://doi.org/10.3390/su2093100

EOTA – European Organisation for Technical Assessment. (2018), EAD 090062-00-0404: Kits for external claddings mechanically fixed. Retrieved from https://www.eota.eu/eads

European Commission. (2019). *The European Green Deal*. Brussels Retrieved from https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

European Commission. (2020). *A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives*. Brussels Retrieved from https://energy.ec.europa.eu/system/files/2020-10/eu_renovation_wave_strategy_0.pdf

European Commission. (2021). 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. Brussels Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550

Ferdous, W., Bai, Y., Ngo, T. D., Manalo, A., & Mendis, P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review. *Engineering Structures* (Vol. 183, pp. 883–893). Elsevier Ltd. https://doi.org/10.1016/j.engstruct.2019.01.061

Filippidou, F., Nieboer, N., & Visscher, H. (2016). Energy efficiency measures implemented in the Dutch non-profit housing sector. *Energy and Buildings, 132*, 107-116.

Gagliano, A., & Aneli, S. (2020). Analysis of the energy performance of an Opaque Ventilated Façade under winter and summer weather conditions. *Solar Energy, 205*, 531–544. https://doi.org/10.1016/j.solener.2020.05.078

INSST - Ministry of Labour and Immigration, Government of Spain. Manual handling of loads. Technical guideline of National Institute of Health and Safety at Work (2011). 27a8b126-a827-4edd-aa4c-7c0ca0a86cda (insst.es)

Jensen, P. A., Maslesa, E., Berg, J. B., & Thuesen, C. (2018). 10 questions concerning sustainable building renovation. *Building and Environment, 143*, 130-137.

Lessing, J. (2006). Industrialized House-Building: Concept and processes, Licensiate thesis. Lund: Lund University. Retrieved from https://www.lth.se/fileadmin/projekteringsmetodik/publications/Lessing_lic-webb.pdf

Li, Y., & Chen, L. (2022). Investigation of European modular façade system utilizing renewable energy. *International Journal of Low-Carbon Technologies, 17*, 279-299.

Mitma - Ministry of Transport, Mobility and Agenda of the Government of Spain (2023). Inspection and safety in overland transport. Weights and dimensions. Esquema Longitud - Vehículos rígidos, Tren de carreteras, Vehículos articulados, Trenes de carretera de transporte de vehículos | Ministerio de Transportes, Movilidad y Agenda Urbana (mitma.gob.es)

Moran, P., O'Connell, J., & Goggins, J. (2020). Sustainable energy efficiency retrofits as residenial buildings move towards nearly zero energy building (NZEB) standards. *Energy and Buildings, 211*. https://doi.org/10.1016/j.enbuild.2020.109816Sandberg, N. H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., . . . Zavrl, M. Š. (2016). Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. *Energy and Buildings, 132*, 26-38.

Navaratnam, S., Ngo, T., Gunawardena, T., & Henderson, D. (2019). Performance review of prefabricated building systems and future research in Australia. *Buildings*, Vol. 9, Issue 2. MDPI AG. https://doi.org/10.3390/buildings9020038REGULATION (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC Text with EEA relevance. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011R0305

Semprini, G., Gulli, R., & Ferrante, A. (2017). Deep regeneration vs shallow renovation to achieve nearly Zero Energy in existing buildings: Energy saving and economic impact of design solutions in the housing stock of Bologna. *Energy and Buildings, 156*, 327-342.

Streicher, K. N., Mennel, S., Chambers, J., Parra, D., & Patel, M. K. (2020). Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. *Energy and Buildings, 215*. https://doi.org/10.1016/j.enbuild.2020.109870

Tsemekidi-Tzeiranaki, S., Bertoldi, P., Paci, D., Castellazzi, L., Serrenho, T., Economidou, M., & Zangheri, P. (2020). *Energy consumption and energy efficiency trends in the EU-28, 2000-2018*. EUR 30328 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-21074-0, doi: 10.2760/847849. Retrieved from: https://publications.jrc.ec.europa.eu/repository/handle/JRC120681

Van Roosmalen, M., Herrmann, A., & Kumar, A. (2021). A review of prefabricated self-sufficient façades with integrated decentralized HVAC and renewable energy generation and storage. *Energy and Buildings (248)*. Elsevier Ltd. https://doi.org/10.1016/j.enbuild.2021.111107

Viana, D., Tommelein, I., & Formoso, C. (2017). Using Modularity to Reduce Complexity of Industrialized Building Systems for Mass Customization. *Energies, 10(10)*, 1622. https://doi.org/10.3390/en10101622

Wasim, M., Han, T. M., Huang, H., Madiyev, M., & Ngo, T. D. (2020). An approach for sustainable, cost-effective and optimised material design for the prefabricated non-structural components of residential buildings. *Journal of Building Engineering, 32*. https://doi.org/10.1016/j.jobe.2020.101474

Wilson, C., Pettifor, H., & Chryssochoidis, G. (2018). Quantitative modelling of why and how homeowners decide to renovate energy efficiently. *Applied energy, 212*, 1333-1344.

TABLE 7 Sizing measures for hybrid panel (PVT)

TECHNOLOGY	CODE NAME	ST PANEL DIMENSION (width) [mm]	ST PANEL DIMENSION (height) [mm]
PVT PANELS	PVT2VL	1106	1756
	PVT2VU	1066	1796
	PVT2HL	1796	1086
	PVT2HU	1756	1126
	PVT3VL	1591	1756
	PVT3VU	1551	1796
	PVT3HL	1796	1551
	PVT3HU	1756	1591
	PVT4VL	2076	1756
	PVT4VU	2036	1796
	PVT4HL	1796	2056
	PVT4HU	1756	2096

TABLE 8 Dimensional analysis of PV+SS. Panels that exceed 50kg are indicated in green. Source: Onyx solar.

	PV PANEL width [mm]	PV PANEL height [mm]	PV PANEL weight [kg]
Optimized substrate	**2600**	**1000**	**78**
	3200	**1440**	**138**
	1060	710	15
	1420	1060	30
	1420	**1420**	**80.7**
	1420	790	22
	1590	710	23
	710	710	10
Optimized PV	1700	1000	34
	1475	480	14
	1650	850	28