Development of an Offsite Prefabricated Rainscreen Façade System for Building Energy Retrofitting

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Abstract

As the European building stock is in evident need of deep energy retrofitting to meet current European decarbonisation targets, the construction market calls for industrialised systems to boost massive renovations and activate economies of scale. The article outlines the development of an offsite fabricated system for building energy refurbishment through rainscreen façade elements. A focus is placed on such elements as they offer excellent system integration possibilities and the opportunity to boost the level of offsite fabrication, compared to other already industrialised façade systems, such as unitised façades. This research was carried out within the framework of BuildHEAT research project, funded by the European Union Horizon 2020 framework programme. The system concept is based on a systemic approach that combines energy efficiency, multifunctionality, integration of renewable energies, and ease of installation as design drivers. System development has rolled out through different phases, with an increased level of detail. During the schematic design phase, a set of different prefabricated façade panel dimensions were analysed. Afterwards, the component and system integration were assessed according to their impacts in terms of energy performance and fulfilment of mandatory technical requirements. As a last step, the most promising technical combinations underwent detailed design to verify construction feasibility and eliminate any bottlenecks during the fabrication phase. Results show that the proposed prefabricated solutions allowed: (i) simplified active system integration (photovoltaics, solar thermal, and building services), (ii) ease of installation on site, minimising the impact of renovation actions on occupants without compromising on final quality and reducing installation costs. Current limitations to extensive market diffusion of the system are related to two main aspects: (i) the need for on-site adjustments; and (ii) increased manufacturing costs compared to traditional external insulation interventions (e.g. ETICS). The current cost of the system (2020) is in the range of 3 - 1.5x the cost of, respectively, an ETICS or a vented rainscreen façade. However, as a next step, including the life-cycle perspective in the calculation, as well as accounting for economies of scale, the system will be evaluated, expecting a cost figure comparable to the rainscreen façade.

Keywords

Renewable energy integration, re-cladding, prefabricated construction, system integration

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1 INTRODUCTION

When tackling deep energy retrofitting interventions of buildings, higher complexities and costs are incurred with respect to lower impact energy retrofitting solutions, due to the number of components to be considered, as well as their interconnection. Moreover, building to meet high energy performance standards have to include the RES generation, in particular PhotoVoltaic (PV) and Solar Thermal (ST) systems that are widely used. Such solutions incur extra costs needed to adapt the design onto traditional building components and to ensure a reliable installation. For this reason, a better economic case for deep renovation has to be found adopting a more systemic approach to renovation. As such, the retrofit action works has the chance to improve energy efficiency, as well as occupants´ comfort and safety, together with increasing the overall building value. Such solutions tend to endow the envelope with multiple functions that complement thermal insulation, it being the primary objective of the intervention. Specifically, it is possible to include building services – both energy generation and distribution systems – in the package, as well as punctual system terminals or shading systems. On the other hand, the inclusion of system components in the envelope is deemed to make renovation works more complex and impactful on building occupants. This is mainly due to need to access the building from the inside in order to complete ducts and cabling connections.

Currently used technologies for opaque façade retrofits rely on the use of External Thermal Insulation Composite Systems (ETICS), which do not offer any dedicated technical solutions to integrate PV panels and ST collectors and building services components (electric cabling, water piping and air ducting). In addition to the above, ETICS also require the use of fixed scaffolding infrastructure during the installation phase and strongly rely on the workmanship handcrafting experience to guarantee results that match expected performance and aesthetics.

Ad hoc products and systems for PV and ST building integration - BIPV-BIST state technologies are available (EPFL, 2016), having been developed for many years, but are still mainly a niche market. The SWOT matrix reported in Bonato, Fedrizzi, D'Antoni, and Meir (2019) as well as the barriers highlighted in Maurer et al. (2018) show how the limits of implementation of innovative solar façade systems can be found in many interdisciplinary aspects, from the economic to the social fields.

Besides these developments, which focus only on solar integration, research and innovation has been recently developing envelope solution sets, which may be installed with minimal impact and disruption to occupants, despite the inclusion of active systems for energy production and distribution, as described, for example, in Andaloro, Avesani, Belleri, Machado, and Lovati (2018) and Ochs, Siegele, Dermentzis, and Feist, 2015). A list of further research projects developing multifunctional envelope solutions for the retrofit of buildings is reported in D'Oca et al., (2018). In fact, the impact of renovation works on building occupants can be significantly reduced when taking advantage of offsite fabrication techniques, which allow the construction site phase to be speeded up and minimise construction works on the indoor space (Colinart, Bendouma, and Glouannec (2019). This is possibly thanks to the anticipated design and engineering effort that has to take place before the component production phase (Arashpour, Abbasi, Arashpour, Reza Hosseini, & Yang, 2017; Lu, Chen, Xue, & Pan, 2018). Pre-assembled components can be then installed on-site in a shorter time and with less need for supporting structures and works. It must not be neglected that the adoption of such systems requires an accurate energy and geometrical audit, as it is not possible to perform component modifications on site (Lattke & Cronhjort, 2014; Silva, Almeida, Bragança, & Mesquita, 2013). It is easily inferred that the offsite fabricated solutions allow for a shorter construction site duration and support the achievement of higher quality results, due to the elimination of several potential installation errors that can possibly occur in traditional construction sites (Gasparri & Aitchison, 2019; Ochs et al., 2015; Op't Veld, 2015). Finally, offsite production has a potential 20% cost saving for owners, as estimated in Bertram et al. (2019).

The Offsite prefabricated Rainscreen Façade (ORF) concept presented in this paper takes the need for systemic façade retrofit solutions - specifically to ease the integration of PV and ST components to decrease the building non-renewable final energy consumption, and the benefits offered by the adoption of an offsite fabrication approach, as development drivers. The ORF aim is to bridge the technological gap between the traditional ETICS-based passive façade and the aforementioned R&D experiences of the multifunctional prefabricated façade, through the development of a systemic façade solution based on components mainly available on the market. Hence, the use of a customisable standardised frame system has been addressed as a core aspect of the façade concept development. In this sense, the choice of starting the development from a rainscreen façade is justified by the presence of a substructure, meeting the need to host several kinds of cladding elements (passive and active) and offering the potential for offsite production and plug-and-play installation.

The objectives of the paper are to give an overview of the development process, to present the façade's main features as well as to discuss the achieved façade technological solution. The paper is structured in different sections, zooming into details of the design and development process. A complete overview of the development process is provided as follows: (i) first, design drivers on which the façade system is developed are presented, together with the schematic design method applied to preliminary technology development; (ii) then, both mandatory and non-mandatory technical requirements for the new façade system are introduced. Once the methodology is thoroughly illustrated, façade development results and its main features are showcased: detailed designs are presented, together with the testing of technical requirements and the achievement of performance targets. A deep dive into main components is also made, focusing on the façade interface with existing wall, active systems, anchoring and fixing systems, and cladding. The paper closes with a list of current application possibilities and limitations, as well as providing preliminary insights into cost issues arising during the development phase. Cost issues are presented at an aggregated level of detail and will be further investigated at a later stage. However, authors identify the life-cycle approach as an option to overcome current cost limitations.

2 MATERIALS AND METHODS

2.1 FAÇADE DEVELOPMENT DRIVERS AND DESIGN PROCESS

The Offsite prefabricated Rainscreen Façade (ORF) system has been developed based on the ventilated façade concept, exploiting compatibility with market-available construction materials and components, but proposes a project specific panel concept, which has to satisfy the technical requirements of the European building product regulations and the following peculiar development drivers, derived from the research project framework under which this system was developed.
The new façade must (i) ease the installation of passive and solar active cladding, in order to assure the implementation of systemic deep energy retrofit, reducing the building's heating demand while preventing overheating and assuring indoor comfort; (ii) lower the installation effort and the impact on inhabitants for a deep retrofit action, simplifying and standardising the installation of active elements, piping, and ductwork on the outside of the existing façade, with consideration also given to the maintenance operations. This means that both active and passive cladding, as well as the building services components, have to be accessible and replaceable. The façade system developed within the framework of this research must respond to the technical requirements set by the European Commission within the H2020 framework programme call topic, under which this work has been developed. The above requirements determine that the novel façade system has to be: (iii) cost-effective, being able to compete on the market; (iv) replicable, able to be easily adapted to a broad portfolio of residential building typologies; (v) flexible, compatible with the commercial passive and active cladding systems (such as PhotoVoltaic panel – PV, and Solar Thermal collector - ST) needed by the energy concept of the renovation.

Consequently, the ORF has been developed through a multi-stage design process, grounded on existing literature review from past research projects on prefabricated façade systems for energy retrofit. Research projects in the review include, but are not limited to, the following: H2020 More Connect, 4RinEu, Drive0, Energy Matching. The adopted approach was "research by design", refining the technical solution according to design drivers set by the H2020 programme and specific project requirements until a shared solution among research partners was found. This complex design process spanned from the preliminary system concept to the definition of the final solution to be applied on-site for two demo case buildings, using an increasing level of detail. Based on the above-mentioned background and guided by the design drivers reported here above, the design process started with a schematic design phase. Its objective was to identify possible façade technological concepts, with technical features able to fulfil the product, and to address the expected impacts. The three pre-assembled façade concepts are: (i) micro-panels, (ii) sandwich panels, (iii) macro-panel.

2.2 ORF SYSTEM COMPONENTS

The main components that constitute the façade system are described in Table 1, including their main functional requirements.

TABLE 1 List of OPVF system main components and related function details

COMPONENT	FUNCTION DESCRIPTION
SUB-STRUCTURE	The system sub-structure is the façade main frame that hosts the functional components (passive and active claddings), connecting the new façade to the existing external wall, as well as retaining the external cladding. Main sub-structure requirements are mechanical resistance, to bear dead and wind loads, ease of installation, construction tolerances absorption, accessibility, and removability of the outer layer for maintenance and flexibility purposes.
THERMAL INSULATION	The thermal insulation is needed to increase overall façade thermal resistance and should also have appropriate fire reaction, in order to minimize risk of fire spread along the façade plan. Its hygrothermal behaviour is very relevant to avoid condensation risks and therefore to increase durability.
PASSIVE CLADDING	The façade finishing determines the aesthetic appearance of the building and its durability. The façade system is conceived to host different façade market-available passive claddings using the same type of substructure.
ACTIVE CLADDING	Façade integration of ST and PV modules is more and more an option to increase the solar energy self-consumption towards a net Zero Energy Building. A number of products and documentation can be found in literature. Nevertheless, active cladding integration increases the degree of complexity of the whole facade and requires dedicated engineering effort to optimize system connection to the inside of the building, as well as the integration of distribution systems within the façade. This is one of the main barriers that prevents their diffusion on the market and that the ORF want to tackle through the development of a pre-assembled and flexible façade sub-structure.
ENERGY AND SERVICE DISTRIBUTIONS	Façade integrated piping, ducting, and cabling distributions can provide each flat the needed thermal energy, fresh air and electric power minimizing the indoor construction works and therefore the impact on inhabitants. The advantage of such kind of integration might be counterweighted by a more complex façade installation phase, as well as requiring accessibility for maintenance.
WINDOWS	The window node solution is a critical step to achieve overall indoor comfort, energy demand reduction as well as durability of the components. Two different approaches for the window integration in the prefab façade has been studied, addressing a fully integrated and a non-integrated window. In the first case, the window is hosted in an insulated frame, loaded on the façade prefabricated substructure. In the second, the new window is not integrated in the prefab façade, which is hence a macro-panel, wider than the base one – constituted of cladding elements, insulation layer and substructure shaped around the window hole
HEAT RECOVERY MECHANICAL VENTILATION	The use of a mechanical ventilation system is considered as necessary when pursuing a deep energy retrofit action, to reduce heat losses and increase indoor air quality. Decentralized mechanical ventilation unit can also be considered, as they allow easier integration within the façade system, avoiding space and cost consuming indoor ducting installations.

2.3 FAÇADE TECHNICAL REQUIREMENTS

After the finalisation of the façade concept, a further list of requirements was defined based on the essential requirements established in the 305/2011 EU directive for construction products (European Parliament, 2011) and complemented with the technical standard ETAG034 for ventilated façades (EOTA, 2012b). The regulatory assessment skipped the air-tightness requirement verification due to the assumption that the façade as retrofit kit is a second layer on an already existing façade, for this reason such a requirement has less priority than in the case of new construction. This is not true in the case of window integration, which has not been considered in this paper.

The macro-panel structure was developed by adopting an integrated design logic, focused on both construction process optimisation and performance achievement. In fact, on the one hand, it was designed in detail, providing information on materials to be used, macro-panel dimension ranges, anchoring to the existing structure and customisation opportunities in terms of cladding options, as well as active component integration. On the other hand, the designed solution has then been verified in terms of technical performance requirements, such as: mechanical, thermal, hygro-thermal and condensation risk, water tightness, impact and wind resistance, and fire reaction. As the ORF is still a non-standard market product, all of the above have been assessed based on calculations and tests undertaken on a series of 1:1 scale mock-ups. The summary of the performance requirements and their related assessment method within the project is provided in Table 2.

TABLE 2 List of OPVF system technical requirements and related assessment method used in the project

REQUIREMENT	ASSESSMENT METHOD
MECHANICAL RESISTANCE	The mechanical resistance of the ORF system is measured on the main frame (see "substructure" in TAB. 1). The maximum expected deformation has been assessed on the frame elements as representative of failure risks for the whole system. Calculation has been made according to the Italian decree D.M 14/01/2008 (Italian Government, 2008)- given that one of the demo-site buildings is in Italy, which is derived from the current European regulatory framework for mechanical resistance calculation in the construction sector. KPI: maximum deformation in operation [mm], calculated
THERMAL RESISTANCE	The thermal resistance calculations have been performed following the procedures defined in the EN ISO 10077:2017 (EN ISO, 2017). Linear thermal loss coefficient has been calculated based on a bi-dimensional parametric analysis, which has informed the final shaping of panel geometry, as seen in the results section. After that, the incidence of thermal bridges generated at panel edges has been evaluated. The ORF has been compared against a reference building standard energy renovation case. The façade has been considered as adjacent to the existing one, in contact through a 100 mm-thick continuous soft rockwool insulation layer. The incidence of thermal bridges has been evaluated as difference between the ORF façade and a traditional external insulation (reference). KPI: thermal resistance [m^2 K/W], thermal transmittance [W/m^2/K, thermal linear loss coefficient [W/m/K], calculated
HYGRO-THERMAL AND CONDENSATION RISK	The hygro-thermal behaviour of the solution has been assessed coupling a steady state Glaser diagram and a dynamic state calculation performed with Delphin software. The latter allows to consider the hygrothermal dynamic behaviour on a 2D domain, as needed for the presence of the substructure in the insulation panels. Calculations are based on some assumptions: short-wave solar radiation is not considered, as well as rainwater flow on the external side of the surface. The simulation time has been set to two full years, considering the first year as a stabilization phase. KPI: cumulated mass of condensation water [g/m^3], calculated
WATER TIGHTNESS	Water tightness does not need to be certified in the case of a ventilated façade kit, as stated in the ETAG034 (EOTA, 2012a). However, a test campaign has been performed, directing a continuous water jet against the surface for 10 minutes with no interruption. This phase has been followed by a visual inspection at all layers. KPI: presence of water drops, visual inspection
IMPACT AND WIND RESISTANCE	Impact resistance has been verified using a hard body impact procedure on the external cladding system, using three different bodies: 0,5 kg hard body plus 3 joules, 1 kg hard body plus 10 joules, 3 kg soft body plus 10 joules. The test has focused especially on the Polymer Concrete cladding panel, which has been developed as innovative material within the ORF project for the passive cladding. On the other hand, this test was not performed on PV and ST modules that can also be used as external cladding, being them commercial products equipped with own product declaration and performance certificates. Wind resistance has been assessed using a support test bench with a steel frame, where façade modules have been positioned and joints sealed to create an airtight chamber that allows to apply wind pressure or suction. Pressure levels up to 3000 Pa have been applied. Effects of wind pressure on façade system have been assessed through deformation meters located at fixed points and a visual inspection of components after test completion. KPI: presence of breaks, tested
FIRE REACTION	Fire reaction of the PC cladding panel has been assessed at façade system level based on single burning item test (SBI) according to EN 13823:2020 (EN, 2020). The SBI test is performed directing a flame source with determined firing power (30,7 ± 2,0 kW) generated through propane burning towards the sample to be tested from an interior corner point. The test lasts for 20 minutes, and the assessment process is based on the following set of parameters, aiming at determining the material fire reaction class. KPIs: Total Heat Release during the first 600 seconds (THR 600) [MJ], Fire Growth Rate Index (FIGRA) [kW/s], Lateral Flame Spread (LFS) [m], Smoke Growth Rate Index (SMOGRA) [m2/s2].

2.4 FAÇADE COST CALCULATION

Façade design, manufacturing, and installation costs have been calculated based on expenses incurred during the research project demonstration phase within which the solution was developed. The façade manufacturer noted in a bill of expenses all costs, allowing the system cost per m^2 installed to be calculated (Table 3).

It must be noted that transportation costs have been accounted for in the bill of expenses. However, in larger deployments of the same system, transportation costs should be less impactful, provided that the designers choose manufacturers located within a certain geographical range of operation.

TABLE 3 Cost analysis breakdown

	COMPONENT	DESCRIPTION
1	**Anchoring elements**	Commercial products (as per curtain wall) to anchor the macro panel frame to the building structure
2	**Soft insulation layer**	Insulation material (e.g. rockwool) and related fixings
3	**Macro panel frame**	Alu profiles needed for the macro panel assembling of the macro panel
		Assembling of the macro panel with all its components
4	**Rigid insulation layer**	Insulation material and related fixing
5	**Waterproof layer**	Gaskets to be applied between macro-panels
6	**External finishing layer**	Anchoring system that allows the single finishing panel dismantling
		External finishing material
7	**Packaging**	Wooden frame and plastic to allow the safe handling of the assembled macro-panels
8	**Transport**	Truck from the factory to the construction-site
9	**Site work**	Installation phase, as well required construction site equipment, additional materials, general expenses

3 RESULTS

The output of the development and design phases are presented in this section, in terms of façade macro-panel features and performance assessment results.

3.1 FAÇADE FINAL DESIGN

3.1.1 Overall façade system features

The schematic design phase resulted in three main concepts being investigated, as illustrated in Fig. 1. The micro-panel concept (Fig. 1 -1) is built on a metal frame structure carrying both the cladding and insulation layer, equipped with a connection element to favour easy anchoring to the substructure. Its functioning mimics a vented rainscreen façade, including the use of a mullion substructure to support the panels. The sandwich panel concept (Fig. 1 – 2) is based on a pre-assembled multi-layer element including cladding and insulation, directly screwed to the substructure, with no need for an additional frame, conversely to previous case. No air cavity is present in this configuration. The macro-panel concept (Fig. 1 -3) mimics a unitised system and is equipped with a half frame on each edge of the panel. These halves are then coupled with their twins as two panels are positioned adjacent to one another, in both the horizontal and vertical direction. The frame is conceived with multiple slots to allow both flexibility in terms of cladding anchoring and to allocate further layers as per the rainwater protection. In this case, the existing-new façade fixing is realised exclusively through multi-directional brackets.

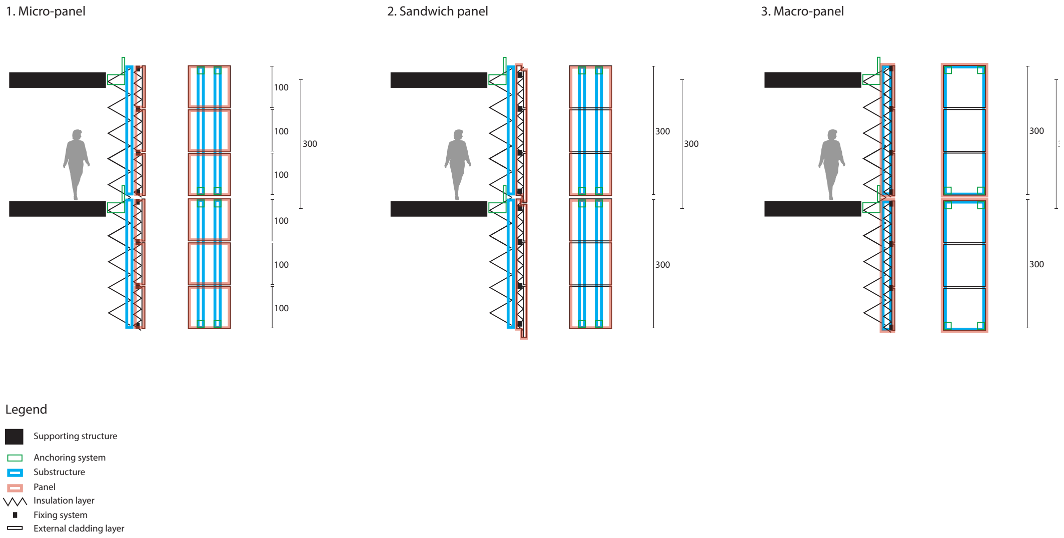

FIG. 1 First preliminary concepts of the offsite prefabricated façade. In red pre-assembled panel units, in blue substructures, in green anchoring system, zigzag line for insulation layer, filled black for building slab

With respect to the three façade concepts of Fig. 1, the refining phase in concept design led to the exclusion of the micro-panel approach, as the latter brought about similar advantages to the other two proposals, but with increased costs generated by the large number of fixing points and increased total length of the framing structure (needed to cover the same façade surface as in the macro-panel scenario). Further on, the sandwich panel was also discarded for two main reasons: it did not provide a suitable solution for the simple integration of active systems and it required a complex geometrical solution to panel joining, in order to avoid manual work being performed on site. The above are deemed to generate extra costs in case system integration is a mandatory project requirement and an extra degree of complexity to be managed during both the production and transportation phases. In fact, the rebated shape of the modules is easily subjected to breakage and needs to be handled with special care.

Hence, as the first result, the preliminary design identified the macro-panel approach as the most suitable to be developed in further detail. Specifically, the macro-panel choice was based on three main features: (i) full exploitation of the industrialisation potential, through the replacement of the traditional metal substructure applied in vented rainscreens with the more comprehensive macro-panel metal frame, (ii) flexibility both in cladding and active system integration, as well as in panel sizing, as the metal frame can be adapted to different structural needs, (iii) commercial availability of ORF system components, to improve replicability and to allow for a partially optimised value chain of the macro-panel, at present limited to the offsite fabrication phase.

In general, the ORF macro-panels are conceived to cover the inter-floor distance in height, to allow for pre-determined fixing points at slab level and so they can have variable widths based on the type of cladding element (both passive and active) to be applied and therefore on the desired façade appearance pattern (Fig. 2).

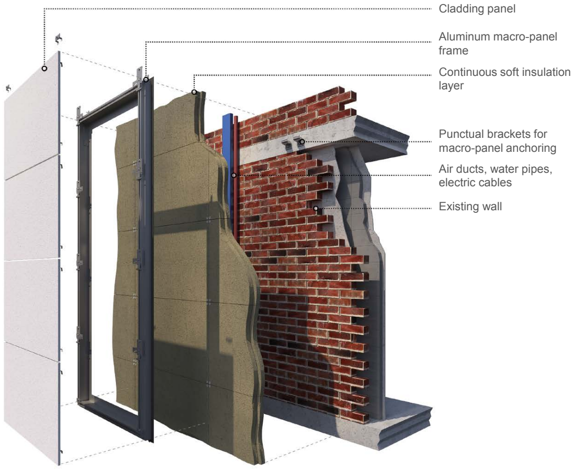

FIG. 2 Rendered image of the BuildHEAT façade final concept and its constituent layers

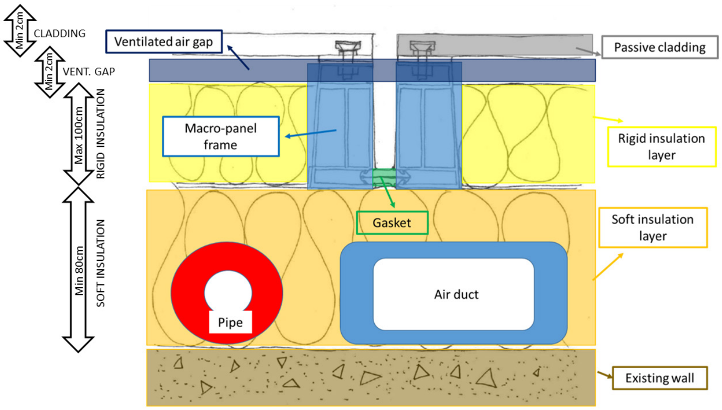

FIG. 3 Concept horizontal cross section of the different layers for the ORF system in the passive cladding configuration (moderately ventilated air cavity and cladding)

In terms of system thickness, the system requires a minimum of 200 mm front translation of the façade plan, considering at least 80 mm compressible soft insulation to absorb eventual construction tolerances, related to non-verticality or non-horizontality of the existing wall. This insulation layer sizing is also driven by the final façade thermal transmittance to be reached. From this perspective, the possibility to host a rigid second insulation layer in the macro-panel has to be considered. Consequently, this information on system thickness has been calibrated on a Mediterranean climate as the first demo installation and is subject to verification and variation in case more severe climate conditions apply. The final schematic design of the ORF horizontal or vertical section is illustrated in Fig.3.

The preassembled façade module is composed of an extruded aluminium frame, running all along the macro-panel edges, which is able to host a rigid second insulation in its thickness and allows for different type of cladding fixings thanks to its peculiar innovative shape. This frame shape (Fig. 4) allows for an easy adaptation to several cladding types, spanning from opaque passive to active systems, such as PV or ST, mimicking the vented rainscreen physical functioning. A set of horizontal and vertical gaskets can be additionally fixed to the frame dedicated groove, drastically reducing the risk of driven rainwater penetration to the soft insulation layer.

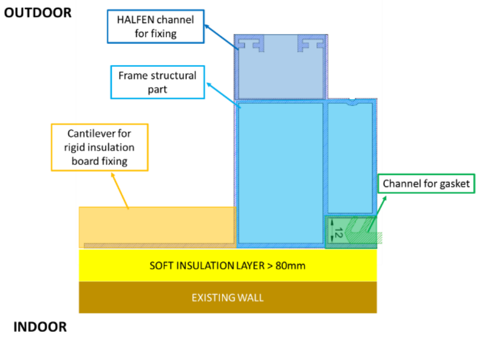

FIG. 4 Detail of the macro-panel aluminium frame in its main parts and functionalities (drawing not to scale)

3.1.2 Macro-panel anchoring and cladding fixing

Following the driver of flexibility in integration, a further key element of the new façade is the standardised cladding fixing to the sub-structure (Fig. 5), which allows for easy removability of passive cladding as well as the PV panel.

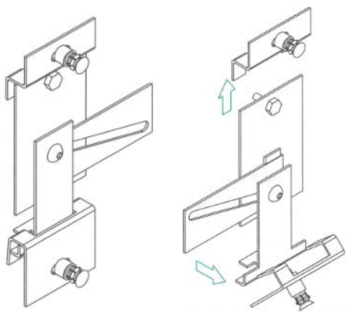

FIG. 5 Standardised fixing system for removable passive and active (PV) claddings

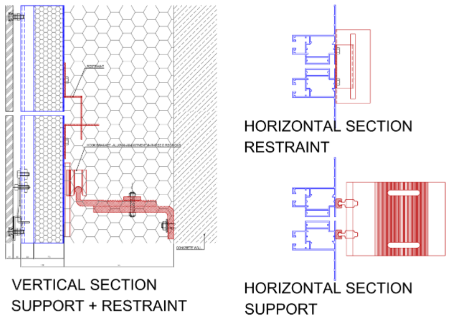

FIG. 6 Macro-panel frame anchoring system to the concrete slab, as for curtain wall

The ST fixing has been developed ad hoc using Z-shaped steel plates connecting the macro-panel frame to the ST. The collector dead-load is however carried by the macro-panel frame transom (or an additional suspended one). The macro-panel anchoring to the existing façade is realised at slab front level through metal brackets (Fig. 6), the same kind of commercially available system used for a curtain walling system.

3.1.3 Interface

Managing the interface between the existing façade and the retrofit module is crucial for a well-executed retrofit action. As said before, in the ORF concept, as has also emerged from literature, this is done by including a compressible insulation layer located between the new and the existing façade. This first insulation layer aims to guarantee continuity of insulation and provide eventual space for active system distribution components, such as cabling, ducting, or piping. At present, this layer is not engineered to be assembled offsite and its installation requires manual work to be performed on site. However, there is room for the industrialisation of this element.

3.1.4 PV and ST integration as active cladding

The integration of active components was investigated in depth during the concept definition phase, as a relevant parameter to develop a flexible and replicable façade solution for the systemic deep energy retrofitting of buildings. As mentioned, the integration of commercially available PV and ST systems were assessed through a technical market analysis. Based on these (PV and ST main relevant features such as sizes, fixing requirements, cabling and piping, wet connections) were the macro-panel substructure design, the fixing system selection (in order to allow the removability for maintenance purposes), in close contact with PV and ST manufacturers, and the use of a dressing cap (as for a curtain wall) to cover the exposed frame view and improve the overall macro-panel aesthetic. All system connections (electrical, wet connections) have been solved using commercial products for plug-in junctions available on the market. The final design of the macro-panel frames is reported in FIG. 7, Fig. 8 and Fig. 9.

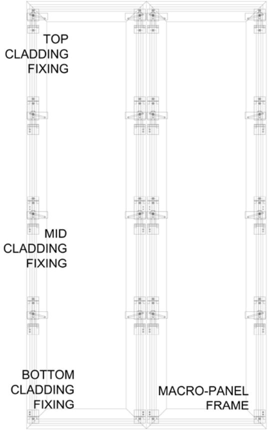

FIG. 7 Base macro-panel frame front view. Top, mid, and bottom passive cladding fixings' types are indicated.

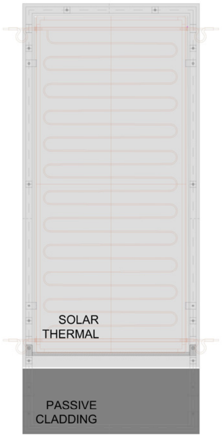

FIG. 8 Front view of the ST integration in a dedicated macro panel with bottom passive cladding. In this case, an additional removable transom is foreseen as well as dedicated fixing points for the ST collector retention against horizontal loads

FIG. 9 Front view of the PV macro-panel hosting a top passive cladding. The PV panel frame is mechanically fixed to the removable façade fixing system (as per the passive claddings) thanks to rivets.

3.1.5 Decentralised mechanical ventilation unit

On the other hand, the decentralised mechanical ventilation unit façade integration was investigated in more detail, with the aim of designing a brand-new ventilation machine unit, optimising both the machine performance and the impact on building occupants. The maintenance-related accessibility requirement is easily achieved using a vented rainscreen with removable cladding, which was already a core technical requirement related to the flexibility and cladding customisation of the system itself. Hence, four different options for decentralised ventilation unit integration have been qualitatively analysed according to machine positioning with respect to the façade and related window holes. They can be described as (in italics, the short name adopted in the table below): (i) in the existing façade, below the window unit - under window, (ii) in the existing façade, hanging from the upper ceiling – ceiling hung, (iii) in the existing façade, above the window unit and exploiting the shutter box space, when possible - shutter box, (iv) in the new façade, adjacent to the existing one and located below the window unit – new façade. The four scenarios have been compared in terms of technical requirements and functionalities related to both the façade system in general and the ventilation machine integration.

TABLE 4 Summary of comparative analysis among the four different scenarios identified for decentralized ventilation machine integration

	UNDER WINDOW	CEILING HANGED	SHUTTER BOX	NEW FACADE
impact	*	**	**	***
social acceptance	**	*	**	***
noise protection	*	*	*	***
replicability potential	*	**	**	***
façade thickness	***	***	***	*
machine thermal losses	***	***	***	*
ease of maintenance	***	***	***	**
construction cost	*	**	*	***
component cost	*	**	**	**
duct connection	***	**	*	***

* worst case / ** average case / *** preferred option

Results are summarised in Table 4, ranked from worst to preferred according to configuration issues. As seen in the synthetic table, there is no optimal solution, each scenario carrying both advantages and disadvantages. As a consequence, within the frame of this project the integration of the decentralised ventilation unit as a stand-alone system has been discarded. The integration of a decentralised ventilation unit as a separate system still remains in the range of customisation opportunities to be further investigated in the future.

3.1.6 Window integration

As noted in Table 1, the prefabricated window macro-panel was conceived in two ways. In the first one, the new window is fully integrated into the window macro-panel thanks to the use of an insulating frame made of high density XPS, loaded on the macro panel aluminium substructure. The second scenario foresees that the new window installation is done separately from the façade insulation, cladding, and window jamb finishing, which are integrated in the prefabricated macro-panel. As a result, this latter approach was finally chosen because of the overall minor complexity of the prefabrication, transport, and installation phases of a prefab macro-panel without the presence of the window onboard. Moreover, the macro-panel development explained up to now has led to the design choice of a distance of at least 80 mm between the macro-panel substructure and the existing wall. As a result, it would have been too challenging for the macro-panel to bear the window weight with such a cantilever. Finally, a fully integrated window scenario would have added the requirement for airtightness on to the window macro panel. Such a feature would have needed a dedicated development that deviated from the original idea of a unique macro-panel sub-structure able to host different kind of components. The final design of a prefab macro-panel that matches the window opening is represented in Fig. 10.

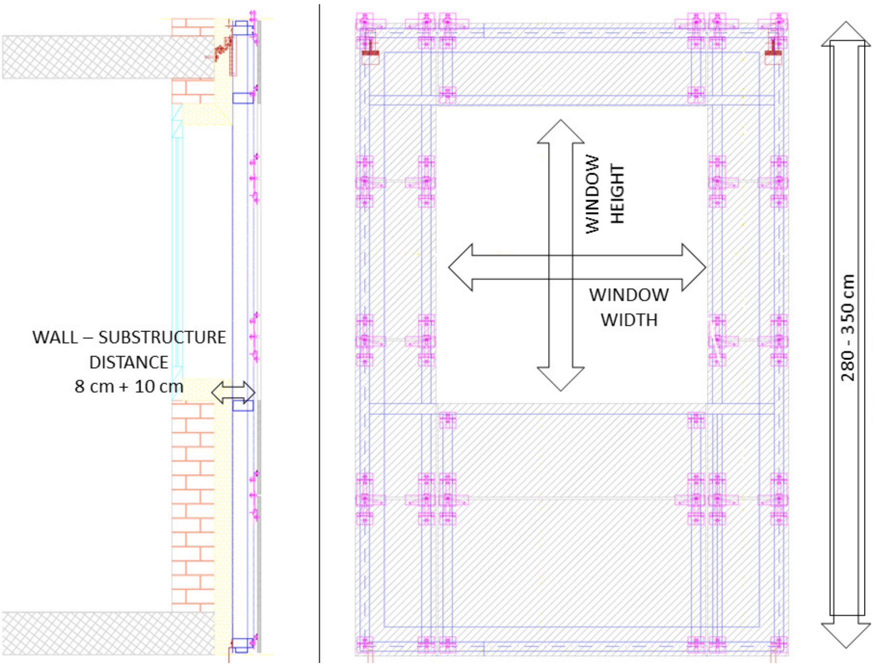

FIG. 10 Design of the window macro-panel without the integration of the window

3.2 TECHNICAL PERFORMANCE ASSESSMENT RESULTS

The ORF system performances have been assessed based on the requirements identified in the methodology section. The results are briefly summarised in Table. 5.

TABLE 5 Summary of technical performance assessment results

REQUIREMENT	ASSESSMENT RESULTS
Mechanical resistance	The extruded aluminium frame shape has been dimensioned in order to obtain a maximum 1/200 of frame length deflection at centre point. This resulted in a total frame length equal to 100 mm, which ensures a sufficiently rigid system to comply with the constraint of maximum deformation within 15 mm (calculated as 1/200 over the 3000 mm slab-to-slab distance).
Thermal resistance	Thermal resistance has been verified against a baseline retrofitted wall made of the following layers: internal plaster, 15 mm; hollow brick layer, 80 mm; air cavity, 80 mm; hollow brick layer, 120 mm. The reference building is retrofitted using 160 mm rockwool insulation, while the ORF is characterized by the same amount of insulation plus the external extruded aluminium frame. The calculated U value for the reference retrofit and ORF are respectively equal to 0.189 W/m^2/K and 0.217 W/m^2/K. The psi-value (thermal linear loss coefficient) for the ORF is equal to 0.0167 W/m/K. Hence, the effect of thermal bridge and consequently reduced average U-value needs to be accounted for when designing the retrofit action. As a further development option, thermal break within the frame or a different framing material, such as timber, could be considered to mitigate the impact of the thermal discontinuity on the overall energy performance. Overall, a traditional ETICS system results more convenient in terms of cost/thermal performance ratio. However, the design driver was to push the industrialized approach towards a plug-and-play façade system. In this case, energy performance falls within regulatory limits but is not pushed to the maximum achievable performance levels.
Hygro-thermal and condensation risk	Based on both the steady-state and dynamic calculations, the eventual risk of surface condensation is not expected. However, when wall materials with very low or zero vapor resistance are used in the existing wall, a high moisture transfer towards the outside could occur. In this configuration, in a limited number of peak conditions over the two-year simulation timeframe, the 95 % threshold in relative humidity could be passed at the contact between insulation and the metal frame. However, the spatial integral calculated shows that the surface condensation phase is rapidly followed by a drying phase, with no accumulation foreseen in the insulation material. As a result, the risk of interstitial condensation is also is unlikely to happen in the case of existing buildings. In addition, this risk is analogous to what can take place in the case of a vented rainscreen at the fixing locations, wall to substructure interface.
Water tightness	The visual inspection performed after the water jetting test presented in the methodology section has shown water drops have entered the air cavity behind the external cladding in a significant quantity, entering both vertical and horizontal joints of the system. In addition, the test highlighted inappropriate positioning of the anchoring hook of the panel, which was causing water infiltration from the air cavity towards the back of the panel through the frame. This issue has been however easily solved fixing it on the main-frame back without any break of the watertight layer. The test proved that the system composed by the extruded aluminium frame and inserted gaskets was overall working properly in terms of water tightness.
Impact and wind resistance	Impact resistance of the system integrating a peculiar innovative polymer concrete cladding has been assessed and determined as CLASS III, meaning that the ORF façade can be installed in building, but not at ground level in areas with public access. Impact tests have been performed on three different sized passive cladding panels, namely 813 x 402 mm, 813 x 410 mm, 1210 x 443 mm, and breaks have been registered for the combination of 1 kg + 10 joules on a 1210 x 443 mm panel. Wind resistance has been tested up to 3000 Pa pressure/suction for all the three cladding options: passive, PV and ST. No breaks have been registered.
Fire reaction	Fire reaction has been tested on a façade corner specimen, equipped with PC passive cladding, with two façade elements, respectively 1000 x 1500 mm, and 500 x 1500 mm sized. According to test procedure, two joints need to be placed in the larger module (1000 x 1500 mm). One of the prototypes was coated with a cool surface reflective paint, while the other was left uncoated. The coated prototype performed better than the other in terms of both heat release and smoke production. In terms of lateral flame spread, the distance was below module width. The materials did not produce any hot melted drops within the first 600 seconds. As the system was not intended for certification, the procedure was executed on a single occurrence, instead of the three-time repetition prescribed by the regulation for certification purposes. Test results were in the range to obtain a B,s1,d0 classification, over the minimum threshold of B,s3,d0 that is required to operate in both the Italian and Spanish construction markets, which were involved in the project through demo case building.

3.3 FAÇADE COST

At the end of the development and after the first demonstration in a real building, the costs of system design, manufacturing, and installation are in the range of 1.5 to 3 times the cost for a traditional façade retrofit solution. More specifically, the authors calculated the ORF system costs at around 3 times the cost of a baseline ETICS insulation and 1.5 times the cost of a vented rainscreen insulated system. A detailed cost breakdown of this system is not shown for confidentiality reasons. However, more details on potential optimisation margins are provided in section 4.2.1.

4 ORF SYSTEM STRENGTHS AND LIMITATIONS

4.1 OVERVIEW

The presented façade system in its final configuration results in a flexible façade retrofit kit for the energy deep renovation of buildings.

The chosen final solution, based on the macro-panel concept, allows for the integration of different cladding solutions, from passive to active (as per mock-up Fig.11 and demo building Fig. 12 installations).

FIG. 11 Performance mock-up of the façade integration, passive (left), PV (centre), and ST (right) claddings

FIG. 12 First demo building installation in Zaragoza (Spain), 2019

The system ensures adequate performance, verified in terms of mechanical resistance, thermal resistance, hygrothermal behaviour, water tightness, impact and wind resistance, and fire reaction. Easy access to all components across the system section is guaranteed, thanks to the offsite assembly design approach and to the use of a removable cladding fixing system.

The current sizing of the first and second insulation layer, and the frame features, determines a reduction of the whole façade's thermal resistance compared to traditional ETICS, which might be not fully appreciated in cold climates. Nevertheless, the macro-panel frame has to be considered under a custom-made vision, for which the use of thermal breaks, grooves, and wooden parts can reduce the thermal performance gap with a continuous insulation system, satisfying the customer specifications. The anticipated engineering effort spent during the project phase also allows for a reduction in construction time, as the substructure and the anchoring systems are both working as plug-and-play. The installation on site is performed without scaffoldings, using just cranes and/or moving platforms. This solution is flexible enough to accommodate intervention on façades up to 30 m in height (i.e. buildings of approximately 10 storey). The first figure relating to timing performance of on-site installation is about 160 m^2/day. A reduction in the installation time is therefore one of the most readily quantifiable notable advantages, saving installation costs in terms of manpower, equipment, and construction-site related expenses (e.g. public land occupancy). However, a more detailed analysis based on a series of complete experiences is needed.

4.2 DISCUSSION

4.2.1 Costs and business models

Based on the cost categories in Table 3, as applied to the demonstration building mentioned above, average façade-specific costs have been calculated to be in the range of 1.5 – 3 times the cost of a traditional façade external retrofit intervention. This is certainly a current limitation to broad market penetration, and the challenges of cost optimisation and value engineering are already being addressed within the frame of the project. In more detail, the ORF system cost is in the range of 3 times the cost of an ETICS system with no external cladding, and 1.5 times the cost of a vented rainscreen with insulated air gap. If the ORF system could be deployed to a larger extent in the construction market, economies of scale can be triggered, lowering down the components' prices. However, comparing the ORF, and multifunctional façade systems in general, to ETICS should be avoided in the future, given the substantial difference in physical behaviour and the number of functionalities that can be integrated exclusively in the ORF system, and not in the passive ETICS system.

To sum up, the main justifications to extra costs incurred in implementing the ORF are found in the following: (i) the ORF system has been implemented within the frame of a research project and only one demo-case building, with a few square meters of façade, implying that economies of scale have not yet been activated; (ii) the ORF value chain is still at an early stage of development, currently initiated but still limited to the offsite fabrication phase, resulting in scattered design and assembly process with very low cost optimisation; (iii) added value to the solution, deemed to lower down costs over the life-cycle lie in novel business models based on the circularity principles. Such models have been already analysed in Orlandi, Ilardi, Catgiu, and Carra (2019). Moreover, experiences of "façade leasing", like the one discussed in Prieto, Klein, Knaack, and Auer (2017), are setting the basis for a paradigm shift in façade from product to service. In this light, ease of dismantling and re-installing is a key feature. In this framework, the ORF could be a mature technology to be exploited thanks to its features of being easy to dismantle and to re-install.

For the above, a reduction in cost can be reasonably foreseen once the production line is stabilised, in terms of physical location component supply network, experienced manpower for manufacturing and installation, increased manufactured quantities.

A more comprehensive value engineering analysis, currently under development, can also demonstrate that the difference in cost at time of intervention is consistently reduced when considering the entire façade lifecycle. The delta can be further mitigated by the inclusion of the commercial value parameter in this analysis. In fact, the offsite fabricated system allows for technical risk reduction, as it minimises construction works to be performed on-site. This impacts the final quality of the result and can be accounted for in the life-cycle analysis when using the multiple-benefit approach. At present, there is no standardised methodology for a coherent cost comparison between the façade energy renovation standard technologies and the offsite fabricated approach. Nevertheless, the inclusion of all relevant technical and commercial parameters in the cost comparison analysis is needed and can support the ORF system business case. Further effort will be dedicated to this specific task in the future.

4.2.2 Technical review

Diving deeper into the technological limitations of the system, which also bear an impact on the total cost of ownership for the system, the authors have identified the use of multiple framing systems according to cladding type as another issue to be tackled in the next developments. The frame section itself is also a main cost consideration, as the profiles have been purposely extruded to couple and create multiple decompression chambers, to allow for the use of a gasket system in a unitised façade fashion. Finally, the use of metal in the ORF frame could be coupled with a timber-based frame and be used exclusively to provide increased stiffness to a timber-based system. Eventually, it could also be totally discarded and just be applied in the system fixing (link to existing wall and panel substructure). However, these options will be investigated as a potential outlook for the medium-term future, also relying on a number of successful renovation actions developed on a timber-based system.

In addition, the integration of a decentralised ventilation unit within the macro-panel (conversely to the level of detail reached in the case of both PV and ST modules) has only been developed at a preliminary stage. It would be worth further investigation in the future to check whether the added functionality can support the ORF system value determination and decrease the cost difference between the non-prefabricated and the prefabricated solution.

4.2.3 Processes

In terms of the construction process, the ORF presents margins for optimisation, as the system at the current level of development still requires a quota of the assembly work to be performed on site prior to macro-panel installation, namely: anchoring of building services distributions, of the brackets at the concrete slabs and of the first insulation layer.

In addition, a construction process issue arises from the presence of the on-site installed insulation at the interface between the existing wall and the new façade system, as it generates manual work that can reduce the impact of benefits brought about by macro-panel offsite assembly. Although the soft insulation layer has to be manually placed over the existing façade, movable auxiliary equipment can be used for this task (no need of fix scaffolds).

5 CONCLUSIONS

This article has presented findings from the research and development activities focused on the development of an offsite fabricated system for ventilated façade energy refurbishment that can provide the construction market with a systemic approach to renovation, combining energy efficiency, multifunctionality, integration of renewable energies and ease of installation as design drivers.

Building heating demand is reduced thanks to a traditional continuous insulation layer and the additional prefab panel, while overheating is prevented thanks to the natural micro-ventilation behind the cladding.

The ORF system development drivers has allowed the following strength points to be achieved. The designed ORF macro-panel frame (i) allows for the installation of many kinds of different passive and active (PV and ST) cladding elements, (ii) the ORF system showed lowered installation efforts thanks to the high degree of prefabrication of the solution, based on a design-for-assembly and maintenance approach, as well as simplified integration of extra technical equipment besides insulation, such as wires, ducts, and other distribution elements. In addition, the system is also compatible with a variety of cladding types, spanning from passive opaque materials, traditionally applied in vented rainscreens, to active systems for the renewable energy sources exploitation, such as PV or ST modules.

The proposed façade system solution can be broken down into three main functional layers (from inside to outside): (i) adaptation layer between the existing wall and the new façade system, composed of soft compressible insulation where eventual piping, ducting, and cabling can be hosted in case an energy system renovation is addressed; (ii) offsite fabricated extruded aluminium macro-panel frame, anchored to the existing wall through brackets and adaptable with both passive or active cladding. This layer also includes an additional insulation element to complement thermal resistance provided by the compressible insulation layer; (iii) external cladding, installed offsite with a removable plug-and-play anchoring system based on a combined gravity and mechanical retention system.

The functioning principle of the ORF is based on the plug-and-play installation approach, so to allow quick and reliable installation as well as permitting easy access to components during building service life. In the current state, this is achieved through the combination of a metal mullion substructure and a metal frame running all-around the panel edges. This is deemed to increase costs and the system could be further optimised in terms of frame typology to be applied according to panel dimension and weight. In addition, the frame structure at current state still requires minor manual operations to be performed on site.

The cost analysis carried out within the project proved that current cost ratio of a traditional façade retrofit solution versus the ORF is in the range of 1:2 – 1:3. However, the attempt to quantify specific costs at a coherent level between ORF façade and a traditional approach showed that there is no current methodology available to compare costs. This is due to the difference in system intrinsic value, as well as the current difficulty encountered in determining added value generated by the increased quality output the pre-assembled solution can guarantee, together with the ease of assigning multiple functions to the façade. However, a substantial improvement in the economic case for adopting prefabricated systems in façade energy retrofitting could be supported by analysing cost variations when adopting different load bearing structure, insulation, and external cladding system, as well as adopting a life-cycle costing perspective and including the added-value of system integration in the analysis.

In terms of future research development, the authors are investigating cost optimisation opportunities in the system. The current manufacturing cost is deemed excessive to allow a broad market penetration of the system. Specifically, cost optimisation is being pursued evaluating both alternative configurations of the same concept (frame dimension variations and number of fixings), as well as the use of alternative framing technologies (e.g. combining a timber frame with a metal mechanical fixing).

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