IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: Chiara Scanagatta and Massimiliano Condotta 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1402** 012038

Bespoke metal cladding. Rethinking the design of the building envelope to ensure sustainability principles

Chiara Scanagatta[1,*], Massimiliano Condotta[1]

[1] Università Iuav di Venezia, Department of Architecture and Arts, Santa Croce 191, 30135, Venezia, Italy

*Corresponding author: cscanagatta@iuav.it

Abstract. Nowadays policies are increasingly oriented towards the use of renewable and bio-based materials to reduce the environmental impact of the building sector. Furthermore, the increasing use of dry construction techniques allows to combine a more sustainable use of resources with an attentive management of the end-of-life stage. Considering the need to shift the demand for material sourcing towards solutions that do not permanently affect the environment, the use of metals is not the first solution that comes to mind, but it offers many possibilities both in terms of sustainability and formal rendering. Metals can have great potential for use but, although the benefits of recyclability and disassembly of this material are well known, the metal cladding sector still finds little room for development. Bearing this in mind, this contribution presents a research work which analysed the possibilities and opportunities deriving from the use of metal cladding for sustainability.

Keywords: envelope disassembly, materials durability, metal cladding, metal reuse and recycling, sustainable design.

1. Introduction

Over the past decade, the policies issued by the European Union became increasingly oriented towards the decarbonisation aim, with repercussions on several sectors; the result of this process was the set of policies named the European Green Deal [1]. Different sectors were tackled, including the construction one since a wide part of the EU building stock – approximately 75 per cent – is responsible for 40 per cent of EU energy consumption. Considering that this energy waste could be reduced both by improving the performance of existing buildings and by applying smarter construction processes, in addition to energy efficiency measures [2][3], there has been an increasing promotion by the EU towards the use of renewable and bio-based materials as means to reduce the environmental impact of buildings. This was possible thanks to the Renovation Wave strategy [4] and the 'Fit for 55' package [5]. To further aggravate the impact of the construction sector, reports show how the production of building materials was responsible for an extra 8-10 per cent of global emissions in 2021 [6], meaning that there should be a reduction of emissions of over 98 per cent, compared to the levels of previous years, to align with the expected decarbonization goal [7][8].

Within this framework of a shift towards alternative materials, another instrument issued by the EU was the Green Public Procurement (GPP) [9], which is a voluntary instrument available to Members States to boost processes of a resource-efficient economy. The GPP is defined as 'a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured' [9] and puts on the table the idea of having not only more environmentally friendly materials but also more careful construction processes. The GPP was implemented by multiple Member States, and one example is the Legislative Decree on the 'Minimum Environmental Criteria' (CAM) introduced by the Italian Ministry of Ecological Transition in 2017 and updated in 2022 [10]. The CAM criteria, in their 2022 version, present a connection with rating systems such as the LEED and the BREEAM and thus give the possibility to verify the impact of some of the criteria by using them. These protocols and guidelines aim to 'measure' sustainability – although it is such a complex aspect and dependent on many factors that it is difficult to measure [11] – through the evaluation of certain indicators including the use of renewable or recycled materials, distance from the production site, and many others; this allows to define a possible measurement system of the overall sustainability of a project. This decree is mandatory for public competitive bidding processes but not for private procedures, and the presented criteria are set for specific environmental requirements which aim at the identification of environmentally sustainable design solutions. Furthermore, the aim of the CAM is to reduce environmental impacts, promote more sustainable production systems and models, and lessen consumption. Despite not being mandatory for every construction process, producers began to draft environmental certifications for their products, on a voluntary basis, right after the definition of the GPP [12], further emphasising the change in the sector.

Building on these premises, a shift towards solutions that do not permanently affect the environment is now a matter of course. Indeed, the use of alternative solutions and materials, combined with renewable and bio-based ones, would allow lowering the environmental impact of the building sector thanks to a reduction in the extraction phases. Nevertheless, this is just one of the steps which have to be implemented to reduce emissions by 2050, and it should be seen as a way of modifying the traditional approach of the building sector.

Moreover, the implementation of other design strategies could contribute to further decreasing long-term impacts. One possible plan of action could be to promote the usage of dry construction systems for both renovations and new constructions; this would allow combining a more sustainable use of resources with an attentive management of the end-of-life stage. Compared to wet systems, dry ones are based on prefabrication principles which envisage the use of non-wet connections, allowing to put the focus on more attentive design solutions which consider the opportunities given by a possible future disassembling and reuse of materials. Such dry systems, in their application with timber or steel frame structures, are historically more used in North America and less present in Europe, where there is a strong tradition of bricks and concrete wet systems [13][14][15]. In this sense, new policies, and instruments call for a deeper cultural change for the European construction sector, which must also involve updating the technical knowledge of the workers to incentivise a shift which could be otherwise ostracized due to a lack of technical know-how.

However, most of the analyses on which new solutions and materials should be used to reduce the building sector impacts do not consider the great potential of metals, and in particular their recyclability. Bearing in mind the European double aim of reducing raw materials extraction, and implementing flexible and disassemblable structures, metals can fit both needs thanks to their physical characteristics.

Regarding the first aim of reducing the use of raw materials, metals obtained from ore mining, are not considered renewable and bio-based materials. Renewables are defined as 'material that is composed of biomass and that can be continually replenished' [16] and bio-based are 'products that are wholly or partly derived from materials of biological origin, excluding materials embedded in geological formations and/or fossilised' [16][17]: these definitions do not fit finite virgin ores. On the other hand, metals can be considered aligned with European materials policies since they could be recycled plenty of times due to their high recyclability index [18][19][20][21][22][23]. Moreover, regarding the aim of implementing flexible and disassemblable structures, metals are typically assembled with dry construction principles [24][25] allowing a high level of reusability.

Bearing this in mind, a leading company in the metal sector, Mazzonetto S.p.A., promoted, in coordination between its research and development department and the Università Iuav di Venezia, a research work to study the possibilities and opportunities, in terms of sustainability, deriving from the

IOP Conf. Series: Earth and Environmental Science **1402** (2024) 012038 doi:10.1088/1755-1315/1402/1/012038

use of metal claddings. The final aim is both of updating existing solutions and of developing new products. The present paper focuses on one part of the research, namely that which sought to assess what contributions metal claddings can bring in terms of sustainability. The aim of this contribution is, therefore, to propose possible guidelines on the use of metal cladding for the buildings of the future, to allow a more sustainable approach to the design of buildings' envelopes while guaranteeing customization freedom for both new constructions and retrofitting.

2. Metals in architecture

Metals in construction can be used for load-bearing structures, envelope cladding, and connection components. Regarding the first case, the most widely known and used are steel frames, while another type, whose use has just recently spread in European countries, is Lightweight Steel Framing (LSF). This latter employs light steel elements as the main structure, and the profiles are usually made of galvanized steel, designed to allow quick and efficient on-site assembly [26][27][28][29]. In both cases, disassembly at end-of-life can be easily reached if dry fastening systems are chosen. Considering envelope cladding, metals can be more readily found in their application to roofs. A long tradition as water resistant layer can be seen in examples as public and religious buildings of the Roman Empire, where lead and gilded bronze were applied for roofing, and as copper and lead claddings on the domes of the churches in Venice during the 'Serenissima' Republic [30][31][32][33][34][35]. The implementation of metals to characterize buildings' façades is relatively recent since their popularity has grown since the beginning of the 20th century, with the realization of iconic buildings such as the Empire State Building and the Chrysler Building. Metal envelope claddings are more commonly used today as a result of the experiments made by pioneers such as Buckminster Fuller and Jean Prouvé who, between the 1930s and 1940s, studied different aspects of the industrial production of metal components in their prototypes of the Dymaxion House [36][37][38][39], the Maison du Peuple in Clichy [40][41], or in the different versions of the Demountable House [42].

These buildings were the ones that set the base for contemporary works as Gehry's Guggenheim Museum in Bilbao (Figure 1) [43], Libeskind's Jewish Museum in Berlin (Figure 2) [44], DEMOGO's Town Hall of Gembloux (Figure 3), RPBW's Music Park Auditorium in Rome (Figure 4), and Gehry's Walt Disney Concert Hall in Los Angeles (Figure 5), examples of metal cladded buildings capable of showing the iconicity of this material.

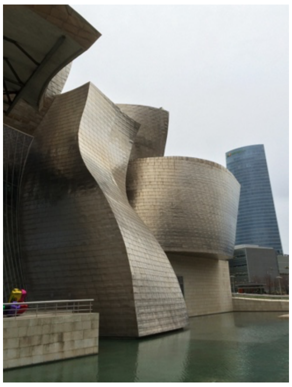

Figure 1. Titanium metal-clad of the Guggenheim Museum in Bilbao by Frank Gehry.

Figure 2. Titanium-zinc cladding of the Jewish Museum in Berlin by Daniel Libeskind.

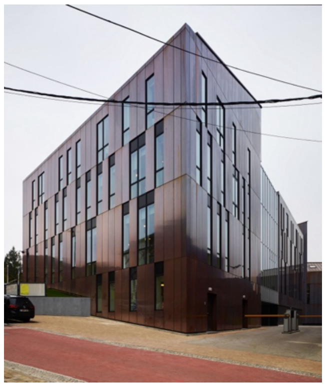

Figure 3. Copper metal-clad of the Town Hall of Gembloux by DEMOGO.

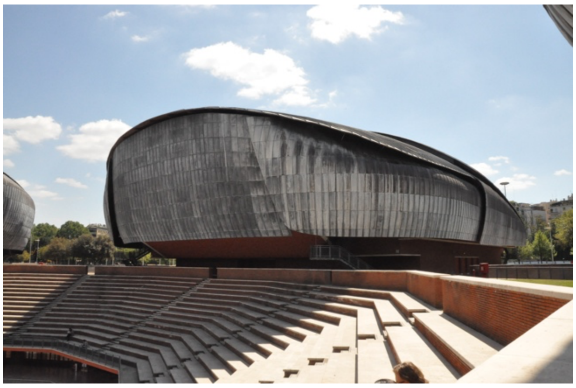

Figure 4. Lead cladding of the Music Park Auditorium in Rome by RPBW.

Figure 5. Stainless-steel metal-clad of the Walt Disney Concert Hall in Los Angeles by Frank Gehry.

2.1. Metals' use in architecture in recent years

Despite its long tradition of roofing application, which persists today, and more recent use on façades, envelopes' metal cladding still finds little room for development apart from high-budget design projects due to costs.

With the aim of better investigating if, and how, this tendency is changing, an analysis was carried out in collaboration with Mazzonetto S.p.A.; the conducted research considered projects published in relevant national and international architectural magazines (Detail, Casabella, The Plan, Arketipo) in recent years (2016-2021).

The study analysed a total of 1430 projects, of which 961 (67.2 per cent) were in Europe; 35.3 per cent of the European examples presented metal claddings. Different types of buildings are published, and, at first glance, the residential ones do not have the highest percentage of buildings with metal cladding (only 30.6 per cent use this clad solution). Nevertheless, this category is the most representative in terms of buildings which use metals since they amount to 29 per cent of all studied projects. This result is an important finding as it represents a large number of buildings, especially considering the amount of residential construction in cities.

Indeed, the number of residential buildings using metal-cladded façades, and not only roofs, raised, recording a change of trend. This is due to the multiple benefits that can come from a wider use of this type of finishing, from more formal ones, as the possibility of creating complex patterns [45][46], to more technical ones, as heating control through ventilated systems, or higher sustainability levels thanks to the material features of disassemblability, reusability, recyclability, and durability [47][48][49].

3. Potentiality of metal envelopes

From this brief analysis, it can be deduced how metal cladding is an architectural solution with much potential to be exploited in sustainable design. Three are the main aspects to be investigated and enhanced, and they are:

- Disassemblability and Reuse.
- Recyclability.
- Durability.

Considering the first aspect, metals in construction today already use mostly dry construction solutions for both load-bearing and cladding purposes. This allows for easy disassemblability, since mechanical fixings are mostly used, but the reuse aspect could be better implemented. If the substructure is made of metal, it can be reused, but if other materials are used for the supporting structure, recycling becomes the easier, or only, option. Furthermore, not all types of metal claddings present connections, between each cladding element, which could preserve the element's shape for reuse after its disassembly.

Recyclability, on the other hand, is guaranteed for the elements composing the cladding and its substructures. This is always true for metals since they can be molten to create new elements; this cannot be taken for granted if other materials are used, for example in composites, or are subject to natural degradation.

Durability is the aspect that could be most exploited. This is already guaranteed for the cladding itself due to the chemical-physical characteristics of the material. What should be further studied and stressed is the opportunity given by such durable cladding which, if correctly installed, could also increase the durability of other materials positioned on inner layers and, in general, of the overall building.

The following sections will firstly analyse metal claddings considering their presence as an existing solution on the market, to understand the situation from a technical perspective is, and what are the possible issues. Later, the possible implementations are studied and defined based both on the market and metals' potentiality. In conclusion, some considerations are made on connections between metal cladding and sustainability in architecture.

4. Metal cladding's common uses

One of the main advantages of using metals is their durability, indeed it is used for the outer skins of different means of transport – vehicles, aircraft, railway carriages and ships – but in modern and contemporary architecture it was chosen for the envelope of buildings which were meant to convey an image of 'high-tech' thanks to the technical achievements underwent in the transport sector. An example of this aesthetic use of transport technologies is the John Deere Headquarters by Eero Saarinen, built in the 60s. This was the first time Cor-ten, a material developed for railroad track construction, was used in an architectural application to answer the client's request for a building with a down-to-earth look.

Today, metal claddings can be chosen when particular design messages are to be conveyed, project considerations have been made with regard to colour and texture, a high level of efficiency in both cladding and protection is required, or when free-form claddings are required; this latter, in particular, is possible thanks to computer-assisted planning processes and the development of substructures that allow mounting very thin sheet metal on highly complex frames (Figure 6) [46][50][51][52].

Figure 6. Example of an articulate frame substructure used for the metal cladding of the new Chamber of Commerce premises in Via Torino in Mestre.

Considering how most sculptural results for envelopes are strictly linked to the frames underneath the external cladding, different types of substructures were analysed within the framework of this research, and the different types of fixing were considered. This analysis was essential to evaluate the level of disassemblability of the cladding systems from a sustainability point of view.

From the study, it emerged that there are two main macro areas of substructures: the ones made with a frame and the ones with a continuous rigid substructure; both can be applied to ventilated or non-ventilated façades.

The first type presents different components, which are mainly made of metals, and are installed by mechanical fixing [53][54][55][56]. The main elements composing the substructure (Figure 7) are the wall brackets (element 1 in Figure 7), connected to the load-bearing part of the building by anchors (element 2 in Figure 7), and the vertical profile (element 3 in Figure 7), on which the cladding (element 4 in figure 7) is fastened. This configuration allows for a ventilated façade, as opposed to a non-ventilated one if horizontal profiles are used. Depending on the type of cladding there can also be a double layer of profiles, vertical plus horizontal or vice versa, with the vertical element being always the one allowing for ventilation. In each case, the thermal insulation layer (element 5 in Figure 7) is positioned within the length of the wall brackets; furthermore, possible thermal bridges caused by the metal composition of the brackets are avoided by having a plastic component (element 6 in figure 7) separating it from the load-bearing structure.

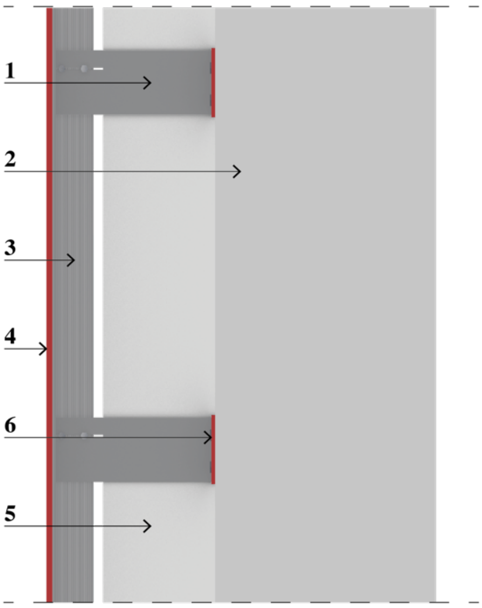

Figure 7. Typical frame substructure for a ventilated façade system.

The second type of substructure, with a continuous rigid plane, can be made with different materials [57][58] and can be used with either a ventilated or non-ventilated system underneath. The continuous rigid element can be made of wood or with a corrugated metal sheet. A third option is to have either a cement wood or fibre-cement board and, in all four cases, the different elements composing the substructure are connected using mechanical fixing.

The most common basic forms of metal envelopes, which can be found today, include systems as: open joints, metal sheets, coffers, louvres, overlapping planar elements, cross-welt seams, and standing seams [50][51][52]. Based on the type of form, which presents different technical features, the substructure type changes. One example is that of seam type, made with a thin sheet, for which a continuous rigid substructure is mandatory, while coffer systems, which are made more rigid by their box shape, can be installed using frame systems.

The analysis of existing substructures and cladding systems shows that metals already present the basic characteristics needed to reach more sustainable designs, but even more, attention must be paid in order to achieve the European targets.

5. New paradigms for metal cladding

Regarding the potential of metal cladding highlighted in section 3, it is appropriate to analyse, for each of the three areas identified, possible research lines and development strategies.

5.1. Disassemblability and reuse

Disassemblability and reuse aspects are closely interlinked. Both can be considered as already fulfilled if the initial installation phase is done using only mechanical fixings, but improvements can be made to further avoid the use of glues and welding solutions.

Considering the link between the two phases, the lower level of reusability of metal cladding is a direct consequence of the level of disassembly that can be reached at the end-of-life. The possibility of total or partial disassembly, and reuse, is due to different reasons: types of materials used for the substructure and kind of fixing system used for some outer layers forms.

Regarding the substructures, on the one hand, metal sheets and frames can easily be disassembled and reused in their previous form while, on the other hand, wooden frames and planking or cement wood and fibre-cement boards can hardly be reused due to difficulties in preserving them during the disassembly stage and to a deterioration of the material itself. The easiest solution to improve the disassembly and reuse of substructures would be to use only metal sheets and frames, which can be more easily disassembled for reuse compared to other solutions. Moreover, the analysis of the different types of substructures shows that these systems can be easily dismantled at their end-of-life, since the fixings are mechanical ones, making it possible to reuse or recycle the material.

Concerning the cladding itself, its disassembly and reuse depend on the chosen type of joints. Solutions using clamped joints or coupled slats and siding systems can be dismantled while preserving the shape and characteristics of each element: in the same way, shingle systems can be reused since they are fixed using fastening clips. Reusability cannot be guaranteed when seam systems are used since the initial shape of the cladding changes during the installation process; this is because seaming is achieved by first overlapping two sheet metal flaps, which are folded together twice on themselves, resulting in a stable and durable union. To retrieve such components, solutions to 'undo' the folding should be studied. Furthermore, the viability of reuse is based on the shape of the elements themselves. If the disassembled element has a 'regular' shape, as a flat rectangular one, this allows for an easier reuse on other surfaces since it is possible to re-assemble the elements either with the same pattern or with a different one.

The aim should then be to reach a complete disassemblability of cladding systems to allow the reuse of each element composing them.

5.2. Recyclability

Recyclability of the used material is already sufficiently developed in the metal's main framework since load-bearing elements are mostly produced from ferrous scraps and coils are almost completely made of recycled material: but improvements are still possible and needed. When it comes to metal cladding, recycling is widely used for elements with irregular shapes, like curved ones, since these are custom-made for a specific surface and cannot be easily repositioned on a differently shaped façade or roof. Thus, once disassembled, irregular plates are melted down since they cannot be reused. Ideally, this doesn't apply to elements with regular shapes but, in real applications, reuse is hardly ever used and even flat plates are melted down.

With an aim of expanding the presence of metal claddings, and considering the issue of repurposing claddings which do not follow a 'simple' pattern, processes to recycle should be further studied to reduce their energy demand while encouraging to minimize extraction processes to produce new elements. Nevertheless, although recycling is a positive approach to reducing the use of virgin material, reuse should be encouraged since it requires the least amount of material extraction and doesn't involve energy-intensive processes.

Furthermore, multiple composite solutions which combine metal and synthetic insulation layers can be found in the market; these elements cannot be separated at the end-of-life stage, forcing the product to be landfilled as it cannot be recycled. In the same way, the presence of plastic elements should be reduced, since after years of external exposure it becomes difficult to undertake separation processes, which are manually made, making their recycling less cost-effective compared to landfill.

5.3. Durability

Durability is an important characteristic of metals, and its potentiality should be further exploited, especially considering that this is a well-known feature.

The durability of metals varies according to the type of alloy or treatment applied but, in any case, when used as an external coating it significantly reduces maintenance requirements compared to other rendering solutions. Durability guaranteed on the exterior layer, if correctly studied, could benefit the long-lastingness of inner layers as well, especially if metal-cladded envelopes create a waterproof layer without the presence of plastic elements. This is of utmost importance. In fact, EU politics push toward wider use of renewable and bio-based materials which, given their organic origin, have shorter lifespans compared to metals and commonly used solutions to prevent their deterioration involve the use of sheathing membranes and synthetic plasters, which are made with plastic materials not in line with EU guidelines and sustainability principles. Therefore, by using metallic outer claddings, their protective function could allow a wider implementation of bio-based materials, which need protection from weather-related events since they have a relatively short lifespan due to their organic derivation.

5.4. Metals' limitations

Despite the possible benefits of using metals, these coating systems are still not widely and adequately exploited; to understand why, other aspects should be taken into account to have a full view of why they are not as used at their fullest potential. The first is the higher material and installation cost, which disincentivizes from using them for envelopes and, secondly, installation calls for a specialized workforce, resulting in hesitation to move towards this type of layering.

Considering the first point, even the simplest metal cladding is more expensive compared to other solutions, and custom envelope designs noticeably raise costs. However, one must take into account the possible offered advantages, and that the overall cost should be evaluated based on a longer functional period; in fact, even if the cost of installation is higher, the subsequent cost of maintaining the envelope and the inner layers is reduced. Moreover, considering the potential of reuse, there may be a partial payback of installation costs even at the end of the use of the installed elements. Furthermore, if formal aspects of architecture are considered, metals' capability of allowing higher degrees of form-freedom is an important feature which should allow for a wider spread of this type of cladding. This liberty of shaping derives from the material characteristics of malleability which, in combination with different types of substructures, allows to creatively shape buildings' envelopes.

Regarding the issues related to the workforce and their lack of know-how for the installation of modular metal façade systems – besides seam systems mounted on wooden planks – which are more suitable for disassembly and reuse, these originate from cultural aspects. European tinsmiths are quite expert in the installation of steam systems with a continuous wooden substructure but are not confident in using other types of claddings, or substructures, since, due to the historical application and use of roof claddings, they lack the know-how and expertise to correctly install other solutions and products. This is a paradox since, as seen from the analysis of substructures, the installation of frames is not more complex than continuous ones, it only requires attention to detail. Considering the sustainability potential of using different types of substructures, ways of breaking down this reticence should be found; one way could be to incentivise, and thus force, the workforce to invest in upgrading their skills to remain competitive in the market.

6. Conclusions

The research carried out by the Università Iuav di Venezia and Mazzonetto S.p.A. showed that it is possible to develop new metal cladding solutions which could further push the existing sustainability aspects of disassemblability, reuse, recyclability, and durability, while improving the presence of such claddings in all types of architectures, from bigger projects to smaller residential ones. Indeed, based on what was above analysed, metal-cladded envelope solutions should be considered as a complete metal system rather than viewing the cladding and the substructure as separate elements. By doing this, sustainability aspects should be implemented based on the whole system rather than being linked to single elements, allowing for an easier approach.

Focusing on sustainability, even though complete metal cladding systems do not fall into the category of renewable or bio-based materials, various benefits arise from their use for cladding; as a matter of fact, by implementing this system approach, future dismantling would consider both the external layer and the substructure, pushing towards the use of elements which could be separate at the end-of-life.

The opportunity of having a fully metallic system, with cladding elements with regular shapes which could be combined in different patterns, would permit the reuse of each element; this could reduce the need for recycling processes which, despite avoiding the extraction of virgin materials, are more energy-intensive. Preference towards mechanical fixings or clamped joints would allow for easier assembly, disassembly, and replacement; furthermore, if standard substructure elements are used in conjunction with fastening systems already existing on the market, reuse would be further simplified, as use for other claddings could also be considered.

By having the highest possible percentage of metallic components, plastic presence could be reduced; but, to reach this aim, waterproof fixing solutions should be studied as alternatives to sheathing membranes and gaskets. The durability of materials positioned in inner layers, as bio-based insulation panels, could be further enhanced if the external layer is waterproof and non-breathable plastics are avoided.

Formal rendering aspects could also incentivize the use of metal claddings considering the resulting feeling of richness and sculptural presence, and cost aspects may be overshadowed if sustainability and formal characteristics are considered altogether. Workforce reticence can also be overcome if substructures derive from components already on the market, and thus known, with simple installation instructions which reduce the risk of error by installers.

Overall, further development of metal cladding solutions could enhance higher levels of sustainability for building envelopes, while proposing interesting solutions to characterize architectures.

Author Contributions: Conceptualization, Chiara Scanagatta and Massimiliano Condotta; methodology, Massimiliano Condotta and Chiara Scanagatta; investigation, Chiara Scanagatta and Massimiliano Condotta; writing-original draft preparation, Chiara Scanagatta; writing-review and editing, Chiara Scanagatta and Massimiliano Condotta; visualization, Chiara Scanagatta and Massimiliano Condotta; supervision, Massimiliano Condotta. All authors have read and agreed to the published version of the manuscript.

Acknowledgements
The work here presented has been realized thanks to an agreement with Mazzonetto SpA. The paper is the result of the joined research activity of the authors. The technical office of Mazzonetto SpA gave support for technical aspects and tests.

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