Study of a BIPV Adaptive System: Combining Timber and Photovoltaic Technologies

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Abstract

The paper presents the first results of research that was partly conducted within the framework of European COST Action TU1403 – Adaptive Façades Network, on the development of an adaptive BIPV (Building Integrated Photovoltaic) solution able to change its curvature in relation to the external environmental conditions, orientating itself in order to optimise the energy production without the aid of any mechanical and electrical systems. After analysing the characteristics of the main adaptive materials that are currently used for such applications, the contribution outlines the main features of the proposed system, which consists of thin film solar cells coupled with a thin layer of hygromorphic material, manufactured from two wooden slats joined together and produced from different types of wood and trunk cuts. The hygromorphic layer thus obtained can change its shape as a function of temperature and relative humidity of outdoor conditions, thanks to the different expansion coefficients of the two wooden slats. To evaluate the performance of the component, three shape configurations for the adaptive strips have been assumed. For each hypothesis, the lamellae have been modelled using the Rhinoceros 5 Software, according to the curvatures taken during the different months of the year. The Rhino models have been imported into Autodesk Ecotect Analysis to calculate the incident solar radiation and to study the self-shadowing effect in the various configurations (in relation to the climatic conditions of the city of Milan). The paper outlines the system and PV energy production optimisation process, as well as possible applications in the field of façade design.

Keywords

adaptive façades, adaptive component, hygromorpic materials, BIPV technology, wood, timber

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1 INTRODUCTION

The building envelope has a dominant impact on a building's energy balance and it plays an essential role towards meeting the nearly Zero Energy Buildings (nZEB) target (International Energy Agency 2013; European Commission 2013). Nowadays, however, it is increasingly recognised that more flexible behaviour of the façade is desirable (Loonen, Rico-Martinez, Favoino, Brzezicki, Menezo, La Ferla, & Aelenei, 2015; Andresen, Kleiven, Knudstrup, & Heiselberg, 2008; Schumacher, Schaeffer, & Vogt, 2010; Wiggington & Harris, 2002). Adaptive façades should provide controllable insulation and thermal mass, daylighting, solar shading, ventilation and humidity control, etc. Moreover, these façades should collect and convert available renewable energy (mainly solar) in an adaptive way, in order to follow, as far as it's possible, the building's energy needs (Luthander, Widén, Nilsson, & Palm, 2015). Facing the challenges of decarbonisation for the building sector in the EU (a target of 80% for 2050), the building envelope should integrate active functions relating to energy production (collect, convert, store, distribute). In this regard, building façades are often the largest potential surface for integration of renewable energy generation components (photovoltaic, solar thermal, etc.) in urban areas.

The envelope adaptivity can be summarised by many concepts. Considering the way adaptive façade components are controlled/operated, terminology such as that in Loonen, Trčka, Cóstola, and Hensen (2013) is used: intrinsic control implies that it is self-adjusting, since the adaptive behaviour is automatically triggered by environmental stimuli, which allows for low-cost operation and maintenance. On the other hand, extrinsic control first implies the retrieval and processing of information and then, actions to be taken. This allows for feedback and, thus, for artificial intelligence. These components rely on technologically-imposed intelligence (Holstov, Bridgens, & Farmer, 2015) enabled by the application and interaction of sophisticated mechanical and electronic sensors, control systems, and actuators, which results in a dependency on energy supply, high complexity and cost, and potential reliability and maintenance issues (Holstov et al., 2015).

2 THE BIPV ADAPTIVE SYSTEM

The aim of the research method is to advance the design of an innovative BIPV (Building Integrated Photovoltaic) façade system with standardised components that are available on the market. The proposal investigated suitable materials and associated elements that could be used to progress the research into a functional demonstrator, to determine a solution that is capable of self-orientation in response to solar radiation at differing solar elevation angles during the year in an intrinsic way, without the need of an energy supply. The BIPV component consists of thin film solar cells coupled with a hygromorphic material layer (Fig. 1). The component was analysed and modelled to determine: geometry, self-shadowing effects, and energy production, using Rhinoceros 5, Autodesk Ecotect Analysis, and Microsoft Excel software. The climate data considered in the modelling phase was provided by ARPA (Regional Agency for Environmental Protection) Lombardia, over a 5-year time span.

Other factors were considered in terms of: mechanical resistance, component interface details design, production, assembly, and durability to assess life cycle. This progress would hence develop system optimisation as a complete concept, without ignoring the construction and installation issues, which will affect integration with a building envelope, if adopted for future application. Other research application methods have been developed: lamellae lightness, for example, which allows a moveable system that responds to daylight changes. However, these systems require significant substructures that limit geometry scale, the requirement of energy, and the associated high cost of installation and ongoing maintenance issues (Doniacovo, 2016).

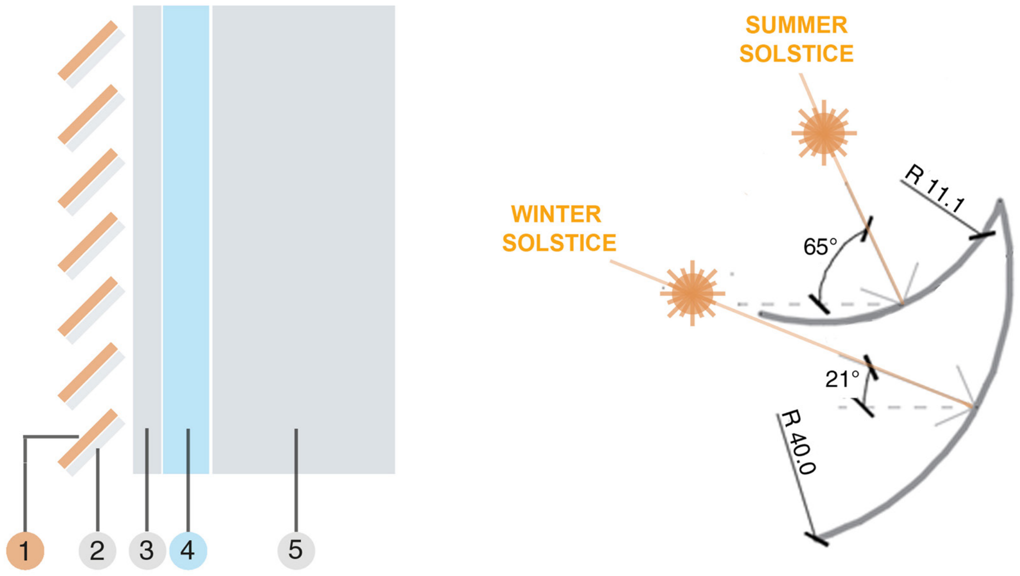

FIG. 1 Façade functional layers: 1 – Energy capture layer, 2 – Hygromorphic layer, 3 – Substructure layer, 4 – Ventilation gap, 5 – Other wall layers (structure, thermal insulation, etc.). Example of lamellae curvature (on the right)

3 THE BIPV ADAPTIVE LAYER

Hygromorphic materials (HMs), thermo-bimetals (TBs), shape memory alloys (SMAs), and shape memory polymers (SMPs) were considered to develop the research proposal. HMs are moisture sensitive and their behaviour and properties are determined by their configuration (single layer, bi-layer, thickness, fibres orientation, etc.) and production conditions (Holstov et al., 2015; Mazzucchelli & Doniacovo, 2017). TBs are the result of coupling two materials with different properties; if subjected to thermal load they modify their length causing the inflection of the coupled element. SMAs consist of at least two metal elements and have the ability to regain a previous geometrical form after being subjected to a thermal load. SMPs will change in geometrical shape (deformed) state if subjected to an applied thermal load that is different to that of their rest state (permanent form).

Hygromorphic materials have lower mechanical strength, however the aesthetic qualities, life cycle sustainability, and a lower production cost give them interesting characteristics. TBs exceed the limit of the mechanical strength typical of HMs, but they may cause overheating problems that should be avoided in the PV component layer. The behaviour of SMAs and SMPs can be controlled efficiently with respect to outdoor conditions. However, they are expensive and their production scale range limits the range of items (mostly springs or wires). For these reasons, it was decided to use HMs for the lamellae adaptive layer, consisting of two wooden strips, one active and one passive, joined together.

For successful application of the proposed solution, key values will determine the effectiveness of operation that is dependent on seasonal changes of temperature and relative humidity. These two factors affect the moisture content of HMs, which in turn influences the component dynamic movement behaviour. The analysis was carried out with respect to the climatic conditions of the city of Milan (Italy), latitude of 45 ° N, characterised by a moderate continental climate, with cold and damp winters and hot and sultry summers.

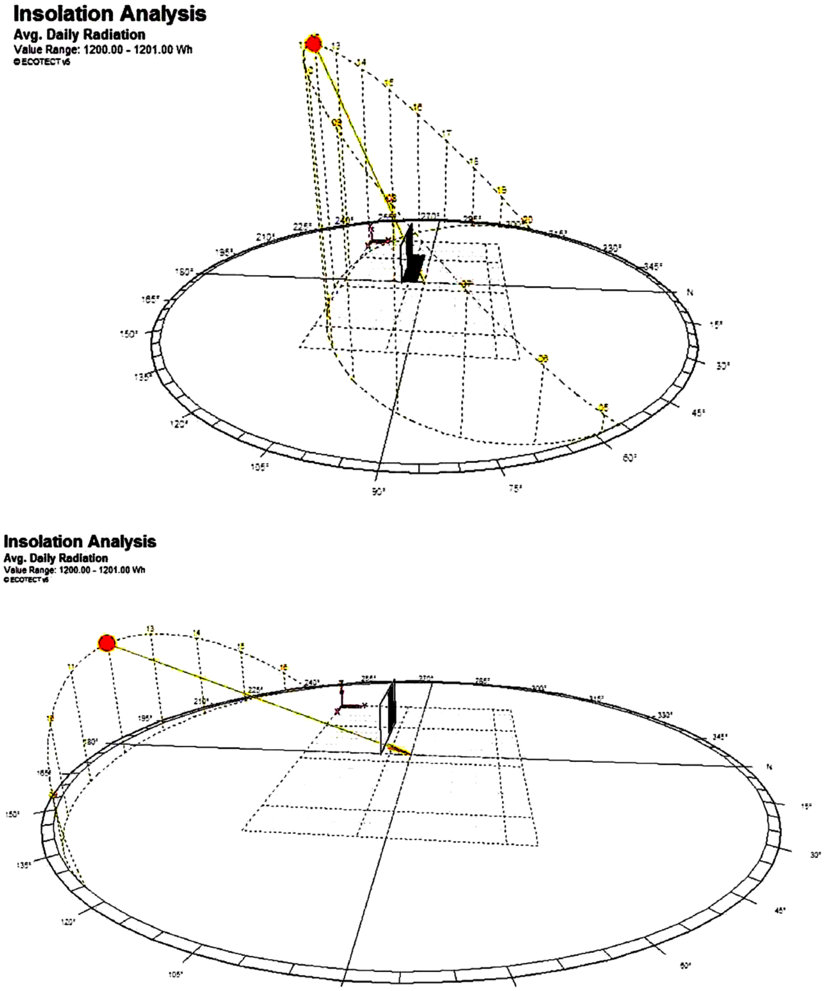

FIG. 2 Solar height in summer (21^{st} June) and winter (21^{st} December)

Optimisation in the geometrical form of the adaptive layer, is determined through two parameters: lamellae inclination with respect to the vertical plane and associated curvature. These parameters will orient the geometrical configuration to solar radiation inclination for maximisation of solar capture. The analysis was carried out on the surfaces exposed to the east, south, and west (only the methodology and results for the south-facing surfaces are presented in this paper). This was evaluated by a software tool, Ecotect 'Insolation Analysis'. This analysis determined optimal solar elevation angles in the summer and winter solstices as illustrated in Fig. 2. The outcome of this approach indicated the following optimum inclination values for the lamellae: β = 65° for the summer solstice; β = 21° for the winter solstice; while the optimal radius of curvature are R = 11.1 cm and R = 40.0 cm, respectively (see Fig. 1).

The maximum and minimum bending radii for the lamellae were calculated using the formulae proposed by Holstov et al. (2015), where the response of a hygromorphic material is a function of the effective moisture content change, that is, the difference in moisture content in the wood and associated species, which in turn depends on air temperature and Relative Humidity (RH). This response is a function of the dimensional variations of the two timber layers that are used to produce the composite material lamella form. The maximum curvature is obtained using rotary-cut strips and placing the active layer in such a way that the direction of the curvature is orthogonal to that of the timber grain. It is necessary to exclude timber species with inversions of grain and timber grain defects, due to the associated effects on layer curvature.

Timber material thickness and stiffness ratios will affect the active movement of the passive layer and hence the selection of layering combinations, as indicated in Fig. 3. The factors ‘m’ and ‘n’ are related to the choice of the optimal thickness ratio between the active and passive layers, ensuring that the curvature change coefficient ‘f’ is the maximum obtainable. Four hypotheses of active/passive layer combination have been considered (Table 1).

HYPOTHESIS	ACTIVE LAYER MATERIAL	PASSIVE LAYER MATERIAL	$N=E_P/E_A$	$M=T_P/T_A$
1	Wooden sheet	Wooden sheet	15-20	0.25
2	Wooden sheet	GFRP polymer	3-5	0.50
3	Wooden sheet	PET polymer	15-40	0.20
4	Wooden sheet	PC polymer	15-40	0.20

TABLE 1 Stiffness ($n=E_p/E_a$) and thickness ($m=t_p/t_a$) ratio values (a=active, p=passive)

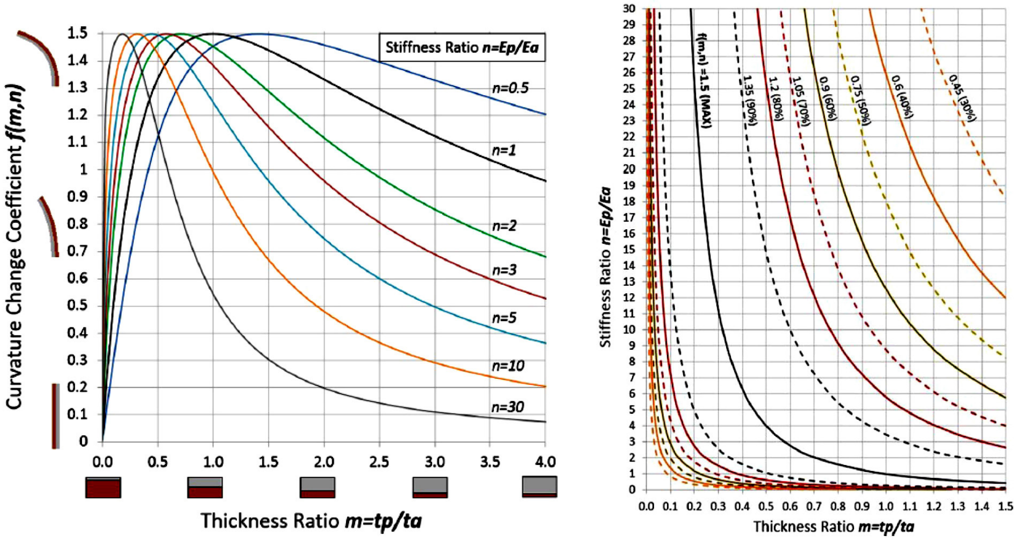

FIG. 3 Relations between curvature change coefficient and stiffness and thickness ratio *(Holstov et al., 2015)*. The factors ‘m’ and ‘n’ are related to the choice of the optimal thickness ratio between active and passive layer, ensuring that the curvature change coefficient ‘f’ is the maximum obtainable.

Results indicate that curvature is inversely proportional to the total thickness. For this reason, increased thickness of the active layers in a composite approach will enhance the response to longterm climate changes. However, reduction in the timber layer depth of the active layers will react to changes on an hourly basis. On the other hand, the thickness also affects other aspects of the lamellae: insufficient thickness can result in excessive deformations under the wind action, lower resistance to weathering, and lower fire resistance. The results demonstrate that the lamellae angles of bending by different material configuration can be calculated and compared to an optimal choice for the combination of materials.

HYPOTHESIS	MOUNTAIN MAPLE	BLACK WALNUT	WHITE BIRCH	EUROPEAN BEECH	OAK	SIBERIAN LARCH
1	139.3	146.6	130.7	108.2	109.6	131.8
2	141.3	147.1	129.1	106.5	108.0	131.3
3	157.3	165.1	149.4	125.1	126.5	149.7
4	160.6	170.0	157.0	132.4	133.6	155.4

TABLE 2 Obtainable radius of curvature R [mm] (21st of June, t_a = 4mm, R_0 = 450 mm)

The results (Table 2) show that the summer optimal curvature (R = 111 mm) can be obtained using beech or oak lamellae coupled with another timber or GFRP (Glass Fibre Reinforced Polymer) layer. The ideal winter curvatures are not strictly defined, but summer presented the optimal conditions for performance that was considered preferable (Doniacovo, 2016). The initial curvature in a summer thermal load was determined by K = 1/450 mm-1 to reach the desired bending radius in the summer period, maintaining adequate thicknesses to satisfy the other performance targets. The component durability and resistance under atmospheric conditions was evaluated according to UNI EN 350, UNI EN 355, and UNI EN 460 standards, and to the guidelines developed within the European WoodExter project, 'Service life and performance of exterior wood above ground' (2012). The results indicated an oak wood configuration as the desired species as a solution that gave better resistance to biological attack and was more highly sustainable (Mazzucchelli & Doniacovo, 2017).

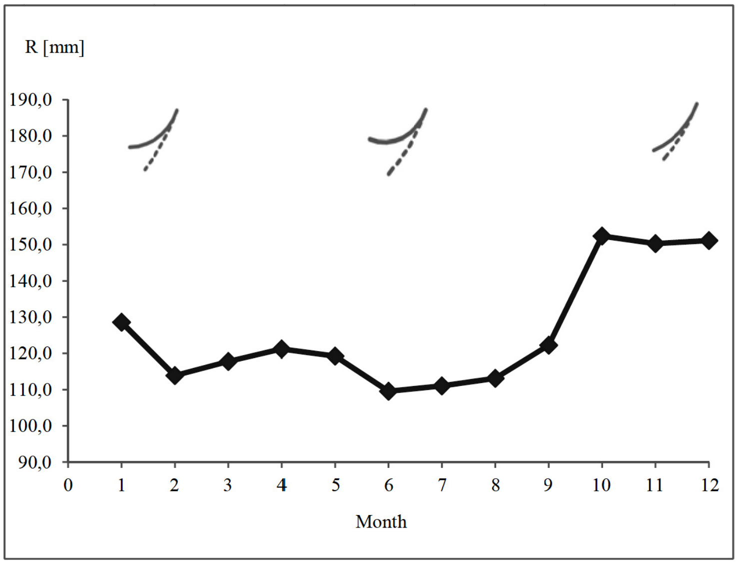

FIG. 4 Example of monthly average oak lamellae curvatures (active layer: 4 mm thickness, R_0=450mm)

From the modelling results (Fig. 4), it can be noted that during the summer months the lamellae monthly average curvature is rather important, so that the component, if located on a south-facing façade, can capture the sun's rays with higher solar elevation angles. From October to January the curvature is not marked, and this allows the same component to capture the sun's rays with low elevation angles.

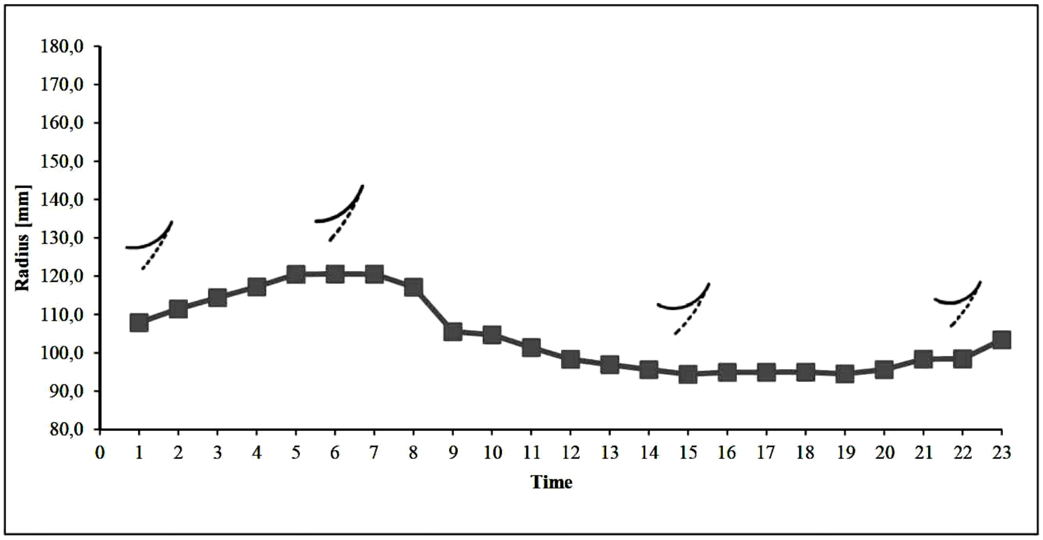

FIG. 5 Example of daily variation of the curvature radius – 21st June

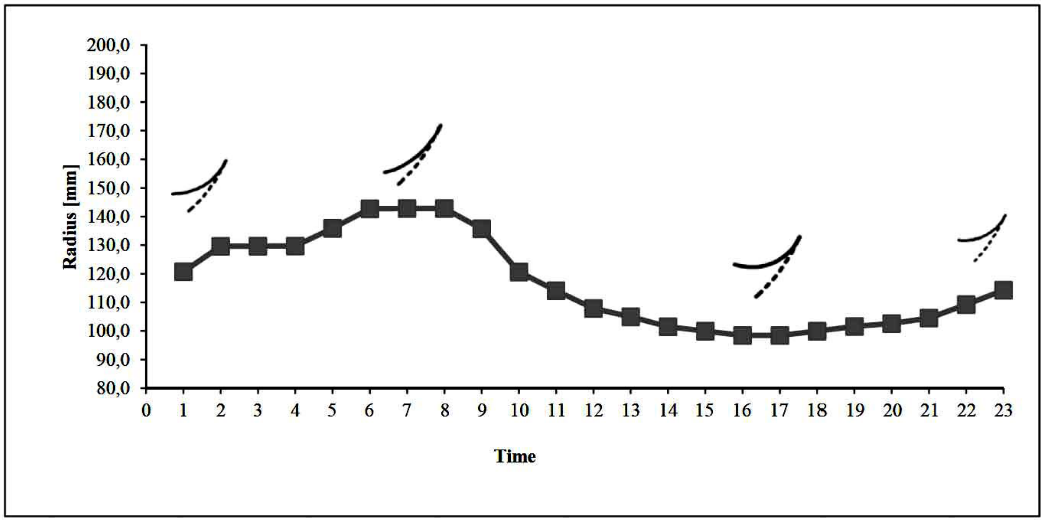

FIG. 6 Example of daily variation of the curvature radius – 21st September

The daily behaviour of the lamellae was also analysed. Using the formulae proposed by Holstov et al. (2015), and assuming that the HMs can adapt instantly to the climate conditions, the curvature for each hour of the day was calculated. From the analysis carried out, it can be noted that the lamellae are in a "closed" configuration overnight and the associated bending movement increases in response to solar orientation over time. In this regard, the component shows a dynamic behaviour that allows it to adapt to the sunlight height on the horizon, not only referring to seasonal changes, but also referring to a single day. In any case, over the course of a single day, the curvature remains rather unchanged for long periods of time, with a radius that, for example, varies from 98mm (12.00 am) to 94mm (6.00 pm) in June (Fig. 5), and from 107mm (12.00 am) to 99mm (6.00 pm) in September (Fig. 6).

Compared to the monthly average curvature used to verify the component's performance, in these periods the radius deviates by about 4-8mm, a deviation that is considered acceptable for the energy analysis. This was associated with the proposed lamellae of increased depth to the active layer (4mm) and their dimensional variations are decidedly slower than those studied by Holstov et al. (2015). The lamellae thickness is therefore adequate to achieve the monthly and seasonal performance targets (Mazzucchelli & Doniacovo, 2017) as well as to withstand weather actions.

Lastly, because the lamellae are subject to repeated deformation cycles, the connection between the active and passive layers should be sufficiently resistant to transfer the shear stress between the two layers, but also flexible enough to bend repeatedly without damaging themselves. For this particular use, an epoxide adhesive was chosen.

4 PHOTOVOLTAIC LAYER AND ENERGY ANALYSIS

The energy capture layer surface consists of photovoltaic modules. Among the currently used PV modules, the most efficient are the mono- or polycrystalline types. However, these types of module can't be used in the proposed system because of their rigidity, which would prevent the lamellae from changing shape to follow the dimensional variations in tracking the sun path. Hence, flexible solutions include thin amorphous silicon film and organic photovoltaic cells. Both have lower efficiency in comparison to crystalline silicon, but they perform better in diffuse light conditions and have an associated increased life cycle sustainability (Tress, 2014; Mazzucchelli, 2013). For this application, thin film photovoltaic cells (0.2 mm thickness, with a weight of 0.28 kg/sqm) were chosen. They can be easily fixed by adhesives and it is even possible to fasten or rivet them to the most varied material surfaces. These cells are embedded in two ethylene tetrafluoroethylene (ETFE) films (Mazzucchelli & Doniacovo, 2017). In order to evaluate the performance of the component, three lamellae shape configurations, covering a surface of 60x75cm, were analysed (Fig. 7):

- rectangular 15x60cm, organised in parallel rows;
- rectangular 15x10cm, organised in parallel rows and with an offset of half their height;
- rhomboidal 15x15cm, organised in parallel rows and with an offset of half their height.

Geometry façade form lamellae were independently modelled using the software, Rhinoceros 5. To evaluate curvature surfaces (as described in Section 3), the incident solar radiation values on the different lamellae configurations were compared with those obtainable with respect to a vertical surface and a flat lamellae configuration with a fixed inclination of 43° with respect to the vertical plane (see Fig. 8). This inclination value represents the average of the optimal values during the summer and the winter solstice in Milan.

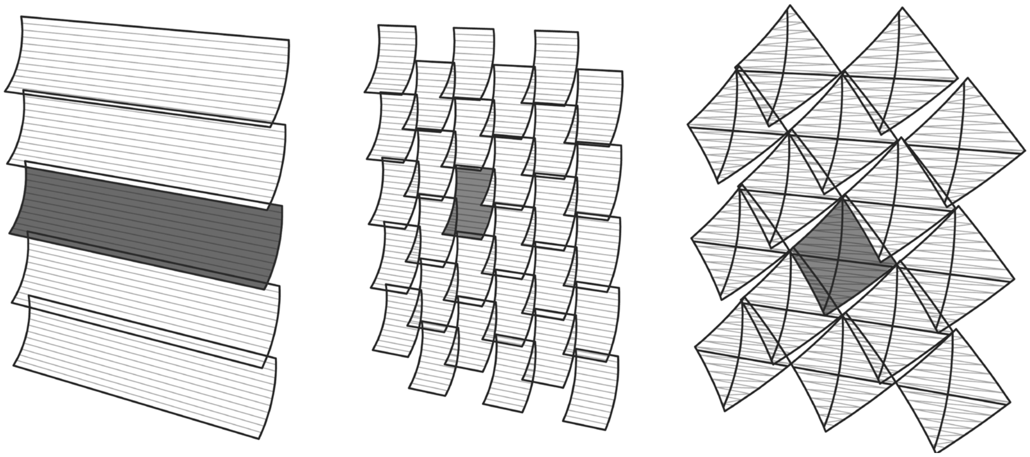

FIG. 7 Lamellae configurations: rectangular 15x60cm, rectangular 15x10cm, rhomboidal 15x15cm. The dark lamellae are those which were analysed.

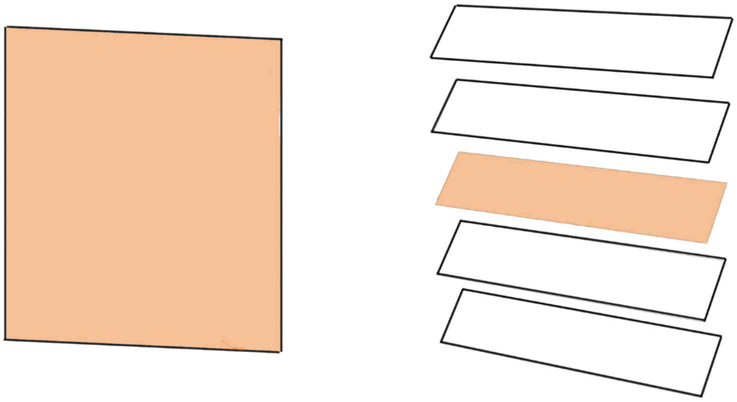

FIG. 8 Lamellae comparison models: vertical surface (on the left) and flat flakes with 43° inclination

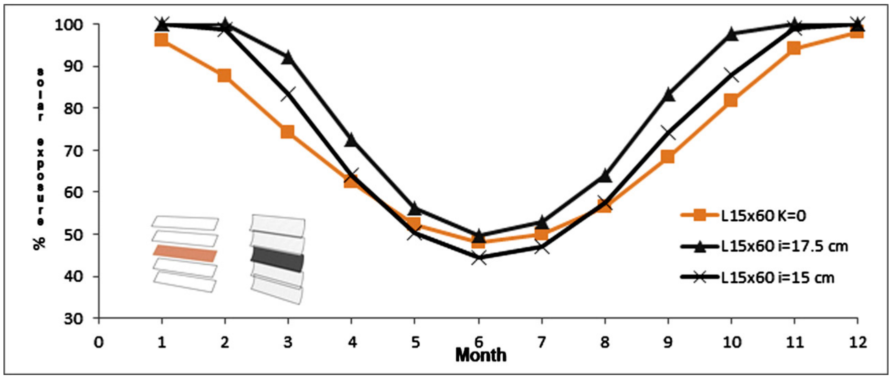

FIG. 9 Percentage of lamellae area exposed to the sun monthly. The effect of the adaptive layer can be noted.

The Rhino models were imported into Autodesk Ecotect Analysis to calculate the incident solar radiation and to study the self-shadowing effect in the different lamellae configurations. The first analysis studied the shadows in order to choose the optimal shape of the lamellae and the optimal distance between rows. Through the 'Shading Analysis, Overshadowing and Sunlight Hours' options, the modelling was set for a specific period according to daily average radiation values. Subsequently, the calculation was extended to each month, taking care to associate to each month the corresponding lamellae monthly average curvature.

From the performed modelling, it's possible to note (for example, in Fig. 9 15x60cm lamellae) that in all configurations solar radiation exposure is higher during winter, due to the low solar declination, and it decreases as it approaches the summer solstice, when the sun is at the highest point on the horizon. This is due to the shadow zone in the area close to the substructure. The lamellae that capture more solar radiation are those of 15x60cm in size, whose solar exposure improves greatly if there are spaces of 17.5cm between rows (Fig. 9). The 15x15cm lamellae indicate good performance in terms of the solar radiation capture to orientation. However, they cannot be separated due to aesthetic constructive reasons (Doniacovo, 2016). Lastly, the 15x10cm lamellae show low performance when the rows are at a 15cm spatial configuration, while the behaviour greatly improves if the distance is increased up to 20cm.

A second analysis studies incident radiation on the different lamellae configurations. Through the 'Incident solar radiation' tool, the modelling was set for a specific period. The calculations related to each month, combining the corresponding lamellae curvature. Through values obtained for each infinitesimal analysed surface, an average of the obtained values was calculated. This average was applied to the entire surface of the lamella. The results show that the 15x60cm lamellae with a 17.5cm distance between rows increases the capacity to absorb solar radiation by 14%, when compared to the hypothesis of a vertical surface with the same orientation. The lamellae of 15x60cm in size and a distance between rows of 15cm provide a light increase (equal to 1.01%). However, 15x10cm lamellae show a decrease of 11%. Such a reduction in performance can be attenuated to the spacing of the lamellae rows with a distance of 20cm or 25cm. In these cases, the increase in performance is 4.89% and 17% respectively, but the 25cm distance configuration is not recommended for aesthetic reasons (because the substructure is visible). Lastly, the 15x15cm lamellae show a slight decrease in performance when compared to a vertical PV surface. However, it is not possible to change the distance between rows for constructive and aesthetic reasons. Fig. 10 indicates incident solar radiation over a period of one year by a demonstrator square meter prototype with variations in differing lamellae typologies. The value for the vertical surface is also shown to allow a comparison among the different configurations.

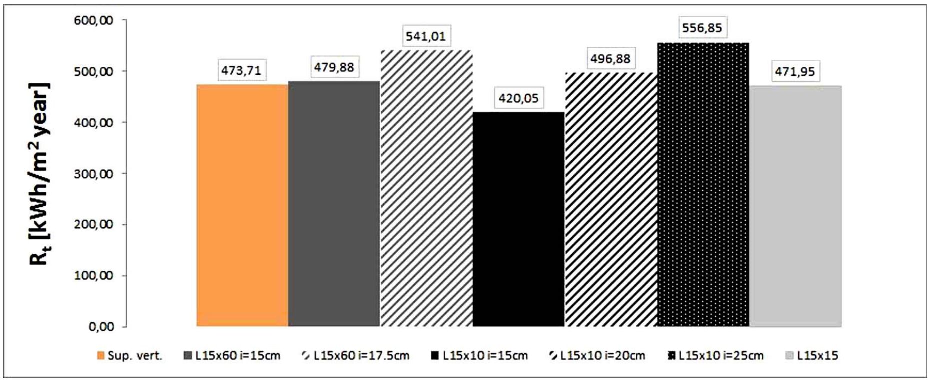

FIG. 10 Incident solar radiation on different kinds of lamellae configurations

The PV energy production analysis (photovoltaic cells efficiency: 8%, balance of system efficiency: 85%) was carried out on two types of lamellae only: the 15x10cm and the 15x60cm ones. First, the case of the15x60cm lamellae was considered. The results obtained are shown in Fig. 11. Increasing the distance between rows up to 17.5cm, the energy production shows an 8% increase when compared to a vertical surface case and a 7.1% increase when compared to the configuration with a distance of 15cm between rows (Mazzucchelli & Doniacovo, 2017). Considering the 15x10cm lamellae, the energy produced does not reach the values obtainable using a vertical PV panel but, considering a distance of 20cm between rows, it is possible to increase the performance by 8.19% when compared to those of 15cm. In this last case, a thin PV foil that is also installed on the vertical surface above the lamellae is considered (see Fig. 13). By further increasing the distance between rows, there are no benefits in terms of energy production and, indeed, the energy produced is lower than that of the 15cm distance configuration.

In conclusion, the higher performance increment is obtained when using 15x60cm lamellae, with a distance of 17.5cm between rows.

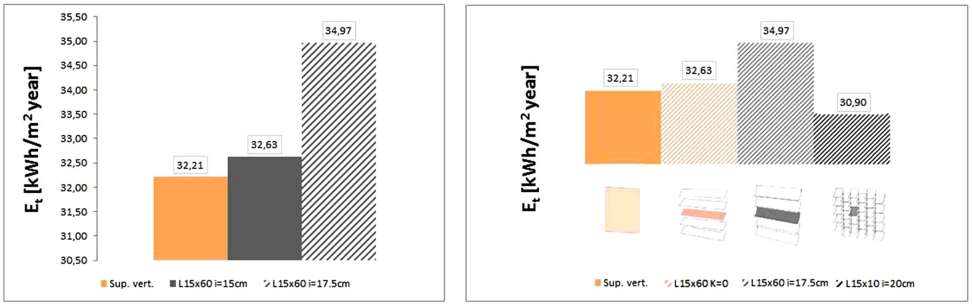

FIG. 11 Energy produced for 15x60cm lamellae (on the left) and comparison between different kinds of lamellae (on the right)

5 BIPV COMPONENT APPLICATION

This solution proposal can be easily integrated into the building envelope and it's applicable at a large-scale level. This implies that cost and technological complexity must be as optimised as possible. The BIPV adaptive lamellae can be installed on a wood frame to create modular panels that can be used as façade cladding (Fig. 13 and Fig. 14) or as a sun-shading system (Fig. 15). The basic preassembled module consists of a wood perimeter frame and transoms, where the lamellae are fastened with screws. Concerning the union between the lamellae adaptive layer and the photovoltaic one, steel male-female screws are used (Fig. 12).

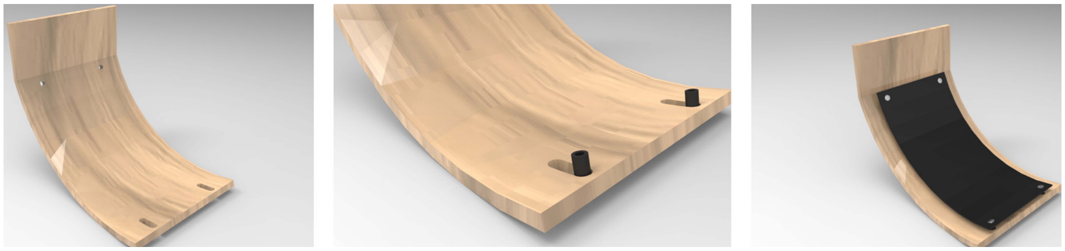

FIG. 12 Lamellae adaptive layer (15x10cm) with fixing holes (on the left). Detail of the slotted holes and the neoprene gaskets (on the centre). Lamellae with adaptive and photovoltaic layer (on the right)

The assembly between the adaptive and the photovoltaic layer allows for adjustment of this last one to the shape taken by the self-adjusting lamella. For this purpose, slotted holes on the lower part of the lamellae have been provided. The male-female screws, inserted into special cylindrical neoprene gaskets, can slide in these holes when the lamella modifies its shape. The position and the different shape of the holes, where the fixing screws are inserted, is illustrated in Fig. 12. This connection allows a 0.5cm back-PV cell ventilation, which also helps to reduce their overheating.

FIG. 13 Renders of 15x10cm (on the left) and 15x60cm lamellae panels (on the centre). Wooden panel substructure detail (on the right)

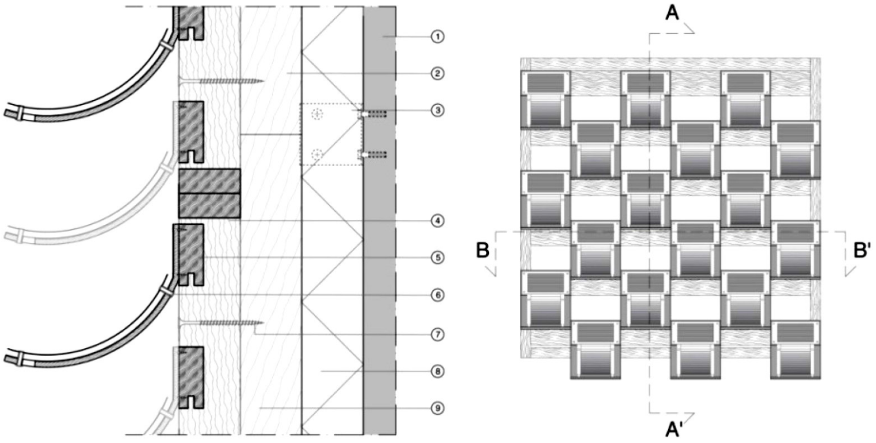

FIG. 14 Detail of the 15x10cm lamellae panel (on the left) and front view of the 60x75cm panel (on the right)

In the sun-shading configuration (Fig. 15), the panels consist of a wooden framework (40x100mm in section) and intermediate transoms, where the lamellae are fastened. In the case of mobile sun-shading, the handling system is made up of steel guides anchored to the upper floor, where sliding carriages, connected to the panels, are inserted. The panels are connected to reels with a manual rewind mechanism with a torsion spring, to move the panels safely and ergonomically. Lastly, the electrical wires that connect the PV cells are inserted into special grooves of the wooden frame profiles.

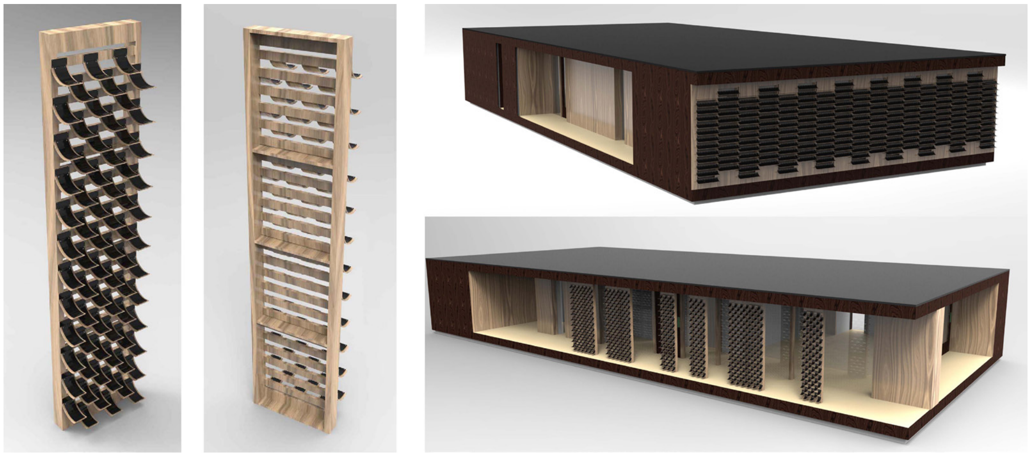

FIG. 15 Example of BIPV adaptive lamellae integration as façade cladding and as a sun-shading system

6 CONCLUSION

The presented research progresses the design of an adaptive BIPV façade system to be able to self-orientate the photovoltaic layer in an intrinsic way and without the need of any energy supply. To reach this goal, thin film solar cells are coupled with HM layers that respond to changes in environmental humidity by modifying their own curvature. In winter, the hygromorphic layer is designed to be almost vertical, so that the solar cells can receive direct sunlight in a favourable way. In high solar radiation conditions, the lamellae naturally present a higher curvature, orienting the solar cells so as to maximise the production of photovoltaic energy. This solution furthers advances other promising features, including the use of a natural adaptive material such as wood. The energy analysis shows that the lamellae adaptability leads to an increase in the energy production through optimal studied configurations (e.g. the 15x60cm one), when compared to a vertical PV surface or to flat PV tiles with fixed inclination. In this regard, the next step of the research will be the further optimisation of the system geometry and the realisation of a full-scale prototype to verify the model results, as well as to test the lamellae durability, the lamellae repeated deformation cycles effects, and the effective delayed response incidence on the expected performance. Moreover, if the climate does not guarantee significant daily and seasonal changes of relative humidity, the use of different kinds of wood or HMs, reacting to different relative humidity levels, could also be considered and tested.

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