

Research for Development

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# Lightweight Energy

Membrane Architecture Exploiting  
Natural Renewable Resources



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# Research for Development

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Editors

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Renewable Resources



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# Foreword

Starting from the title, this book contains all the keywords the built environment is asked to deal with, to address more effectively the huge challenge deriving from the environmental emergency. “Lightweight” is a strategy to reduce the CO<sub>2</sub> emissions burden, “energy” is needed to run our activities, “membrane” reminds us of the crucial importance the envelope is more than ever playing on a building performance, “natural” recalls the newly re-emerging biophilia trend which moreover appeared of dramatic urgency in pandemic times, “renewable”, one of the pillar concepts of circular economy, “resources”, in other words what we extract, produce and exploit in a hopefully circular way to make our activities run and, finally, “architecture”: because ultimately buildings are intended and designed to be comfortable, healthy and beautiful.

How to analyse, develop and combine all these aspects? This is the challenge behind this book, which moreover describes an innovative approach for building products and solutions, with a special focus on ultra-lightweight materials and membrane structures.

As a matter of fact, the challenges, I mentioned, ask for a holistic integrative approach. The progress in addressing the climate issues, even adopting some sustainability strategies, has been barely visible so far. A different mindset is needed, implying the transition to a regenerative scenario for the built environment and the building industry.

Beside the design strategies, isn't a building anything else than an assembly of materials? Under this perspective, this is where most of the sustainability issues lie. Manufacturing companies are now called to a reconsideration and in most cases a radical transformation of their production processes, addressing the whole life cycle of their products. As the International Living Future Institute (ILFI) Living Product Challenge certification reads out, “What if products improved your quality of life and helped ecosystems thrive?” For that, research and continuous innovation, as well exemplified in this book are key.

To leave the fossil fuels era, which is hopefully the end goal the economic sector should pursue with conviction, a strategy towards carbon neutrality is to be adopted. This is where the solutions described in this book find a great relevance. Achieving

Zero Carbon buildings is again a matter of combining design strategies and materials in the most optimal way, to reduce the overall greenhouse gases emissions. From this angle, it is fundamental to reduce the products' embodied energy, which again depends on their characteristics, including their weight. This is where again the solutions described in the book find their place at the centre of the discussion.

The other global current hot trend is surely well-being, with a warning: well-being should be achieved without creating negative impacts on the environment. In other words: Are we able to guarantee a comfortable (biophilic, I would add) indoor environment, ensuring on the other hand a restorative or even regenerative scenario for our buildings, communities and cities? Are we able to design, build or renovate buildings with a positive handprint, which are fine for (human) beings as well for the environment? This is the challenge inside the challenge.

Once again, a smart, innovative, ground-breaking research approach might represent the starting point of a process able to ignite the mindset transformation of a new community of designers, manufacturers, builders and owners of the twenty-first century. This book will provide brilliant and informative insights into this direction.

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# Introduction

The term membrane in construction refers to a thin flexible layer able to carry tension, overturning the conventional relationship between self-weight and carried loads. In architecture, membranes are commonly associated with the diffusivity of light through ultra-thin layers and often also with the temporary building.

In the realizations of these recent years, we notice countless improvements in the membrane architecture's technology, and an increasingly wide number of engineering firms are mostly specialized in tensile structures. Despite the emerging needs of lighter and faster alternatives for efficient buildings, membrane structures still have a low market penetration compared to the wider predominant building technologies, as there are still two main barriers. The first is a cultural bias, as soft materials are hardly considered strong and durable to qualify an entire building. The second barrier is the lack of shared knowledge for designers on how to make an architecture built with thin membrane layers energy efficient.

Furthermore, due to the current energy resource crisis, it is shared evidence that it is no longer sustainable to postpone the extensive use of renewable energy technologies and the design of Nearly Zero Energy buildings. The effective application of these strategies to lightweight, membrane-based buildings needs special attention.

A question comes up from these premises: May both lighter-mass and lighter-energy design criteria effectively coexist and reinforce each other to enhancing the development of membrane tensile architecture?

The authors aim to propose the first nucleus of systematic knowledge on the behaviour of architectural enclosures and building envelopes made of translucent membranes and transparent foils, then focusing on the potentiality, the current limitations and future developments of using the resistant support of membranes as a means of interaction with external resources. Through an in-depth examination of the interactions between natural resources—water, wind and sun—and ultra-thin membranes, designers will be able to understand how current and upcoming technologies bring very close the time when we can create the building enclosures as biological skins: without seams, a whole but with many performances, and always able to react appropriately to external conditions.

The book aims to explore membrane materials as a means of translating natural and renewable resources into a novel kind of architectural skins, more flexible, dynamic and reactive ones. The book also aims to demonstrate that, besides the attitude of continuously refining the overall membrane systems' efficiency, it is time to calibrate a set of environmentally sustainable design strategies, specific for these ultra-thin and extremely reactive to the climate kinds of architectural skin.

After the **first chapter** in which the authors give an essay of the present technologies and imagine a development path for membrane structures intended as an interactive and intelligent skins for the tomorrow architecture, the theme of designing in a more energy-saving way, making the best use of renewable solutions, is in the **second chapter** for the first time systematically treated in relation to lightweight building systems and tensile membranes.

As the coated textiles and transparent foils use has been recorded growing as enclosures for insulated buildings, the authors underline the need to explore the dual concept of lightweight and light-energetic building. The thin and flexible surfaces of textile architecture represent a frontier application nowadays to trigger a change in the designing approach of all buildings. In the **third chapter**, therefore, all the main design strategies are considered to obtain the efficiency of this particular type of construction with ultra-thin skin. Here the authors start a cross-cutting and combined exploration of the climate-based design methodology and strategies. Both active and passive systems are investigated, referring to alternative productive resources like sun wind and water, for energy storage and interiors' well-being. Furthermore, attention is paid to the opportunity to combine the use of multiple natural resources in the definition of innovative membrane architecture. The exploitation of water and wind resources, which can be adequately captured through the meshes of fabrics, is considered particularly relevant and innovative. In dealing with this topic, the authors want to convey their awareness that knowledge on this topic is currently being transferred from real applications conducted on other building technologies, while further experiments, supported by accurate evaluations of the peculiarities of the construction material, must be urgently oriented on membranes and fabrics. Consistent with this intention, the authors present some case studies and ongoing research projects in the second part of the book.

Understanding the energy behaviour of membranes and foils used as building envelopes therefore passes through another fundamental topic of discussion in this book, namely the integration of flexible photovoltaic in membrane construction systems. It seems an obvious fact, but it should be emphasized that a membrane skin of the building moves continuously under the effect of the wind, and therefore, also the photovoltaic cells integrated into this surface must be able to maintain their performance in this continuous swaying of the structural surfaces. The radiative effect of the sun on the ultra-thin layers of fabrics and transparent sheets is considerable, and therefore, the question clearly arises: Why not to exploit this solar energy directly through the surface of the membrane? Another evident fact is that the industrial processes for the production of membranes for architecture are the same that make it possible to encapsulate the materials used today to create flexible photovoltaic cells. Starting from these assumptions, in the **fourth chapter** that closes the first

part of the book, the authors present the state of development of flexible photovoltaic technology and it is still too rare application in the field of membrane structures.

After an in-depth framing of the methods and approaches of how to design a new kind of lightweight and energy-lighter building according to the entire life cycle and in relation to the key performances of textile architecture and membrane structures, the second part of the book shows case studies of basic and applied research and industrial development, which have seen the authors engaged in recent years, experimenting with new approaches and new forms of energy lightness for an increasingly dematerialized architecture.

Four main research and development paths are presented that seem mostly in line with the adaptability needs of contemporary architecture and with the eco-efficiency constraints of lightweight construction. Through the different case studies, the authors return to discuss the issues addressed theoretically in the first part of the book, this time experimentally applying the eco-efficiency evaluations to the new results emerging from the various case studies.

The first two—the SOFT-PV project from the **fifth chapter** and the TIFAIN project from the **sixth chapter**—focus on those advances in facade materials and photovoltaic systems applicable to membrane architecture based on fabric and transparent sheet. In these two experimental cases—a basic research the first and an industrial development research the second—the multi-disciplinary approaches that typically drive innovation in the construction sector are highlighted. The life cycle assessments of a membrane-integrated-organic-photovoltaic skin and of a curved transparent envelope that can be integrated with various generations of photovoltaic cells are then explained step by step. The goal of optimizing daylighting, energy efficiency and energy storage in multilayer transparent facades is at the heart of these two case studies.

Subsequently, in the **seventh chapter**, the authors focus on another frontier theme for the development of ultra-light architecture, namely the efficiency of architectural textile collectors for the collection of dew and fog, thus being able to exploit a renewable water resource that is usually not used.

The last case study, presented in the **eighth chapter**, concerns a demonstrator pavilion, that the authors contributed to design and build, precisely with the intent of experimenting—thanks to a learning by doing approach—the complexity of the design theme that is at the centre of the discussion in this book: designing for the urgent achievement of an energetic and environmental lightness and not just with the weight and the shape in mind. Much further developments could arise from that the first transportable building prototype and its filtering skin, presented in the last chapter. Thanks to that case study, the authors are willing to start a systematic review of the knowledge on the internal comfort of ultra-lightweight skins and membrane architecture in general. Eventually, thanks to this last case study, the authors believe that this even small but meaningful quantum of experimental knowledge can have a great value in what is easily applicable to countless situations, in which similar construction technology is applied today, consequently increasing the overall quality of the built environment.

The ultimate goal of the book is that from these emblematic cases of lightweight and light-energetic architecture, suggestions for improvement can also be drawn for conventional and massive constructions, in order to obtain a lighter and more sustainable use of all forms of energy on our planet.

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# Towards the Smart Filter



Alessandra Zanelli and Carlotta Mazzola

**Abstract** The chapter aims to introduce the reader and the designer in the field of membrane architecture, presenting its potential and future challenges. In particular, the chapter presents some innovative applications of membranes in facades and roofs, in order to suggest scenarios of further developments of the building skin, such as light and heat filters, active and reactive systems. The chapter continues with an investigation into the potentialities of the various materials available today to filter light into membrane skins and to optimise the overall efficiency of an architecture built with membrane-based tensile structures. Eventually, promising ideas on how to increase the user's interactivity with a new concept of soft, membranous building envelopes are presented.

**Keywords** Membrane architecture · Lightweight envelope · Transparency · Translucency · Comfort · Interactivity

## 1 Membrane Architecture, Beyond the Translucency

Membrane architecture refers to a thin flexible layer able to carry tension which is pre-stressed either by pulling the membrane at the edges or blowing in air under pressure. If compared to a traditional building system, membrane architecture appears dematerialised, due to its lighter weight, that combined with its mechanical strength makes it a dynamic filter, thanks to the intrinsic reaction of fabric to the external building conditions or user's requests.

Unfortunately, this unconventional architecture is not yet fully exploited from the point of view of linguistic, aesthetic and architectural potential, as designers find difficult to fully understand the overturned relationship between dead load and carried loads that characterises these lightweight membrane architectures compared to those set on traditional static schemes.

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Membrane architecture is currently made of technical textiles and/or polymeric foils. They have unique properties that conventional building materials do not possess simultaneously: low weight for square metre, flexibility and the ability to take various shapes under tension, starting from lightweight and very thin components.

Within this chapter, those architectures made of ultra-thin, permeable to light membranes, are analysed, highlighting the dual aptitude of fabrics and foils to be, on one side, natural light diffusers and, on the other side, artificial light projectors.

The lightweight membrane-based envelope appears dematerialised: it is no longer a barrier between interior and exterior, characterised by an opaque part and a transparent part, but rather a dynamic filter of internal–external flows, capable of responding to the needs of well-being, sustainability and energy saving and able at the same time to express architectural language.

Homogeneity of the membrane-based translucent envelope leads to the research of unusual façade concept, in terms of distribution of solar radiation both in lighting and thermal transfer (while providing almost the same solar factor and thermal resistance) and imply a better control of the indoor thermo-optical comfort of occupants in different comfort situations. However, the thermo-hygrometric performance of textile-based envelope can be hardly compared to those of opaque building materials and high-mass building systems.

Fabrics and foils useful for the current membrane-based architectural envelopes, due to their minimum thickness, have almost irrelevant thermal conductivity, inertia and insulating properties (Alongi et al. 2021; Cremers 2010b, a). That results in a poor ability to dampen the effects of external temperatures fluctuations: any temperature change on the outer layer of the membrane is linked to an almost instantaneous change on the inner surface. In the next paragraph 1.2, we will discuss the best design strategies to overcome this characteristic of membranes, which could represent a problem for their application in enclosures and insulated buildings.

Membranes have an unprecedented relation with the natural light that enables the designer to create new transparency-translucency gradients to envelope the architectural space. Membrane architecture can be configured as a daylight filter, capable of transforming itself into a night light object, from which derives the particular designation of smart filter (Sobek 2016; Cremers 2009; Cremers et al. 2016).

The semi-transparency or translucence of the membranes is one of the most interesting qualities of so-called textile architecture nowadays and is undoubtedly an aspect that cannot be neglected in the design process; sometimes, it is exactly this aspect, together with the lightness, to orientate the designer's choice towards the choice of the fabric as main building material.

If well treated, light permeability can offer significant advantages, such as reducing artificial lighting and even saving energy. Thanks to the luminous radiation that can penetrate inside, through the thin textile skin, direct and indirect heat is gained. To obtain significant luminous quality in interiors is a necessary in-depth knowledge of light transmittance's degrees, of the different textile and non-textile fabrics currently available on the market. Moreover, it is essential to take into consideration the luminous performances together with the thermal-hydrometric and acoustic ones, from the first stages of the development of the project.

The natural daylight hits the membrane skin and is transmitted and diffused inside the building, so the surface of the lightweight envelope appears from the interior as a luminous continuum, characterised by a variable intensity, depending on the orientation of each part in relation to the sun.

In other words, the interiors of these architectures always appear dynamic to the light; system of cover and/or envelope of limited thickness (from a 100 to 300 hundred of microns of transparent foils up to 1–2 mm of translucent coated fabrics) generates unusual lighting conditions and it affects the design of visual comfort. In general, it should be taken into account that most of the membrane products for architecture have a high light diffusion effect, since solar radiation is widely transmitted and reflected across their inner surface in the direction of the underlying environment.

In the specific case of full height tensile structures systems, it is necessary to avoid an excessive uniformity of inner light perception, for example, by providing areas of different luminous intensities, such as glazed inserts, textile false ceilings and multi-layer membrane parts.

Advances in materials science lead to the development of ever-more transparent materials for the building envelope, with solar factors and thermal resistance similar to glass, encouraging new design approaches to the building skin (Harvie 1996; Campanella 2010).

By making wise use of materials, lightness can also lead to rarefaction of the architectural envelope and to the construction of an increasingly dematerialised division between interior and exterior and allow an unprecedented control of the light and the quality of the space. Plastics give a sense of dematerialisation of the architectural space they define.

The use of membranes as a system allows a unique control of the light and a remarkable lightening of the envelope. The combination of opaque/transparent walls is overcome, offering unprecedented shades of transparency and translucency that surround the architectural space and create a relationship with new natural light. Nowadays, we can speak about the binomial performance of transparency/translucency, where the first refers to an unobstructed view through the materials and the second one to a diffuse light permeability (Gürlich et al. 2018).

Innovative membrane products (fabrics and foils or films) are growing on the market, extending the range of possibilities for creating light architectures, characterised by different degrees of transparency/translucency.

The transparency of these ultra-lightweight architectures should reveal essentiality, economy, ecology and a sort of designer's coherence, which typically only arises from a deepen materials' knowledge. In these new architectures, transparency not only communicates an aesthetic quality, but represents the honesty and clarity of the design process that created the architecture.

In the light of this overview on the so-called textile architecture, the chapter is unfolding into three main objectives. First of all, it is important to frame the potential of the different textile and polymeric materials available on the market today to filter natural light through a membranous skin. Furthermore, we want to address the usability of a textile membrane used as an overall inside-outside skin of the building, supporting the work of the designer who wants to evaluate the advantages and possible

criticalities in the use of a textile screen as the main vehicle of flows—bright and energetic—between the outside and inside of the building. Finally, the chapter aims at opening an updated discussion on how to make the most of the textile filter to obtain an energy-efficient building.

## ***1.1 Types of Membranes for Today's Architecture***

Architectural membranes include a wide range of materials but polymers in the form of fabric or extruded foils are the most used (Schiemann and Moritz 2010). Besides the low weight of the materials themselves (i.e. around 0.2–1.4 kg/m<sup>2</sup>), the good weathering and load resistance and low thermal conductivity of the majority of polymers and fibre-reinforced polymers make them suitable for lightweight building system applications. Polymeric membranes and foils can be used as building envelope and load-bearing structure at the same time, and for this reason, they are generally called “structural membranes” or “structural skins” (Forster and Mollaert 2004a, b).

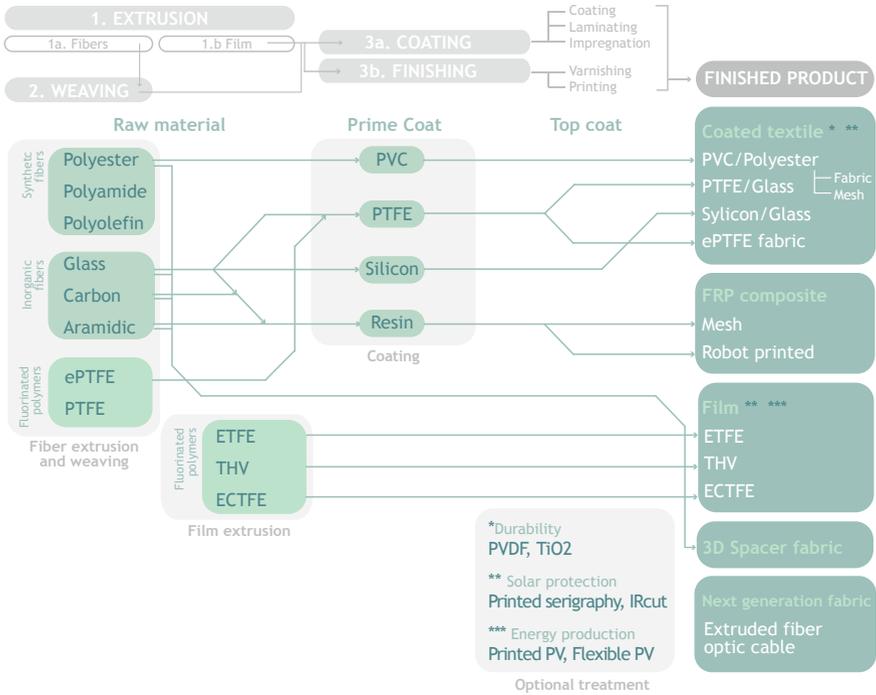
Textile-based or transparent foils-based structural membranes often prevail over other construction systems due to its very low weight (i.e. around 0.2–0.5 kg/m<sup>2</sup> for transparent fluor-polymer systems up to 0.5–2 kg/m<sup>2</sup> for multi-layer textile membrane systems and for extreme loading situations). Fibres and polymer granulates (Fig. 1) can be combined in different ways, creating custom-made materials, opening a wide range of potentiality to designers. Actually, this variety has not yet been fully exploited till now, as much as 90% of membrane structures are made of a very limited range of families of flexible composites (coated fabrics) and an even more limited range of transparent foils (fluoropolymeric extruded films).

Within the coated fabrics, we can mention:

- PVC/Polyester, mainly used in form of waterproof sun shading systems (mesh), as well as in the facade refurbishment and in seasonal and demountable sport halls;
- PTFE/Glass, mainly used for permanent covering systems and durable and large-span structures;
- Silicon/Glass, produced within a few years ago, that aimed at combining the flexibility of the coating with the strength of glass fibres, and overcoming the typical foldability issues of PTFE/Glass composites. Silicon/glass textiles are not currently in production.

Within the Fluor polymeric foils, we can mention produced by roll-to-roll processes starting from fluoropolymer granules:

- ETFE, the most used transparent high performative extruded foil for membrane architecture today; it is currently used for transparent pneumatic cushions, greenhouses and a wide range of alternatives of glass facades (Lamnatou et al. 2018);



**Fig. 1** Fabrics and composite materials available for architectural use. The finished products are related to their production chain (in brown). Performances can be improved by adding an optional treatment to the semi-finished product. (Edited by the authors.)

- THV, with an excellent chemical resistance and clarity, but with very few application in indoor architecture, due to its less tensile and tear strength;
- ECTFE, a fluorinated polymer with an outstanding transparency, UV resistance and light transmission, all qualities that seem to make it suitable for the architectural application, but currently not jet used in this field (Toniolo and Carella 2016).

In a further classification, we can distinguish a new family of membranes, where the fabric and the coatings are made starting from the same polymeric material. This means that the final flexible membrane product would not be a composite, but a mono-component product, easier to be recycled at the end of its service life. In this last category, for now we can mention:

- e-PTFE, on the market with the name of Tenara® fabric, created by the extrusion of PTFE yarns and then finished by PTFE coatings; it is the only mono-component coated fabric currently on the market of textile architecture.

The last-born membranes for architecture are meshes, again a kind of flexible composite products, but created thanks two different production processes:

- STFE, a new flexible highly transparent composite recently developed by Serge Ferrari Group, with the aim to provide structural strength for large free span architectures; it is a polyarylate mesh made of high tenacity yarns co-extruded with fluoropolymeric coatings, and then, the mesh is fully covered by a transparent hybrid fluoropolymeric film;
- I-MESH products, a new family of laminated meshes, where the lamination process of laying high strength and long fibres (carbon, basalt, glass fibres) over a thermoplastic resin has been borrowed from the nautical sector to allow the creation of bespoke membranes, varying the mesh densities (Ottone et al. 2019).

Further optional treatments are applicable to the above-mentioned textiles, as well as on transparent foils, in order to achieve specific performances in relation with the functionality of the building systems.

Various finishing coatings and prints might increase the optical and aesthetic performances, as well as their clean-ability and durability. For example, the TiO<sub>2</sub> (Titanium dioxide), compatible with the majority of fabrics now available on the market, makes the surface of the membranes self-cleaning, improving its performance of resistance to air pollutants over time.

About transparent foils, the IR-cut finishing layer applied on ETFE is promising a better performance in solar shading (Cremers and Marx 2016), while the photovoltaic printing is still the most challenging surface treatments applicable on membrane architecture nowadays (Li and Zanelli 2021).

The technological transfer from automotive and nautical fields allows an ever-growing innovation in the field. Precisely, this seems to be the direction in which the new research on lightweight fabric architecture will have to go, in order to obtain more efficient and performative building materials, while maintaining awareness towards the environmental issues at the same time.

## ***1.2 Membrane Architectures as a Dynamic Filter of Light***

The examples of dynamic filters presented in the following pages confirm the continuous progress in the production technologies of fabrics and foils.

The frequent transfer of innovative technical textiles from other sectors to architecture is the driving force behind all current experiments and achievements in this field of application.

The designers of the case studies presented below may not be necessarily specialised in textile membranes and their structural performance, but certainly they are very sensitive and careful architects for defining the qualities that the smart filter must have and they are curious and versatile in the research and experimentation of different fabrics and foils materials to concretise their idea.

This is evident in the case study of the floating pavilion in Tokyo (Fig. 2) where a mix of fabrics and foils and rigid materials has been combined with the aim of

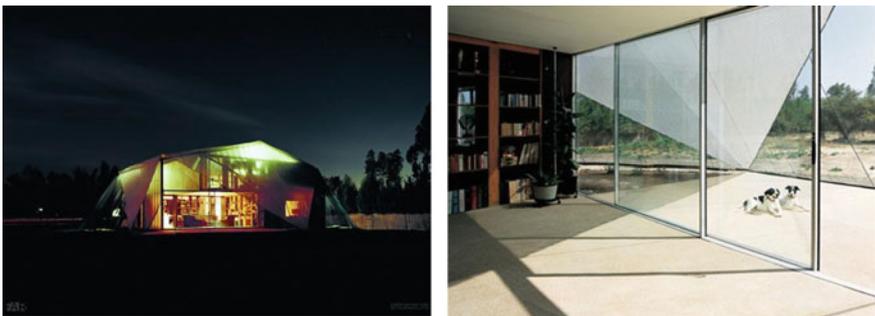


**Fig. 2** Floating pavilion Echigo-Tsumari, Fujiki, Tokio, Giappone, 2007 (Source Ryumei Fujiki)

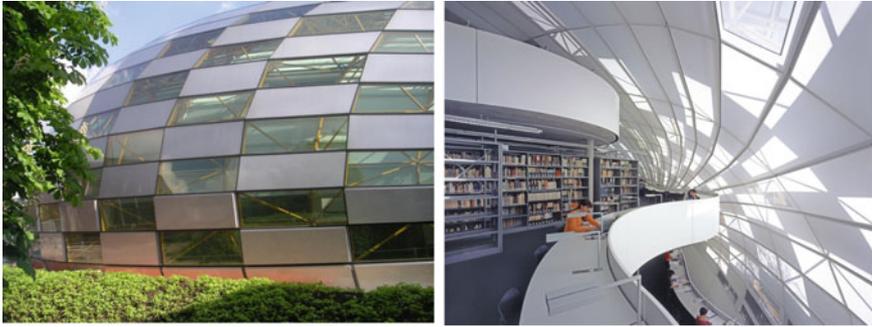
creating an inside suggestive path for visitors and of great visual impact during night events, from the outside.

Nowadays, more and more designers are experimenting with the combination of different textile materials available to create unusual atmospheres, even in housing projects, which is the sector more resistant to material and technological innovations. For example, in the “Wall House” (Fig. 3) the whole enclosure is made by membranes usually used in agriculture that have been implemented in their performance through sophisticated processing during packaging. Walls from being irremovable barriers, in this project, are transformed into sinuous shading systems and become a flexible visual and light filter that can be modified by the inhabitant.

In other cases, for example, in the envelope of University of Berlin’s library (Fig. 4), the outer layer creates a continuous façade with opaque and glazed parts, while the inner layer is made by textile material. Here, the main objective of the membrane is to create a diffused internal light suitable for reading and concentration needed by the library users. Acoustic performance has been improved by micro-lighting perforation of the internal fabric, while transparent ETFE inserts somewhere allow the outside visibility and, therefore, the time’s flow perception.



**Fig. 3** Wall House, FAR frohn and rojas, Santiago de Chile, Chile, 2007 (Source Photos by Christobal Palma)



**Fig. 4** University of Berlin Library, Foster, Berlin, Germany, 2006 (*Source* Foster and Associates archive)

The designers had to develop innovative technological devices in the envelope system, starting from an integrated study of light, thermal-hygro-metric and acoustic performance, which could guarantee the transformability of the smart filter in different seasons and along the day.

The use of semi-transparent coated fabrics has always suggested to designers the need to insert transparent parts to ensure a bright and perceptive comfort appropriate to the staying of people inside covered spaces by textile systems. With the introduction of completely transparent ETFE film as building material, the problem of designers today appears substantially different: now a shading system is needed to contrast the overheating of the translucent envelope, due to the excess of direct solar radiation. In fact, when the function of the project requires a large amount of solar radiation, it is possible to use a single film of ETFE, that is transparent up to 97% and permeable to UVA rays up to 88%. Besides in all other design occasions of light filters, the use of ETFE involves the industrial treatment of the film with screen prints and UV screens, to be placed on the outer layer of the vertical closing component or cover. Finally, a printed ETFE membrane as the outermost layer of a conventional transparent glass façade may become a double barrier for both functions of wind protection and overheating screen.

Recently, thanks to widespread regulation about the importance of solar shielding in the energy balance management of buildings, an increasing number of designers are considering the use of smart filters, stimulating the creation of innovative solutions.

Newsworthy is the case of American Embassy in London, a glass cube swathed in shimmering sails of semi-transparent film of ETFE, that together with the glass reflect the natural lighting colours effects (Fig. 5).

Another example is the San Mamés Barria Stadium in Bilbao (Fig. 6), in which the façade is characterised by a continuous series of rectangular elements in torsion that recreate the effect of sails in motion. These elements are aligned on each floor, except for the ground floor. Moreover, during events an artificial lighting system creates ever-new configurations.



**Fig. 5** American Embassy, Kieran Timberlake, London, Great Britain, 2018 (Source Photos by Richard Bryant)



**Fig. 6** San Memés Barria Stadium, IDOM, Bilbao, 2014 (Source Photos by Aitor Ortiz)

With the main function of the wind protection, an outstanding project of double façade system was developed for the Unilever headquarter in Hamburg (Fig. 7). The designers developed an innovative solution of double skin, where the outer layer is made of ETFE-framed foils, while the inner layer is a glass curtain wall integrated to an aluminium brise-soleil solar shading system. The ETFE-framed panels create an original architectural pattern of the building skin, while their main functionality is the reduction of the wind speed effect on the aluminium and glass inner façade, without decreasing the level of natural light achievable into the offices.

After having presented the most reliable and durable architectural and structural membrane products (textiles and foils) available on the market today, in this paragraph we have not deliberately delved into the most important realisations, that are well known and traceable through the information made available both by producers, manufacturers and by the international network TensiNet, which is involved in the promotion of scientific research and industrial development of this type of tensile membrane buildings in Europe (Forster and Mollaert 2004; Campioli and Zanelli 2009; Llorens 2015).



**Fig. 7** Second skin in transparent membrane of ETFE foils for the Unilever Headquarter, Hamburg, designed by Behnisch Architect and formTL Engineering, 2010 (*Source* Photos by Behnisch and formTL)

The examples above-mentioned are intended to show how wide is the action ground of the designer, who today can take into account the following paths of incremental innovation.

On the one hand, it is possible to innovate membrane architecture by sourcing textile materials, also from other application sectors (filtration industry, agriculture), and trying to enhance the translucency of these fabrics.

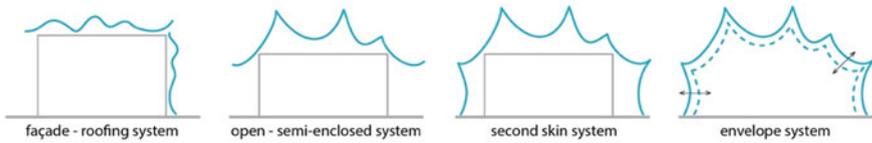
Another way of experimentation is to couple the membranes of ETFE or coated fabrics to other materials, thus developing new concepts of unconventional skins, as the above-mentioned case studies.

A further daring way of experimentation is to make the membrane layer of the building active, or interactive: we will talk about this aspect in the last paragraph of this chapter.

Actually, the biggest challenge is the subject of the next few paragraphs: how to achieve comfort through the most reliable range of textile materials available today? The demand for light and at the same time performing envelopes comparable to other conventional massive solutions is increasingly widespread.

## 2 Well-Being of Enclosed Spaces Made of Membranes

Thanks to the flexibility of the materials used, structural membranes can take various shapes and they can be used for different architectural applications, such as coverings for open spaces, façade, roof, second skin or to form homogenous textile buildings (Zanelli and Campioli 2009). Innovative polymeric foils, textiles and non-woven products are increasingly widespread on the market, extending the range of possibilities to create lightweight architectures characterised by unique shapes and degrees of transparency that traditional materials do not possess (Fig. 8).



**Fig. 8** Lightweight tensile building envelope: variety of arrangements and building applications (Source Mazzola 2020)

Structural skins promote a new concept of enclosure that no longer delimits the spatial zone simply through a façade or a roofing system as in conventional buildings but it is defined by a wrapping envelope. The lightweight flexible envelope provides a viable alternative to conventional building systems because it promotes the reduction of resources and materials used, and it allows greater substitutability of the building components and system adaptability to changing context conditions and user requirements (Schmid et al. 2015). The tensile envelope—interacting with both exterior natural energy flows and the interior building environment—takes on a new meaning of dynamic boundary and filter between inside and outside since, as the human skin is affected by dynamic processes from both sides (Knippers et al. 2011). In this perspective, the membrane-building envelope becomes a “third skin” in addition to the human skin and the clothes. Membrane envelope systems frequently define an internal controlled environment which necessitates enhanced performance of the tensile surface to ensure the well-being of occupants. In this context, the control of the comfort condition and environmental performance of spaces enclosed by membranes becomes a fundamental requirement to be considered during the design.

Textile membranes usually offer good performances in terms of material efficiency, transportability and light translucency, but, on the other hand, the negligible thickness and reduced mass of structural membranes often translate into a limited control over the thermal-, optical- and acoustic comfort and makes it difficult to measure the physical performance of the membrane-enclosed space since it follows different rules than for conventional and massive buildings.

The performance of the flexible envelope is strictly influenced by aspects such as sun movements, temperature and humidity variations, daylighting and cloud cover. Aside from these external factors, the indoor temperature results from different resultant temperatures and factors such as the location and orientation of the interior-exterior surface, the presence, quantity and position of occupants in the space and the activity carried out in the building. Given the low mass of the materials, changes in the condition of the interior environment (e.g. daily occupancy) or exterior environment (e.g. temperature, climatic variations)—that can vary quickly in the period of seconds, minutes or hours, e.g. day-night—causes a sudden change in the condition of the structural skins and, consequently, in the indoor comfort condition of the membrane-enclosed space. Variations of this type must, therefore, be carefully considered in the design phase to assure users adequate thermal and optical comfort conditions. The design issues consist precisely in the reduction of transmissive heat losses during winter and incident solar radiation during summer to limit overheating

and heat generation while providing appropriate daylighting conditions and energy savings.

To determine the environmental performance of a tensile envelope, the technical data sheets made available by the producers of structural membranes can be regarded as a first useful reference. However, the information contained in the technical specifications—given the almost negligible mass of the materials used—is not sufficient to determine the overall environmental performance of the membrane-enclosed space because it depends on several factors and not only on the single material properties. The lack of reliable data available on the effect that the above-mentioned factors have on the overall envelope performance has identified the need for research in this field to improve predictive modelling. The environmental performance of spaces enclosed by membranes and foils is a topic increasingly addressed by a number of scientific research works, together with the development, experimentation and application of high-performance materials and advanced technological systems. A series of papers available in the scientific literature report field measurements and numerical simulations that replicate the climatic and usage effects on the indoor environment with respect to the thermal, acoustical and optical performance of lightweight membrane envelope (ElNokaly et al. 2002). Among the field measurements reported, while some research works focussed on the thermal-physical and energy performance evaluation of membrane-enclosed (Devulder et al. 2007; Suo et al. 2015) and semi-enclosed spaces (He and Hoyano 2010), or spaces enclosed by ETFE cushions (Afrin 2015; Afrin et al. 2015), others have focussed on the optical performance evaluation (Masih et al. 2015; Lau et al. 2016). These field measurements give important information about the actual behaviour of the lightweight tensile envelope, taking into account the effect of external environmental factors that are not always easily replicable in laboratories. In addition to predictive studies and measurements to evaluate the envelope performance that have been reported in a large number of scientific papers, there are more and more experimental constructions and prototypes that study material and technological systems aimed at increasing the lightweight envelope performance.

To increase both the thermal and optical comfort condition of a space enclosed by a lightweight flexible envelope and ensure the needs of well-being, health and security of users, the designer can intervene on three levels in relation to the context and required performance of the project:

- (i) *at the material level*, e.g. by choosing a material with increased properties or functional coatings;
- (ii) *at the technological system level*, e.g. by adopting multi-layers envelope solutions; or
- (iii) *at the building level*, i.e. adopting passive and/or active strategies to increase the performance of the lightweight envelope.

In the following pages, these three possibilities will be explained in detail to increase the performance of the translucent lightweight envelope.

## 2.1 *Improving the Energetic Performances Through Surface Treatments*

At present, the range of available products used to constitute structural membranes is very limited range and they can be grouped in two types of materials: (i) *textile membranes*, woven fabrics coated on both sides or uncoated fabrics made with coated fibres, and (ii) *foils*, very thin polymeric extrusions with a thickness of less than 0.5 mm. Most of the textile architectures built today are made up of a selection of few membrane materials, such as PVC/polyester used in form of waterproof coated fabric or sun shading open mesh, PTFE/glass, glass/silicone and PTFE fabric and ETFE foils (see also paragraph 1.1.1).

The properties of structural membranes are well known and regulated by standards and information can be found in the technical data sheets made available by producers and manufacturers, while the optical and thermal performances of membrane skins are not specifically harmonised. It means that general facades design guidelines and standards have to be taken into account for the definition of the membrane skins, despite the different behaviour of these thin skin from traditional glass-based envelopes and more traditional massive and opaque solutions.

To overcome the lack of harmonised knowledge and design rules to predict the behaviour of a membrane skin, the thermal and optical properties of membranes and foils are often delegated to their surface's treatment in the production phase, which has become more and more a common practice in the industry.

ETFE foils can be tinted during the film extrusion process with various tints spanning from white-milky to red and blue. Standard or customised printed patterns can be applied to clear transparent layers with the aim of reflecting part of the solar radiation and hence mitigating heat transmission and glare in the envelope inner layers. Functional printings assure both aesthetic and graphics effects to the envelope and environmental protection since they increase thermo-optical comfort performance. For example, by increasing the shading coefficient and solar radiation reflectivity and absorption of foils or correcting the colour of natural light that penetrates in the transparent skins. White and silver are the most common colours used as light scatter and sun protection because in architectural applications light transmission is as important as shading and generally the designer wants to keep the high light transmittance offered by transparent foils such as ETFE.

Optional treatments can be applied to semi-finished products to improve material properties of membranes and foils in order to meet specific building requirements and, therefore, increase the applications of flexible translucent materials in the building envelope. The development of surface treatments, called top coatings, has been increasing in recent years, and there are more and more products available on the market. For example, TiO<sub>2</sub> nanoparticles or PVDF coatings are generally applied to coated membranes to enhance the self-cleaning behaviour and offer a long-lasting clean appearance of the surface, protecting the fabric against dirt and moisture. Or low-emissivity coatings, applied on PTFE-coated fibreglass and ETFE, are used to limit overheating of the indoor environment, thus improving the interior

climate comfort conditions (Göppert and Paech 2015). Selective functional coatings are widely employed on translucent membrane structures in hot climates to reduce the near-infrared part of the solar radiation while transmitting the visible spectrum. For instance, a new infrared-absorbing ETFE foil has been developed by Nowofol (i.e. Nowoflon ET 6235 Z-IR) to decrease the heat transfer, i.e. G-value, through the transparent building envelope. The comparison of IR-foils with conventional clear and printed ETFE foils based on dynamic simulations of different solutions (Cremers and Marx 2016) demonstrates the effective reduction of the solar heat gain coefficient and a higher absorption coefficient that results in the longwave radiation absorption on the foil surface.

## 2.2 *Technological Solutions: From Single-layer to Multi-layer Systems*

The thermo-physical and optical properties of technical textiles and foils used for lightweight building envelopes are useful parameters for identifying the technological performance necessary to control thermal and lighting flows between the exterior and interior—which have strong implications in achieving the indoor environmental comfort conditions. However, to evaluate the performance of a structural skin, in addition to single material properties (e.g. thermal conductivity, radiation behaviour), it is also important to consider the combination of materials and their behaviour in the whole envelope system and taking into account building physics aspects. For instance, it is relevant to consider aspects such as the thickness of the thermal insulation layer and the distance between layers to provide ventilation and air-permeability, reduce vapour diffusion from the inner to the outer layers and avoid condensation.

The low mass and thickness of the materials used for the realisation of lightweight tensile envelopes require at project level the development of technological solutions to improve the originally inadequate performance. Several technological systems are used to build membrane envelopes able to satisfy the well-being needs of users, and they can be grouped into two main categories:

- *single-layer systems*, i.e. the building envelope is made of one single layer of flexible material; and
- *multi-layer systems*, i.e. more layers and materials are combined to constitute the building envelope and thus to increase its performance.

### *Single-layer systems*

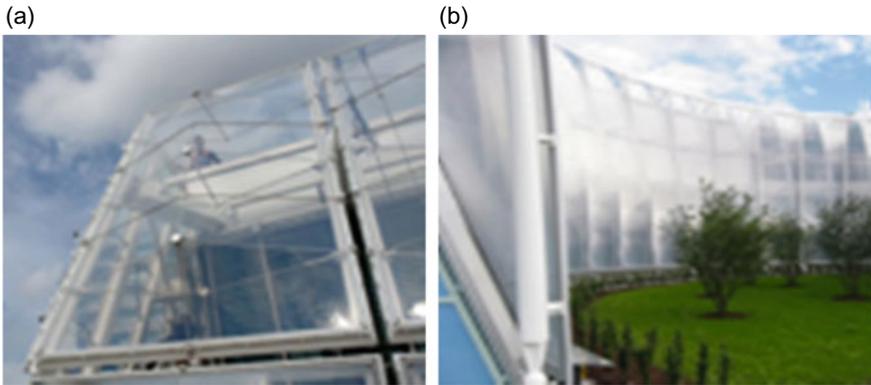
The level of performance of single-layer envelope systems relies only on the properties of the membranous layer. Single-layer structural skins are characterised by relatively high U-value due to their low mass and thickness, and therefore, they can generally provide a fairly low performance. In recent years, several research works

have been carried out to design and produce performative materials and top coatings to meet specific requirements, i.e. mainly improving thermal and optical properties. These Research and Development activities have led to the production of new materials with, for instance, enhanced durability, self-cleaning ability, fire resistance, tensile strength, tear resistance or being able to protect from electromagnetic fields, ultraviolet (UV), infrared (IR) and visible light.

Single-layer envelopes are by far the most common technological systems used for temporary applications, shared by many types of structures, ranging from air-supported structures for seasonal sports facilities to pre-stressed membrane structures for pavilions in the occasion of temporary events. Temporary buildings require easy installation and transport from one place to another and very often comfort control is a secondary aspect of the project and therefore a technological solution that guarantees a low performance is accepted if it complies with the other project requirements.

In permanent applications, single-layer systems are mainly used either as a second skin to create a controlled indoor environment (e.g. sunscreen, wind and rain protection), or for creating a visual enclosure in semi-closed spaces which do not need to be thermally insulated such as stadia or bus stations (Göppert and Paech 2015). The second skin of the Unilever Headquarter in Hamburg (Fig. 9a) is a successful example of energy efficiency retrofitting to protect the existing façade from strong winds coming from the bend of the river Elbe. Built in 2009, the Unilever façade was the first structure that used single ETFE foils with a variable thickness of 250–300  $\mu\text{m}$  as an alternative to the most common pneumatic cushions. The double-curved sinuous screen, tensioned by a sub-system of struts and stainless-steel cables, creates a transparent surface capable of resisting strong winds and thus protecting the first glazed skin without reducing the amount of natural light which penetrates inside. In the Gerontology Technology Centre in Bad Tölz, Germany (Fig. 9b), a second skin made of a double-curved ETFE single layer was used to create a thermal buffer between the building and the exterior. The transparent screen has the dual function of moderating extreme weather temperatures, thus allowing visitors to have access to the exterior circulation around the building and reducing the building energy consumption and heat losses. During winter, this zone is heated by solar radiation and gets an intermediate controlled temperature range. To prevent excessive solar gains and overheating of the walkways, the foils are printed with a silver dot fritting pattern and sensor-controlled vents open during the night to cool down the floor and the ceiling area (Jeska 2007; Cremers 2009).

Otherwise, single-layer systems are often used to create shading and mobile elements, namely blinds and convertible structures with the predominant function of solar shading. Membranes are indicated to be used as adaptable sunscreen due to their reduced weight, flexibility and the possibility to obtain different translucency degrees of solar gains. In addition to the flexibility and light filtering properties, the use of textiles as removable shading systems is very common because membranes are easy to handle and instal also by the users based on needs and are easily removable and storable when not in use. For instance, the textile shading systems of the IBM pavilion were made of stretchable membrane sails hung to the tunnel structure during the hottest and sunniest hours of the day. In addition to providing shade, the



**Fig. 9** **a** ETFE second façade of the Unilever Headquarter Building, Hamburg (Germany), Behnisch Architekten with formTL, 2009 (Photo Credits: formTL). **b** ETFE second skin of the Gerontology Technology Centre, D. J. Siegert, Bad Tölz (Germany), 2004. ; (Source Jeska 2007Cremers 2009)

coloured tensioned membrane allowed the reconfiguration of the internal space and to make the tunnel-shape space more organic and varied.

#### *Multi-layer systems*

Since in many cases extremely thin and flexible membrane materials cannot themselves offer adequate thermo-acoustic performances for membrane-enclosed spaces, a good solution to improve the performance is to use a multi-layer design approach (Knippers et al. 2011). Multi-layer systems combine a variable number of layers made of materials with specific functions (e.g. permeability to water, light and noise, thermal insulation, radiation reflection and fire resistance) to provide better thermal and optical performance with reduced U-values compared to a single material (Göppert and Paech 2015). The high-performing envelope design approach aims to create multi-layer insulated membrane structures appropriate for diverse climates and compatible with the functions and qualities of the membrane-enclosed space. To use lightweight flexible materials correctly, it is first necessary to accurately determine the physical properties of the individual materials in order to evaluate the contribution of each layer that composes the multi-layer envelope system. In addition to the contribution of each material, it is equally important to determine the most effective manner and order of assembling the layers to achieve the required envelope performance since these aspects affect the overall performance of the system.

To create a multi-layer envelope system, it is possible to use either *functional layers spaced out by technological means* or *air-filled pneumatic cushions*. These two construction systems differ from the way the layers are supported: while in the first case, the layers are tensioned or pre-stressed using superposed layers mechanically spaced out by technological details, in the second case they are separated by air under pressure. Both systems are composed of at least two layers and an intermediate air gap that positively influences the envelope thermal performance but only the second

solution needs a continuous mechanical air blowing system to control the internal air pressure that influences the energy consumption of the building. The insulating properties of air entrapped between a variable number of flexible layers can bring a beneficial effect in terms of thermal comfort both during the warm weather to dampen the effects of solar radiation, i.e. light and heat, and in the cold weather to provide natural thermal insulation.

*Functional layers spaced out by technological means*—One option for realising multi-layer systems is to use parallel superposed layers that are mechanically spaced by technological details and in which each layer has a specific function. This technological system can be made of thin flexible layers with an air chamber in the middle, which in some cases is filled with opaque or transparent thermal insulation materials.

In summer, the addition of a functional layer with shading function above the waterproof layer can help prevent the membranous surface from heat up excessively, causing overheating of the internal space. The Multipurpose collective shelter (Fig. 10)—developed by the Politecnico di Milano TAN research group in collaboration with the company Ferrino and the Shelter Research Unit (SRU) experts of International Federation of Red Cross and Red Crescent Societies (IFRC) within the European-funded FP7 EU Project “S(P)EEDKITS—Rapid deployable kits as seeds for self-recovery project” proposes a multi-layer envelope system with an external shade-net spaced 50 cm from the poly-cotton layer of the tent made of flat faces. Before arriving at the final solution, a number of materials with different properties (e.g. weight, tensile strength, light transmittance, thermal performance, ageing) were tested. The ventilation gap is functional to avoid heat absorption of the black shade-net—which proved to be the most performing option in the tests. This solution, which is easy to set-up and uses inexpensive materials and low-tech technologies, allows at the same time a clear improvement in the indoor comfort condition. Field-tests conducted in warm climate areas in Burkina Faso and Senegal have shown the reduction of the heating effects of solar radiation in the internal space enclosed by the shelter (Groenendaal et al. 2015).



**Fig. 10** Multipurpose collective shelter (T2), TAN Politecnico di Milano with International Federation of Red Cross and Red Crescent Societies (IFRC) and the Italian company Ferrino within the funded research project S(P)EEDKITS, 2015 (Photos by Gianluca Giabardo)

The diffusion of air-supported structures used as seasonal sports facilities has determined the need for ensuring the well-being of users who must be able to carry out their activities in controlled internal environment conditions. To improve the performance of lightweight tensile envelope in cold weather conditions, in recent years several research works have focussed on the development of envelope systems able to guarantee greater indoor comfort conditions for membrane-enclosed spaces, without detriment to the advantages (e.g. easy installation and high translucency) that this type of structure gives. For example, the latest generation of the so-called Energy technology allows the elimination of both thermal bridges along with the perimeter and condensation effects. A good example of a building that makes use of this technology is the Junior Practice Hall in Helsinki, Finland (Fig. 11), a seasonal gymnasium covered by a double-membrane air-supported structure that is installed for winter training sessions. Given the seasonality of the structure that is assembled and disassembled every year, the designers had chosen technological solutions to simplify the installation phase but at the same time able to ensure good performance for the cold season (Monticelli 2019). The heating system integrated into the inflation unit allows controlling the snow load during the winter period. The building envelope consists of two layers of PVC/polyester-coated fabric spaced by cables with a 40-cm pressurised air chamber in the middle. The double membrane is composed of welded fabric bands with different degrees of translucency which allow the indoor space to benefit from the limited winter daylight. This alternation of more or less translucent parts allows light to filter through the envelope, resulting in a uniformly illuminated interior space that features high lighting comfort and energy saving for the artificial lighting system. At night, the different translucencies create lighting effects through artificial light located in the air gap between the two membranes. This advanced envelope technology ensures an adequate controlled indoor thermal comfort condition without sacrificing the high translucency and transparency made possible by membrane materials.

Multi-layer systems made with thin and flexible materials can provide different degrees of translucency, through the combination of layers with different thermal



**Fig. 11** Junior Practice Hall, JKMM architects with Canobbio Textile Engineering, Helsinki (Finland), 2015 (*Credits* Raikuva Kuvat and Mike Huisman)

and optical properties. In cold weather applications, insulation materials are often added in the air chamber to improve the thermal envelope performance. Thermal insulation materials—placed on the inner layer or suspended to the structural skin—can be either opaque or high translucent/transparent according to the required degree of translucency of the envelope and other project requirements. Generally, to be used in membrane-building envelopes, thermal insulation materials need to be flexible enough to adapt the curved shapes of the skin. Opaque or translucent envelope systems integrate insulation materials such as fibreglass or mineral rock flexible insulation panels. In combination with insulation materials, functional layers such as low-emissivity mirrored layers can be added in the building envelope to increase the envelope performance, namely reducing the indoor overheating effect in warm weather applications. Although these functional layers block infrared rays, on the other hand they make the envelope completely opaque (Lombardi and Canobbio 2016). The 2013 extension of the Serpentine Sackler Gallery (Fig. 12)—designed by Zaha Hadid Architects and engineered by Architen Landrell Associates for the membrane design—uses a multi-layer insulated system of flexible materials to control the envelope thermo-acoustic performance (Zanelli 2015). The permanent building is made of a membrane roof sinuously shaped by a FRP rigid ring beam that touches the ground on three points. The membrane envelope is made with a double layer made of PTFE-coated/glass fabric as an outer layer, an air gap of and glass/silicone fabric as an inner layer. Mirrored fire barrier and the insulation material have been positioned inside the air chamber to ensure low thermal transmittance (i.e. U-value pairs to 0.18 W/m<sup>2</sup>K) (Fig. 12).

The challenge for the future is to guarantee high thermal-acoustical and optical performance going towards an increasing transparency of the building envelope. The greater the transparency of the insulating materials, the greater the benefit in terms of increased natural lighting and reduced energy consumption. However, this implies greater constraints and limits the usable materials: while in traditional membrane envelopes, it is possible to insert additional thermal and acoustical insulation layers and reflective films, in transparent and translucent systems it is necessary to opt



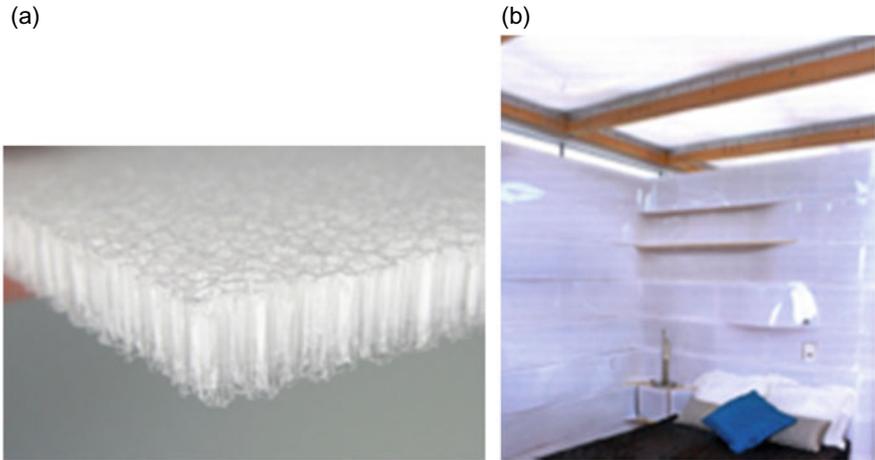
**Fig. 12** Serpentine Sackler Gallery, Zaha Hadid Architects with Architen Landrell, London, 2013 (Photo courtesy by Architen Landrell)

for transparent and translucent materials that allow to see through and diffuse light permeability.

Transparent thermal insulation (TTI) is light-permeable material or component that has thermal properties similar to opaque insulating materials while having a high value of light transmittance, thus allowing solar radiation to infiltrate through the envelope for providing natural daylighting and assisting the heating system (Knippers et al. 2011). TTI materials integrated into a flexible multi-layer system can provide to the indoor space a wide-spectrum diffused light while avoiding any glare effect. At the same time, they are able to guarantee a good level of thermal insulation with a consequent limitation of heat losses and reduction of energy demand, in particular concerning the electricity used for artificial lighting. Despite the evident advantages in terms of light permeability, daylighting and energy reduction that transparent thermal insulation materials can offer, the application of TTI in the building sector is still in an experimental phase and remains a challenging research line for the future.

Transparent thermal insulation layers—used from the early 80 s in the aeronautical sector—are either organic or inorganic materials. Organic light-permeable insulation materials include products with alveolar structures, foams and sponges, composed of different polymers such as polycarbonate (PC), Polymethyl methacrylate (PMMA), cellulose acetate (CA) and polyethylene (PE). TTI honeycomb hollow chamber structures—mechanically flexible in the three dimensions—have been sandwiched between two ETFE foils (Zhang et al. 2006) to significantly improve the envelope thermal performance.

Among the inorganic TTI materials, a noteworthy example is the use of silica aerogels, thermal insulation materials made with 95–98% of air and the remaining 2–5% from silicon dioxide (i.e. silica) particles. Their very low density of only 3 kg/m<sup>3</sup> makes the aerogels the lightest materials that have ever been produced. Silica aerogels—supplied in forms of powders granulate or monolithic—have very high thermal insulation properties, achieving a thermal transmittance of between 0.1 and 0.2 W/m<sup>2</sup>K. Aerogels are very fragile materials that are usually produced in the factory in the form of hermetic components, and due to the difficulties of production, they are still very expensive and their use in the building sector is limited. The Georgia Institute of Technology Pavilion of the Solar Decathlon 2007 (Cremers and Lausch 2008), realised by SolarNext AG in collaboration with Hightex GmbH, proposed the use of aerogel-filled ETFE roof panels to cover an innovative residential unit of about 70 m<sup>2</sup> in size. The roofing system was made up of two distinct elements: the upper layer made of a single-layer arch-shaped ETFE foil that served as weather protection and the highly insulated lower layer which created an illuminated ceiling. The nine-roof insulated panels measuring 4 × 1.5 m were made with tensioned ETFE layers in a metallic frame filled with aerogel granulate. The panels—because of the fragility of the materials and the easy assembly desired—were prefabricated in the factory and only fastened to the supporting structure on site. The result was a homogeneously illuminated ceiling and a highly insulated roof with a light transmittance of about 15% and a U-value of less than 0.3 W/m<sup>2</sup>K. The difficult manoeuvrability and high costs limit the use of aerogels to experimental prototypes presented as the result of scientific research works (Fig. 13).



**Fig. 13** **a** Kapipane by Okalux, Transparent thermal insulation (TTI) slab in the form of a capillary tube structure. **b** Georgia Institute of Technology Pavilion of the Solar Decathlon 2007, SolarNext AG and Hightex GmbH. Internal view of the aerogel-filled ETFE roof panels (Cremers and Lausch, 2008)

Transparent thermal insulation materials have also found an effective application as solar heating materials. A research conducted by the ITV institute in Denkendorf resulted in the construction of the experimental Polar bear Pavilion using bear hair technology. The observation and analysis of the solar thermal functions of the polar bear fur, able to absorb parts of the irradiated solar energy, had stimulated the use of spacer fabrics as solar energy harvesting (Stegmaier et al. 2009; Engelhardt and Sarsour 2015). The Polar bear Pavilion (Fig. 14) aimed to create a textile building provided with a method for energy extraction and energy storage, with climatically controlled interior conditions. The combination of the flexible solar heat generator and the thermo-chemical storage for long time resulted in an energy-independent house with high solar and storage efficiency, whose innovations consist in the development of a flexible textile air solar collector with multi-layer set-up, the energy extractor in the textile cover, the extremely high thermal insulation despite the lightweight construction. The roof of the pavilion is realised through the combination of different layers: on top, the air flowing layer enables a high transparency while providing flexible solar insulation; the ETFE layer serves as top cover, still maintaining high transmissivity for the visible and light and near-infrared radiation; finally, further translucent covering layers increase the thermal insulation, without limiting the sunlight permeability. The energetically self-sufficient textile pavilion is, therefore, able to manage the harvested energy, storing it in summer and realising it during the winter season.

*Air-filled pneumatic cushions*—Alternatively, multi-layer systems can be composed of layers which are spaced by air under pressure, generally realised with ETFE foils in form of pressurised multi-layer cushions. The cushions—made from



**Fig. 14** Polar Bear Pavilion, Institute of Textile and Process Engineering (ITV) Denkendorf, (Germany), 2013

two to five layers supported by metallic frames—are connected to an air blower unit which enables the system to maintain geometric stiffness and withstand external loads. The structural and environmental performance of the envelope can be improved (therefore causing the decrease of thermal and light transmittance values) either by varying the layer thickness and increasing the number of layers and intermediate air-chambers of the cushion or by using performative additional layers to obtain higher thermal insulation or sun shading values.

ETFE multi-layer air-filled cushion is a widespread technology for covering large-scale atriums and façades (Gómez-González et al. 2011). The control of the indoor comfort condition is a key aspect in the design of air-filled pneumatic cushions as this technology is being mostly used for permanent buildings applications. The beneficial effect is searched both for warm and cold climates, although the warm situation is more critical because the high transparency of the material can more easily create greater discomfort that results in the overheating of the indoor space. For this reason, Research and Development departments continuously work to measure the condition of the internal environment and find ever better technological solutions to increase the environmental performance of lightweight envelopes made of air-filled cushions.

### ***2.3 Strategies to Increase the Envelope's Thermo-Optical Comfort Performance***

When the application of high-performing flexible materials and technological systems is not sufficient to ensure adequate indoor comfort conditions for particular weather conditions, other environmental control systems should be integrated into the lightweight envelope system to increase its performance. Considering the extreme lightness and very low mass of membrane-based structures, climate control plays a key role in obtaining a healthy atmosphere for users to perform indoor activities in a state of well-being. The strategies which are put into place to increase the indoor thermal and optical comfort performance can be either active or passive.

Passive systems use natural phenomena and bioclimatic strategies, such as promoting the greenhouse effect for heating in winter or using natural ventilation, shading elements or evaporative cooling for reducing overheating effects and cooling demand during summer while encouraging natural daylighting and energy savings. Instead, active strategies are automated or user-controllable systems, such as controlled ventilation and air conditioning systems, or movable shading devices automatically activated through sensors when solar radiation or temperature reaches a certain value.

Since ETFE cushion is a widespread technology, strategies to improve the environmental performance of spaces enclosed by multi-layer foils systems are continuously experimented and tested (Flor et al. 2017). In particular, the research and technological trend is moving from passive design strategies to active technologies, thus developing adaptive and responsive systems that allow the building envelope to respond dynamically and autonomously to variable climate conditions and/or to changing user needs. Among the several dynamic control mechanisms which have been developed so far to control the indoor summer and winter condition of spaces enclosed air-inflated cushions systems, the majority of applications have remained at the prototype level or in a development stage, for instance, the integration of water spray inside the cushion (Mainini et al. 2016), the addition of a thin water layer in the external surface (Xie 2011) or the injection of gas (Monticelli 2015) or bubbles (Gan 2009). These experiments have been tested in laboratories and with mock-ups but their diffusion in the market is limited. Instead, other solutions such as the rotating lamellas and switchable layers have been tested in prototypes and have become current technologies for the lightweight construction sector. The most common active shading strategy for ETFE cushions is switchable fritted layer technology. The DSD Cyclebowl Pavilion, built for the Expo held in Hannover, Germany (Fig. 15) in 2000, is the first built example that used this technology. The pavilion consisted of a 1800 m<sup>2</sup> façade made of three-layer cushions in which the outer two layers are printed with custom-made leaf patterns. This patented system uses the overlapping of positive–negative patterns to change the cushion’s percentage of coverage: the printed middle layer is moved by the variation of the air pressure inside the cushion chambers, thus making the geometry perfectly overlapping the outer layer printed with the inverted pattern. The positive and negative fritted patterns fit perfectly when overlapped, thus creating a 100% dark environment for interior shows if necessary. This active shading system also allows intermediate positions that block direct solar radiation but let a partial percentage of light translucency to pass through the cushion. As often happens, this technology—presented for the first time in a temporary building—is now commonly used for permanent buildings such as long-span atria.



**Fig. 15** DSD Cyclebowl Pavilion, Atelier Brückner with IPL, formTL, and Vector Foiltec, Expo Hannover 2000, Hannover (Germany), 2000 (photo credits)

### 3 New Frontiers of Interactivity of the Membrane Skin

Through the evolution of advanced chemistry, biotechnology and nanotechnology, the dimensions of artefacts can be miniaturised to the very essence of living matter. The possibility to manipulate the atomic molecular and macromolecular structure of natural origin materials permitted the invention of new materials, such as super-polymers, advanced composites, shape memory alloys and polymers, i.e. materials that switch the traditional relationships of performance between strength, lightness, density and transparency of the materials available in nature.

Ecofacts and artefacts are no longer so clearly distinguishable, the symbiosis between them increased (Fiorani 2003). Using the words of Kevin Kelly (1994) in this millennium, “the realm of the *born*—all that is nature—and the realm of the *made*—all that is humanly constructed—rebecoming one. Machines are becoming biological and the biological is becoming engineered. [...] For the world of our own making has become so complicated that we must turn to the world of the born to understand how to manage it. That is, the more mechanical we make our fabricated environment, the more biological it will eventually have to be if it is to work at all. (Kelly 1994, p. 7).

Nowadays, there is a desire for “artificial sensitivity” widely acquired and internalised in our materialistic culture, now evident both in design and architecture, either on the building’s scale, or in the interactive objects that can be used daily. Thanks to the increase of its artificial apparatuses, wider parts of our architectures—mainly interiors—are becoming intelligent, able to cooperate with their inhabitants, answering to their desire of change (Prestinzenza Puglisi 1998; Kronenburg 2007).

Thus, all building components should also become more and more adaptive, and designed as a hybrid, able to perform as a natural organism and, at the same time, manufactured as a robot or a computer circuit, or at least integrating them into the technological elements.

Typically, the automation integrated into buildings elements currently still follows the level of innovation, research and development achieved in other sectors, such as

automotive field. The interaction between the building and the automation components travels thanks: (a) sensors able to reach the environmental condition or the users presence; (b) the computational brain and interface, set to translate the external stimuli in the desired and pre-set answer; and (c) the actuators, able to react and perform predetermined result.

Interactive architecture shall be distinguished in “naturalised” and “motorised” (Chang 2018; Mulder 2018; Menges et al. 2014; Oosterhuis 2003) and, obviously, this latter strategy still counts the higher number of real built solutions, most of them focussed on the achievement of the desired operational performances such as safety, security, communication, entertainment, more rarely to the challenging goals of comfort and energy efficiency.

Focussing on the interactivity between membranes and the environment, an interesting area of experimentation which is still open concerns the integration of micro-devices for energy saving between the different textile layers, such as the provision of thin photovoltaic strips in the outermost layer of the ETFE transparent cushion, or the integration of bright LEDs into the texture of a fabric.

For example, in the German Pavilion for 2015 Expo in Milan (Fig. 16), the architects embraced the theme “Feeding the Planet, Energy for Life” and incorporated an existing technology (i.e. OPV) in a new way in the building. They designed flexible OPV membrane modules to match their own creative ideas and to integrate them into the overall design of the pavilion.

Focussing on the interactivity between membranes and the end-users, the temporary installation and the architecture for entertainment seem to have found the motivation to justify the higher economic cost of integrating electronically mechanised parts into the construction. For example, the Coca-Cola beatbox pavilion (Fig. 17) in London was entertaining visitors thanks its façade composed by 230 ETFE cushions integrated with both lighting technology (red and white, the Coca-Cola colours) and sound, allowing them to become a part of the performance.

Further advancements in the direction of reducing the impact—and the need of maintenance—of the mechanically controlled building components are the Flectofin® patent, winner of the International Bionic-Award of 2012: a hinge-less flapping



**Fig. 16** German Pavilion for Expo 2015, ARGE, Italia, Milan, 2015 (Source Photo by Schmidhuber/Milla and Partner)



**Fig. 17** Coca-Cola Pavilion, Pernilla and Asif, Great Britain, London, 2012 (Source Photos by Hufton + Crown)

mechanism inspired by the deformation principle found in the Bird-of-Paradise flower. We cannot really talk about a fully membrane component, but the developed flexible façade panel is a very interesting experimentation on the fibre-reinforced plastic (FRP) and its potentiality of autonomous bending induced by the clever designed shape. (Fig. 18). After the full-scale prototyping of flectofin® Lamella and Façade, a similar behaviour is adopted in EXPO 2012 Thematic Pavilion in Korea Yeosu, where 108 individually controlled fins, made of FRP of 9 mm of thick and of variable high between 3 and 14 m create an innovative kinematic façade (Fig. 19).

Now, it is time to move towards a further level of intelligence and sensitivity even when we are designing the building envelope: the challenge today is envisioning the façade not anymore as a complex set of waterproof panels, but as a seamless skin, breathable and reactive to both the external (climate) and internal (users) stimuli, similarly to a biological organism.

Thanks to the flexibility of the fabrics and their attitude to be functionalized, membrane architecture seeks even a stronger link with nature, almost looking for a new oxymorous dimension of natural artificiality, where designers will be able to



**Fig. 18** Flectofin® Lamella and Flectofin® Façade; Project team: Jillian Lienhard, Simon Schleicher, Simon Poppinga, Tom Masselter, Lena Muller and Julian Sartori; academic partners: IKTE-Stuttgart, ITV-Denkendorf and Albert-Ludwigs-University-Freiburg; Industrial partner: Claus Markisen Projekt GmbH; supported by BMBF BIONA, Germany (Source ITKE 2012)



**Fig. 19** Thematic Pavilion at EXPO 2012, Korea; designed by SOMA Architects and engineered by Knippers Helbig. (Source Knippers Helbig, Stuttgart, New York)

explore a blurred boundary between ecofacts and artefacts, imitating the adaptivity and transformability of natural systems for the enhancement of the building skin.

Precisely, this type of intelligent artificiality is the new goal to be reached in the field of multiple integration between electronic automation, bio-based chemical functionalisation and lightweight construction. In the near future, textile architecture, which has always shown an intrinsic aptitude to movement due to its materials lightness and flexibility, may be a privileged area for such experimentation.

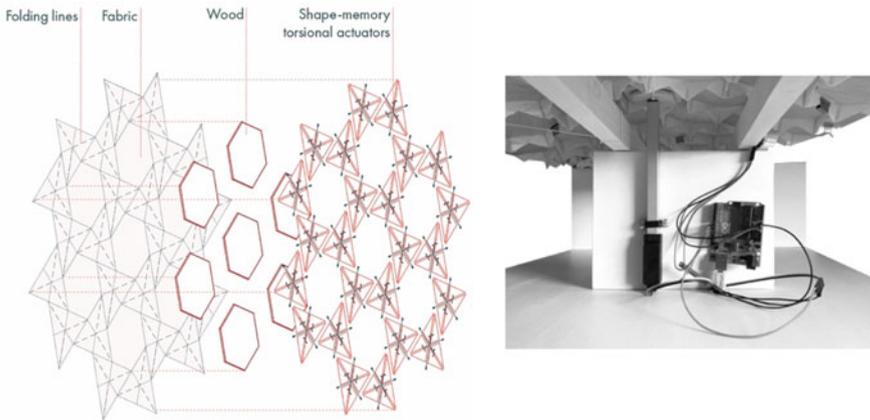
Even the skin of buildings, made of textile materials, can become really active-able in relation to environmental conditions or the users' needs, in other words, intrinsically intelligent through its membrane skin.

This next development path unfolds ongoing research studies on the deepen integration between membrane-based lightweight building structures and shape memory materials (SMMs) based on metal alloys, ceramics and polymers, that have been greatly developed over the past two decades for other application sector, and finally now seem to become suitable also for their integration into the membranes. That is now possible thanks to the further developments on the weaving techniques on one hand and the advancement of 3D and 4D printing techniques on the other hand.

Particularly, shape memory polymers (SMPs) are smart polymers able to return from a deformed configuration (temporary shape) to their original state (permanent shape) when triggered by an external stimulus, such as temperature (thermo-responsive), water (pH-responsive), light (photoresponsive) and mechanical load (mechano-responsive) (Meng and Li 2013; Cortés et al. 2021).

NIMBL is an interesting project that explores the integration between fabrics and shape memory alloys to envisioning a novel kind of interactive membrane architectural surface (Mikavica 2018).

In order to respond to different requirements in the interior space such as flexible lighting solutions and good acoustic comfort, but also to provide different furniture to be used by users, the Nimbl skin is created as an architectural body able to extend itself and change its topography in real-time accordingly. It is inspired by the principles of Evo-Devo studies used in the HyperCell project (Chang 2018), which uses simple single components (cells) with transformation abilities composed in a way



**Fig. 20** NIMBL project, designed by Dragana Mikavica- Politecnico di Milano, 2018: View of the architectural interactive membrane and its integration with the Arduino controller (*Source* Mikavica 2018)

to communicate with each other and to perform together while generating a smooth and flexible surface.

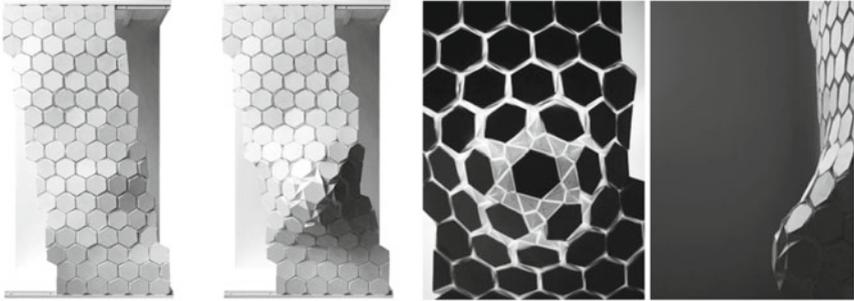
For generating a pattern of the skin, which will be able to flex, morph and extend itself, the origami tessellation techniques are used.

The origami tessellation is an area of origami which uses just one sheet of paper, and by folding it, the pattern can be created. (Fig. 20).

After experimenting with different combinations, the chosen pattern is made by multiplying a cell made of the hexagon in the centre and a pair of triangles on each side. The triangles are seen as a flexible and elastic segment with transformation capabilities that give possibilities for generating different morphologies and allowing the extension of the total surface area. Furthermore, the hexagons, on one hand, are a solid and stable segment which creates a flat and usable surface and, on the other hand, give possibilities for embedding different devices (Fig. 21).

All the cells are acting individually and have their degree of transformation. But even though they are all independent, when combined together they act as agents of a swarm. They are using simple computational rules, in order to communicate with each other and constantly regulate their position in relation to the neighbouring member, in order to achieve dynamical goals and generate collective decisions (Fig. 22). In order to achieve this, the information between units need to be transferred, and this relationship between information and a physical surface is possible through the use of actuators, sensors and mechanisms (Mikavica 2018).

We are aware that the NIMBL project is still at a prototyping step and it is proposing a membrane-based skin that is not fully exploiting the deformability and the strength and the translucency of the fabric material. Nevertheless, it really seems to rise the challenge towards the next level of the engineered sensitivity of membrane-based skins.



**Fig. 21** NIMBL project, designed by Dragana Mikavica- Politecnico di Milano, 2018: View of the prototype and the transformable origami pattern (Source Mikavica 2018)



**Fig. 22** NIMBL project, designed by Dragana Mikavica- Politecnico di Milano, 2018: possible applications of NIMBL interactive membrane skin (Source Mikavica 2018)

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# Life Cycle Design for Lightweight Skin



Carol Monticelli

**Abstract** The typical membranes for building are polymer-based and have origin from fossil fuel but become very lightweight building components, compared with other typical ones. Structural elements stiffen them (bio-based or not) and, due to the lightness, involve fewer structural materials than other components. Through a multidisciplinary experimental design path—focused on the weight factor at the level of the constructive system and the efficiency factor at the level of primary material—it is possible to enhance the efficiency and the aesthetic of lightweight skins and distill the eco-design concepts which can be transferable to the whole construction sector. In other words, the author tries to demonstrate the impacts of reducing weight firstly in textile skins and also other lightweight and hybrid architectures. Coming from this significant weight awareness through experimental knowledge, the author discusses the opportunity to apply multidisciplinary design approaches to reduce energy consumption and environmental loads during the life cycle. This chapter aims to elaborate on those concepts and systematize the obtained results demonstrating the advantages of the Life Cycle Design strategy in the environmental sustainability of novel lightweight skins.

**Keywords** Life cycle assessment · Comparison · Eco-efficiency · Environmental impacts

## 1 Life Cycle Principles Applied to Lightweight Building Systems

Thinking of lighter architecture means enlarging the research into materials, reducing the thickness of components, and optimizing the construction sections. Due to the environmental sustainability's constraints, the main aspects to being assessed during the design phase become more and more: (a) the embodied energy of components

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and the whole building system; (b) the reusability/recyclability of each material embedded in the whole construction; and (c) the expected lifespan of a building, which is closely linked to the way of managing connection details for installation, maintenance, and final dismantle. The following topics can be conceived as strategies for the membrane structures' eco-efficient design (Cost Action TU1303 2017).

Suppose the future of membranes is to become permanent space enclosures. In that case, it is essential to improve the durability of light materials and performances during the use phase (like mechanical resistance and thermal insulation). But for enhancing thermal performance during use, the membrane layer in permanent buildings is increasingly complex.

One of the most critical challenges of tensile structures is to improve their internal environmental qualities. In the past, the temporary use of membranes made introducing insulating layers in their envelope unnecessary. Today, on the contrary, the great diffusion of lightweight structures for permanent use calls for new technical solutions for building optimized envelopes. The skill of previewing and controlling the thermal, acoustic, and light conditions becomes an urgent requirement for architects and engineers.

After a further two decades of production and manufacturing advances, full of relevant achievements both in terms of local regulatory standards (Forster and Mollaert 2004) and their harmonization (Mollaert et al. 2016), textile materials for architecture are considered reliable and durable, either used in the form of a flexible membrane, suitably coated, or used as soft formwork of rigid concrete-based (i.e., textile Beton) or resin shells (i.e., GFRP), and both for temporary and permanent constructions (Monticelli and Zanelli 2020).

The tensile structures' inherent properties of lightness and flexibility need the research of non-conventional solutions to apply advanced insulating materials in the textile envelopes without modifying their aesthetic aspect.

Consumers, stakeholders, end-users, and designers demand information about the environmental loads' implications of lightweight building skins and their construction activities. This kind of information about technical textiles and innovative films for tensile structures is still limited, and the common idea of the petrol-based solutions and the polymeric nature of membrane materials has to be overcome deepening the total quantities involved at the scale of buildings (and the related environmental impact) compared to other building systems solutions.

Life Cycle Assessment (LCA) application on lightweight and ultra-lightweight building skins has been a crucial part of the research efforts by the author in the last decay. LCA procedure applied on lightweight and ultra-lightweight materials for skins, with a specific focus on membrane building materials, helps to point out advantages and disadvantages and the needed correct exploitation of the proprieties of the materials. Nevertheless, a comprehensive description of the environmental performance of building materials, and even more the membrane materials (coated textiles and films), typically comes up from a massive volume of data, which the designers hardly manage in a routine design process, where the deepen aspects on the project are many. Specialists in this field can interpret the typical results of a Life

Cycle Assessment, and, sometimes, the results of different LCA studies are not easy to compare and understand.

A starting point for collecting environmental data is to support a program of development of environmental product declaration (EPD), defining data quality requirements into Product Category Rules (PCR) documents for membranes (COST Action 2017). Environmental impacts of materials can be objectively compared when adequate guidelines are followed. ISO 14025 (2006) describes the procedures required to acquire type III environmental product declaration (EPD). This allows comparability of environmental performance between products. The EPD is based on the principle of developing Product Category Rules (PCR), which specify how the information from an LCA needs to be used to formulate the EPD. An EPD is a transparent and objective report based on LCA, a systematic analysis of the potential environmental impacts of products or services during their entire life cycle. It also includes the upstream and the downstream.

The EPDs developed in Europe, related to skins materials, are primarily based on the PCR for the materials' categories (e.g., PCRs for wood materials, for rubber and plastic products, for flat glass products, for ceramic tiles): For the membrane materials, there are no specific PCRs and the more related ones are c-PCR-004 Resilient, textile, and laminate floor coverings, that are not well-fitting with membranes for building skins. PCR outlines five environmental impacts: global warming potential, acidification potential, eutrophication potential, smog potential (photochemical oxidation), and ozone depletion potential (ozone layer depletion).

A natural step in delivering the kind of information that is standardized through a group of similar-in-function products or materials, as an integral part of generating an environmental product declaration, is the Product Category Rules (PCR). PCR is handy where the environmental impacts of products within a category group are to be compared—perhaps as part of a product specification process.

The EPD is becoming more and more meaningful. In the last ten years, the EPD as voluntary product declaration was not sufficiently taken into account, probably because of a lack of good marketing or because the business was too young and the market was not ready yet to accept it. Since some aspects are not considered yet, it is impossible to compare different products, and two EPD cannot be compared. Especially, since the values are still too far from the shared knowledge of the building sector and, therefore, taken as they are, it is difficult to understand their meaning and possible use to evaluate at first glance.

Nevertheless, in a life cycle thinking perspective, the necessity of increasing the designers' awareness of lightweight and flexible materials and their performances is the priority. Consequently, the most effective life cycle-based design methodology, which will support designers during their daily work, is the need the author foresees, not as a theoretical analysis for scientists and environmental specialists.

Based on this background and the identified needs, a meaningful eco-design approach for textile architecture has still been under definition and evaluation (Monticelli et al. 2016), and three main design principles for the weight reduction and the efficiency of form-structure of both tensile membrane skins and pneumatic cushion envelope have been defined. Their verification before an integral LCA of

building skins and structural membranes helps to point out advantages and disadvantages (lightness) and the needed correct exploitation of the properties of membrane materials.

The *first principle* states that designers have to verify the ratio frame perimeter/covered surface in the case of structural membranes for roofs or entire building envelopes. Following the general minimization criterion of the doing more with less, this principle assesses the eco-efficiency of a defined surface to be closed/covered. The broader area of a membrane “panel” corresponds to reducing the perimeter length (otherwise the size of frames), reducing the involved materials for their production and consequently the related environmental impacts.

The *second principle* is verifying the ratio fixing system (or primary structure)/membrane, and it seems mainly relevant in designing structural membrane façades. The Life Cycle impact of the membranes for façade cladding and the efficacy of their choice seem straightly linkable to the quantity of the elements of the fixing systems; thus, understanding their real need in terms of structural loads and of stiffness and the choice of ultra-light thin supports instead of rigid ones are meaningful.

The *third principle* states that the designers have to verify the ratio membrane structure/mechanical load of the structure considering steel or wood as the primary structural materials involved in the field of membranes: optimizing the mechanical and structural behavior of a membrane structure and the form means to improve the correct use of membranes and the correct interpretation of their embodied properties (time-based systems, Life Cycle Design).

The optimization of these ratios means the excellent exploitation of the characteristics and behavior of the membranes concerning other, less flexible, and lightweight, traditional building materials.

The current stage focuses on enlarging the mapping of case studies by the application ex-post of two eco-efficiency principles to verify their validity and efficacy.

The expected next step is their introduction to the best practices for membrane design and their verification of the specific project during the design process of a membrane system.

These eco-efficiency principles aim to be considered a verification stage in the early design stage, quite similar to the bioclimatic principles that have to be considered to improve the well-being and energy efficiency of the buildings. They verify the design choices from the point of view of the environmental loads, concerning the building shape, the correct exploitation of the potentials of the membranes as lightweight materials. They represent a preliminary assessment, for a consequent optimization, of the environmental performance (due to the quantities of involved materials), before an eventual specific and deep Life Cycle Assessment.

To test the three principles on the field, built examples of textile envelopes and pneumatic cushions in buildings have been analyzed (Monticelli and Zanelli 2020) to verify the reliability of the mentioned eco-design principles of membrane structures Fig. 1. Here, the measuring of environmental impacts seems to be the leading research focus concerning their weight, which is the meaning of their optimization, even

though the awareness of textiles' performances is crucial to making the difference in disruptive design solutions.



**Fig. 1** Building textile envelope solutions and their dimensions as case studies for applying two eco-efficiency principles. Reproduced from (Monticelli and Zanelli 2020)

The reading of the results Fig. 2 indicates that lightweight technologies allow designers a high degree of freedom in shaping geometries and shapes. At the same time, only their optimization will ensure effective LCA sustainability results. This optimization process can be effectively achieved by a broad surface development (principle 1) and by a balanced ratio of the weight of the support structure concerning the envelope (principle 2).

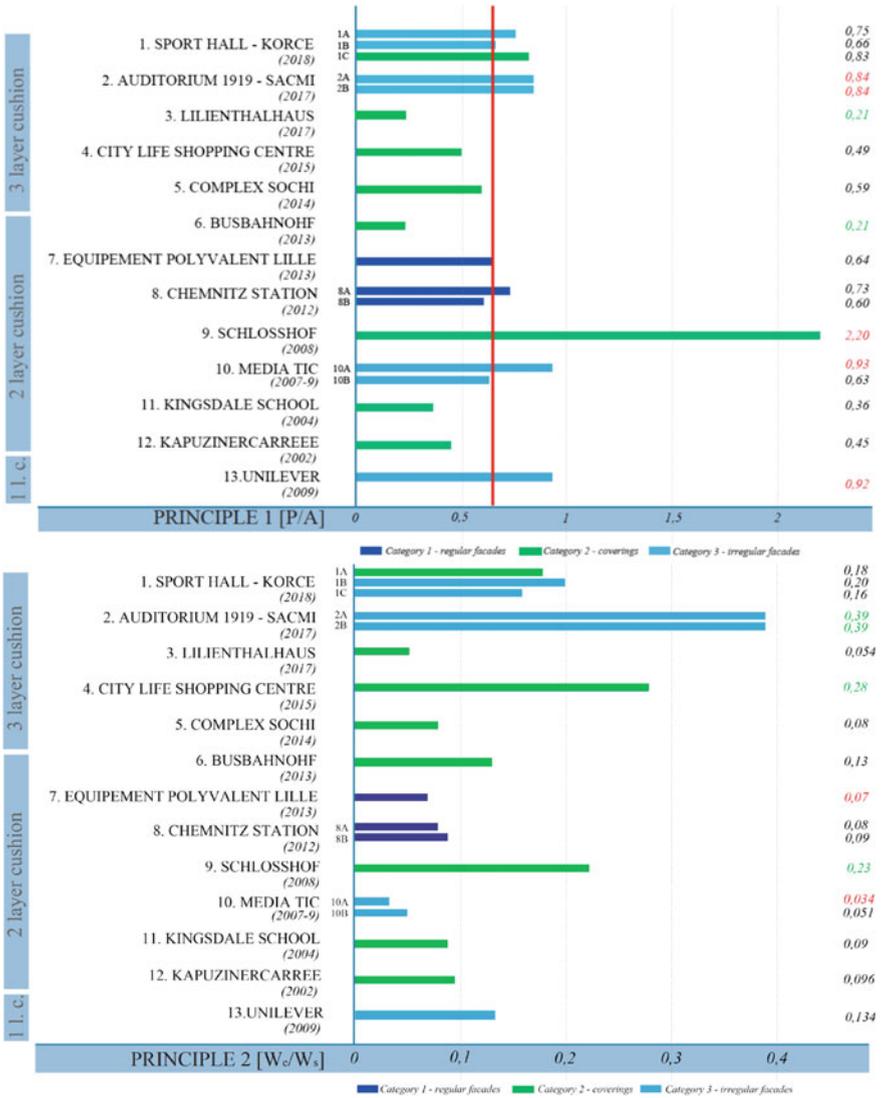


Fig. 2 Results of the 1st and 2nd principles. Reproduced from (Monticelli and Zanelli 2020)

In terms of environmental impact analysis of the lightweight technical solutions, after the first verification of the eco-efficiency principles, the designers could better construe the validness of their design choices or the possible re-orientations thanks to the principles' results. The step further is the LCA of the optimized technical solution to quantify the environmental impacts related to the environmental damages. And in this case, a comparative analysis is advantageous.

## 2 Comparative LCA on Membrane Skins

The application of a comparative LCA in the lightweight and the membrane architectures is the appropriate procedure to quantify and compare the environmental impacts and the consumption of materials and energy throughout the whole life cycle, within the following levels:

*a. Life cycle of matter*—Focusing on more than ten years rooted use of the methodology in the building construction sector, the LCA application analyzes the environmental impacts caused by the production chain of the manufacturing industry, with the system boundaries ranging from the phase of obtaining raw materials (from the cradle) to the phase of packaging and transporting products to the building site (to the gate) (supporting the industry to review all processes of the production chain of woven and non-woven textiles, coated textiles, and laminated foils, identifying which processes need to be optimized, to save energy and reduce harmful emissions).

*b. Life cycle of building components*—After the specific survey regarding the eco-profile of materials (i.e., ETFE foil or PES/PVC textile or PTFE fabric in the field of membranes), the next step of the LCA is the comparison of the environmental impacts of different building components and their technical systems. The investigation at the scale of building components considers the choice of the qualitatively and quantitatively more efficient building system and convenient construction technique, based on the structural and thermo-physic, acoustic performances, and the costs. However, the performance of environmental impacts can increasingly influence the choice of the building products, in an LC perspective of circularity of flows and closing the loops, to select sustainable products and strategies for the future of our ecosystem.

### 2.1 *An Environmental Load of Ultra-Lightweight Materials and the Nonlinear Relation with Their Weight*

It is provided to the reader a comparison of the life cycle of an ultra-lightweight new material—the fluor polymer material ETFE—and its building system, contributing to the increasing literature by assessing new material (Monticelli 2010).

The comparison helps to understand the importance of selecting environmentally efficient building technologies and structural systems based on embodied energy, reducing the number of materials and emissions in the atmosphere, water, and soil. And it highlights the importance of considering all the environmental impact categories to state the eco-compatibility of building technical solutions. The glazing roof is disadvantaged compared to the ETFE cushions, considering only the embodied energy indicator and adding the global warming potential indicator. Therefore, the LCA application defines the potentials and possible limits of alternative technological solutions thanks to a global view about the impact contribution in the life cycle. And from the LCA point of view, it highlights too how the relationship between the weight and the amount of the impact is not linear: “The heavier the material, the more it pollutes” is not the rule, but the production process history and the analysis of the environmental impact indicators, beyond the embodied energy.

It is essential to analyze the environmental impacts’ values per gravity of materials and their building components on the one hand and then to analyze the values when the suitable functional unit is the covered area by these roofing materials on the other hand. In architecture, the design for the construction is based on the design of building systems made of materials; consequently, it is relevant to assess the role of the materials in specific building systems.

Environmental impacts of two different building components for transparent roof systems have been assessed. The compared components fulfill the same function, transparency: extruded ETFE films for the cushion system and tempered glass sheets for a double-glazing system roof. In the following analysis, the system boundary is the pre-use phase (from cradle to gate). The functional unit is the quantity of material necessary to cover one square meter area and, consequently, build a component for the roofing system corresponding with the current building technology characteristics (Fig. 3).

The design shape of the compared components is different, the quantity of involved materials gives different results, and consequently, impact results change. The multi-layer etfe cushion involves less energy (1596 MJ/m<sup>2</sup>) than the other roof system (7395 MJ/m<sup>2</sup>), due to its lightweight and fewer used materials’ quantity. The glazing manufacturing causes dangerous output, influencing the acidification and eutrophication of air, water, and soil (regional, local environmental damages): It depends from the manufacturing process to obtain the float glass. The etfe system shows as result a great impact bond with the global warming potential and the ozone depletion

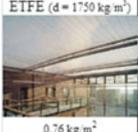
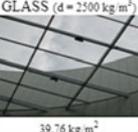
TYPOLOGIES and WEIGHTS		IMPACT CATEGORIES			COMPONENT IMPACT			
ETFE (d = 1750 kg m <sup>-3</sup> )	GLASS (d = 2500 kg m <sup>-3</sup> )	unit kg	ETFE	GLASS	unit m <sup>2</sup>	ETFE	GLASS	
		Global warming pot.	kg CO2 eq kg	88,91	0,85	kg CO2 eq m <sup>2</sup>	67,57	33,80
		Ozone depletion pot.	g CFC-11 eq kg	3,56	0,0001	g CFC-11 eq m <sup>2</sup>	2,706	0,004
		Photochemical oxid.	kg C2H4 kg	7,67	0,56	kg C2H4 m <sup>2</sup>	5,83	22,27
		Acidification	kg SO2 eq kg	102,00	10,60	kg SO2 eq m <sup>2</sup>	77,52	421,46
		Eutrophication	kg PO4--- eq kg	3,12	0,85	kg PO4--- eq m <sup>2</sup>	2,37	33,80
		Embodied energy	MJ eq kg	210,00	18,60	MJ eq m <sup>2</sup>	159,60	739,54
0,76 kg m <sup>2</sup>	39,76 kg m <sup>2</sup>							

Fig. 3 LCA comparison results of glass and etfe as transparent roofing materials. Reproduced from (Monticelli 2010)

(global environmental problems), caused by the emissions and energy content of each product, due to the chemical industry manufacturing chain during the polymerization of monomers to create the granulates. The results point out the importance to assess these light technical solutions not only considering the material stage (relating to their own specific gravity), but also the involved materials in the roof subsystems and, even better, their role in the building.

From the point of view of the Life Cycle Analysis, as shown in Figs. 4 and 5, this comparison of glass/fluoropolimeric plastic highlights how the relation between the weight and the amount of the impact is not linear: “The heavier the material, the more it pollutes” is not the rule, but the production process history and the analysis of the environmental impact indicators, beyond the embodied energy.

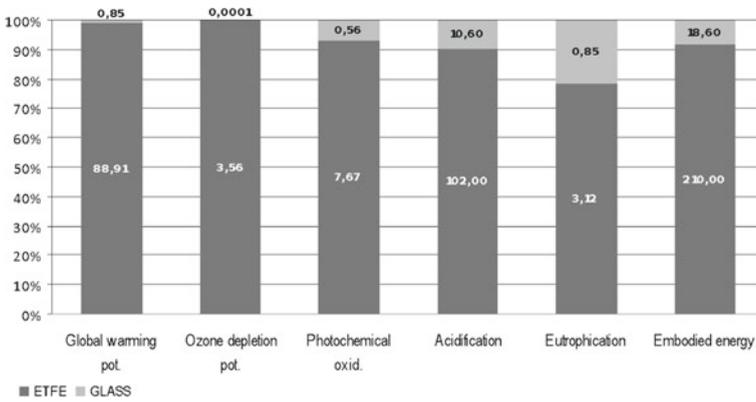


Fig. 4 Results of environmental impacts per kg of materials. Reproduced from (Monticelli 2010)

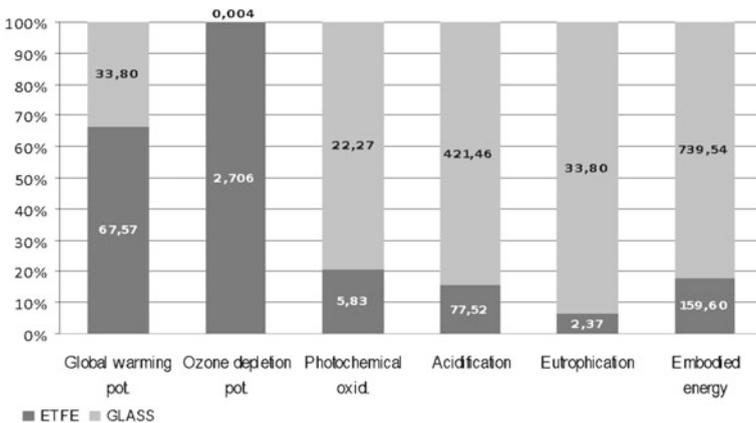


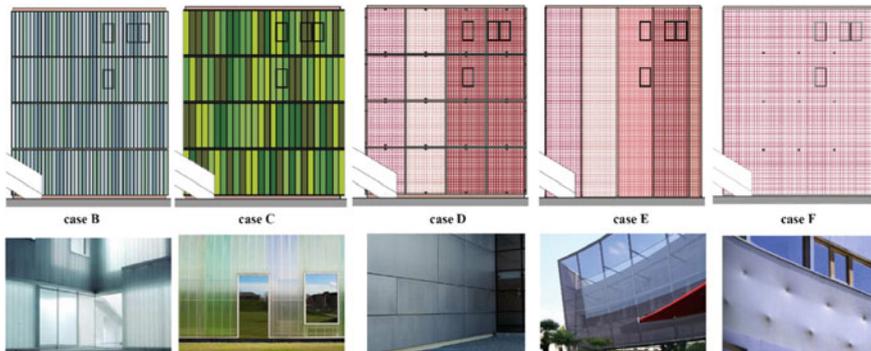
Fig. 5 Results of environmental impacts per m<sup>2</sup> of components. Reproduced from (Monticelli 2010)

## 2.2 *The Ratio of the Environmental Loads Between Different Façade Cladding Systems and Their Structure*

An additional comparative Life Cycle Assessment of the environmental impacts between three lightweight textile facade systems and two standard translucent systems currently on the market (U-Glass and Polycarbonate), designed for the retrofitting project of a social housing building placed in Milan, has been carried out, to show the potential of analysis during the design stage for a conscious selection for materials and building components. The designers should think during the envelope and façade modularity design to improve the benefits of lightweight membranes as a new kind of free-form façade, overcoming the current cladding modularity and optimizing the ratio between fabric panels and supporting elements (Monticelli et al. 2013). The main goal of the LCA application has been the investigation of the environmental impact of five translucent cladding technologies, selected as possible alternative finishing layers of a retrofitting external thermal insulation on an existing wall of a social housing dwelling building placed in the Rationalist district Lorenteggio (1938–1944) in the south-west area of Milan: a U-Glass system, a Polycarbonate system, and three different textile systems on the market. This LCA has been conducted from the point of view of the building sector, and its application between five other cladding systems aims primarily to understand the ratio between the environmental impacts of the fixing tools of each design and these of the cladding layers (Fig. 6).

The results of the analysis of the pre-use phase—from cradle to gate—consisted in the contribution of each façade system to the impact categories, which are environmental emissions and embodied energy. The meaningful comparison is between B, C, D, E, and F; the A is the retrofitted existing wall with the ETICS, a base case (Figs. 7, 8).

Their comparison depicts that the (F) Tex3 with the punching effect has the lowest contribution to all the environmental impacts. It is also the lightest technical solution,



**Fig. 6** The façade design of the different cladding system. Reproduced from (Monticelli et al. 2013)

Impact Category	Unit	(A)	(B)	(C)	(D)	(E)	(F)
Global warming	kg CO2 eq	23159,79	34056,49	35477,68	<b>39318,45</b>	31825,89	28517,26
Ozone depletion	kg CFC-11 eq	0,0020	0,0029	0,0025	<b>0,0030</b>	0,0025	0,0023
Photochem. oxid.	kg C2H4 eq	15,55	22,23	23,41	<b>25,51</b>	20,80	18,79
Acidification	kg SO2 eq	58,57	113,04	102,60	<b>122,77</b>	93,00	79,77
Eutrophication	kg PO4---eq	18,81	38,29	34,10	<b>47,61</b>	33,63	27,88
Embodied Energy	MJ eq	258420,47	429854,29	429821,96	<b>490432,30</b>	380091,09	334509,85

Fig. 7 Pre-use phase—total environmental impacts (emissions and embodied energy) of the six cladding façade systems. Reproduced from (Monticelli et al. 2013)

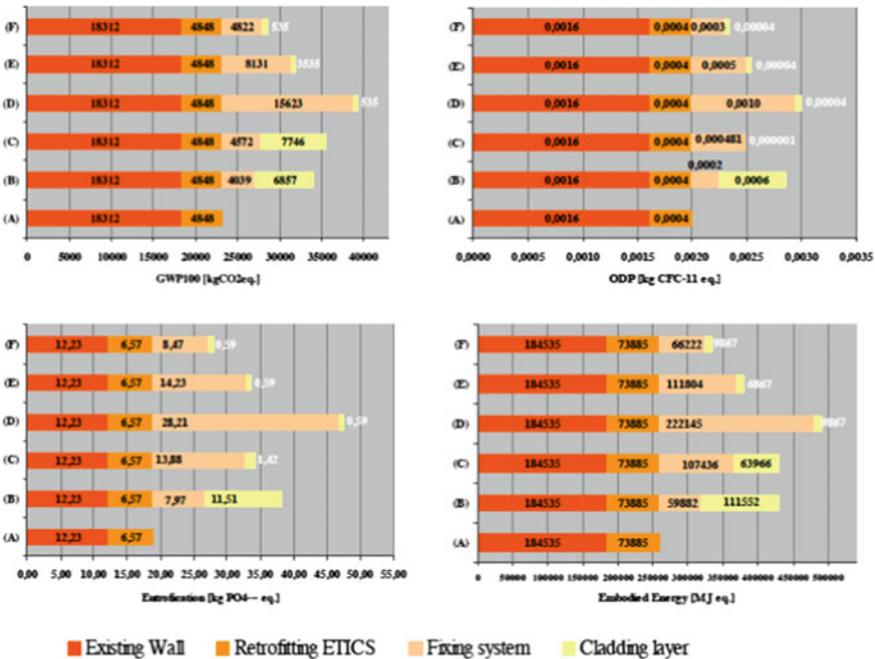


Fig. 8 Pre-use phase—contribution of each part of the compared wall systems to environmental impact categories. Reproduced from (Monticelli et al. 2013)

consistent with the (D) Tex 1, representing the most significant environmental impact contribution. The relation between weight/quantities of materials and impact results is not always so correspondent as said in Sect. 2.2: The (B) U-Glass system is the heaviest but not the most pollutant, and the (D) is the second one in weight but the most pollutant, considering the high quantity of aluminum in the façade system technology, which generates high environmental burdens in manufacturing processes.

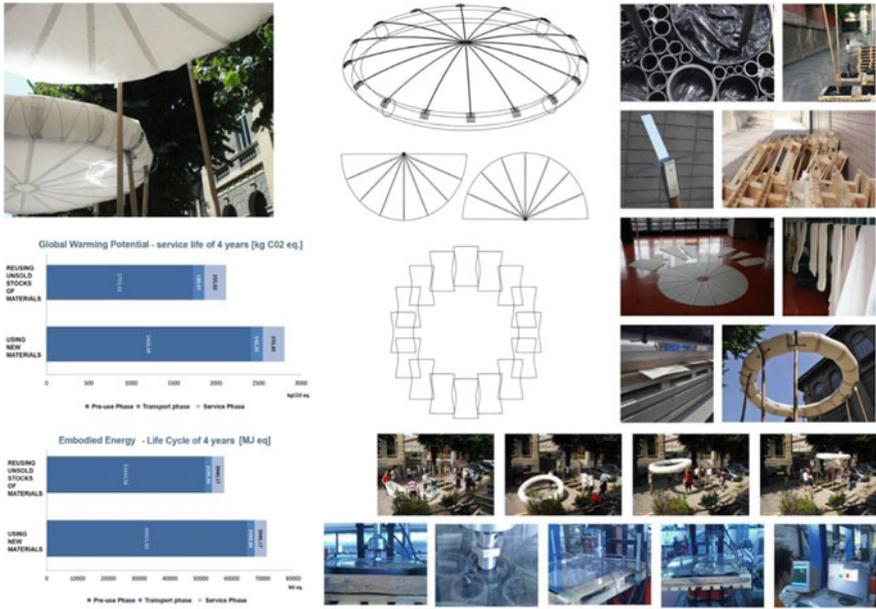
Consideration from a building point of view, which also considers the environmental impact analysis, has to be done: Solution A satisfies the renovation, and the

thermal retrofitting of the walls and their impacts is shown in the Table in the Fig. 7. With the choice of an aesthetical improvement by claddings systems (an optional), the environmental burdens grow thanks to the additional materials and components: (B) U-Glass, (C) PC, (D) Tex1, and (F) Tex3 have, respectively, 166, 166, 190, and 129% more contribution to embodied energy than A; the same applies for the other impact categories. It means that awareness of the designers regarding the environmental performances of their choices has to be expected. The (B) U-glass cladding layer weighs more than the fixing elements (ratio 6:1). Consequently, the environmental impacts of the cladding layer are higher than these of the fixing elements. The weight of (C) PC cladding layer is the same as the fixing elements (1:1). The impacts do not follow this ratio, as shown in Fig. 1; d. (D) Tex1, (E) Tex2, and (F) Tex3 show a considerable difference in weight between the ultra-light textile and the relatively massive weight of the fixing systems, an observable tendency in Fig. 1. The three textile systems show a consistent difference in the results, as a consequence of the design of the façade and the cladding technology system: The (D) seems to be the most pre-fabricated, modular, and adaptable system on the market, and nevertheless, it employs considerable quantities of Al profiles, rendering the technology similar to an assembly of standard rigid panels; the (E) and (F) solutions offer different designs of that façade, improving the textile technology, reducing the profiles, then the amount of material, and at the same time enhancing the actual function of the textile cladding layer, compared to the other rigid cladding layers. All three textile technologies offer the same post-tension of the textile cladding, ensuring good resistance to the wind loads.

The nature of textile cladding layers suggests their application for a curtain wall, made of one foil of material instead of panels, exploiting all their potentials and significantly enhancing the ratio “frame/covered area” by avoiding the use of lightweight fabric with a high weight of the structure, which penalizes the environmental performance.

### ***2.3 The Influence of the Materials and Components Upcycling in the Life Cycle of Lightweight Skins***

The research compares an experimental path of measuring the environmental impacts of a temporary textile pavilion built with recycled materials and supplied within 100 km of distance from the building site and its comparison with the same design solution buildable with new materials. The Nuage pavilion was an ephemeral architecture designed and built by students in July 2013, using recycled PES/PVC textiles to create two toroid pneumatic rings and other recycled materials for shaping the whole supporting system (Fig. 9). Unsold stocks and production wastes of building materials and components (i.e., cardboard tubes, wooden pallets, polyethylene pipes, textiles) have been considered helpful for the short life span of the pavilion, i.e., a maximum of four years. As reuse is often done at a local level scale, due to economic



**Fig. 9** Views of Nuage pavilion installation, an ephemeral architecture made of recycled construction materials, as textiles, cardboard, and plastic tubes, wooden pallets and plexiglas sheet and schematic results of their LCA inventory concerning their storage site. Reproduced from (Monticelli et al. 2013)

savings and energy and emissions savings during the transportation of materials, the study considers the area as much as bounded concerning the building site. The environmental impact assessment was based on the Life Cycle Assessment (ISO 14040) methodology to test the closing loop’s virtuous potentialities and optimize products’ life. The impacts of manufacturing, installation, and short service life of Nuage pavilion were measured, getting more profound knowledge and outlooks of considering the reuse/upcycling design approach in terms of avoiding impacting processes for our common hearth.

### 3 Conclusions

The existing gap between the research approach, which aims to contemplate the environmental performance exhaustively, and the operative attitudes of the designers, answering the eco-efficiency requirements is the step to be overcome. The importance of the definition of the life span of the building and its function, from the first steps of the design process, emerges and has to be considered between the first

design requirements. The author envisages further improvements in applying the eco-efficiency principles starting from the early design phases.

The advantage of the lightweight structure is also demonstrated from the point of view of the environmental impacts, thanks to the reduced involved material amount compared to other technical solutions. The importance of the environmental impact assessment (and the comparison) of light technical solutions is suggested at the material stage, but especially at the building system stage and even better at a building scale. The weight of a building system and its life span, concerning the temporariness or extended use, is crucial to evaluate the effectiveness of the design choices. An important aspect to consider and not underestimate is the relation between the weight of a component and its environmental load: It is not linear and proportional, as shown in the reported case studied (Sects. 2.1 and 2.2).

Concerning the Sect. 2.3 last but not least, consideration is related to the end-of-life scenario: The membrane materials are petrol-based, although the global quantities produced in the membrane building sector are limited compared to other sectors. In any case, the membrane architecture sector is deepening the problem of the end of life and the scenarios “post-use.” Interests might be oriented toward upcycling, reuse (where possible), and remanufacturing as compatible solutions, waiting for the sector’s development toward new sorts of bio-based materials or components made of renewable raw materials and sources.

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# Lightweight Environmental Architecture



Nebojsa Jakica and Maria Giovanna Di Bitonto

**Abstract** The building industry is one of the most energy-intensive industries that also contribute significantly to carbon emissions. The building industry has relied mostly on non-renewable sources dominated by fossil fuels, which are naturally destined to run out and are known for their destructive effect on the environment resulting in climate change. On the contrary, the natural resources-based or so-called bioclimatic design provides a sustainable alternative that exploits natural and climate potential to reduce material resource use and energy consumption. This chapter analyzes active and passive strategies, focusing on lightweight envelope systems from a historical to a future perspective. It demonstrates the global potential of bioclimatic architecture using Sun, wind, and water, both separately and in combination, as the main design drivers. Furthermore, the presented case studies show successful implementations of bioclimatic principles that can inspire future developments.

**Keywords** Active and passive energy systems · Sun energy · Wind energy · And water energy

## 1 Introduction

Numerous resources have reported that the world's largest, \$10 trillion global construction market is responsible for approximately 40% of energy consumption and CO<sub>2</sub> emissions worldwide. It is believed that these high levels of pollution are one of the primary triggers for unprecedented climate and biodiversity crises, also declared by numerous architectural offices around the world recently (Global Petition 2019), as the most serious issue of our time. They also stated: "The research and

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technology exist for us to begin that transformation now, but what has been lacking is collective will. For everyone working in the construction industry, meeting the needs of our society without breaching the Earth's ecological boundaries will demand a paradigm shift in our behavior.”

On the other hand, from a human-centric perspective, we are witnessing a new world health crisis that threatens to cause a series of chain events that will impact how we will redefine the meaning and design of healthy and environmentally friendly buildings. Since we usually spend approximately 90% of our time indoors, and in the current pandemic, even more, the creation of the built environment will be and has already been recognized as a significant determinant that influences public health, accounting for more than 50% of the share (Tarlov 1999).

Moreover, if we compare construction and human resources, the value of the productivity and operational benefits derived from energy efficiency and human comfort can be up to 2.5 times (250%) the importance of energy savings (International Energy Agency 2014). This concludes that healthy buildings have a positive holistic impact on many levels, including building value, return of investment (ROI), and occupant satisfaction (Dodge Data & Analytics 2016). Therefore, it is more relevant than ever to revise currently available sustainable design practices, understanding how the construction industry can revive and reshape to a more sustainable form.

The latest market research shows an enormous interest of close to 90% of construction industry stakeholders to embrace sustainable practices and advanced digital design and production processes in the following years (World Green Building Council 2013). As a pioneer in advanced energy-efficient measures and clean building energy solutions, Europe has established a set of initiatives to reach climate and construction-specific goals. One of them is the Energy Performance of Buildings Directive (EPBD) (European Parliament—Council of the European Union 2018) that requires all new buildings to be nearly zero-energy buildings by the end of 2020.

On the other side of the world, US non-profit organization Architecture 2030 (2014) has made a Roadmap 2050 guidelines and action items for developed and developing countries to formulate custom building sector CO<sub>2</sub> emission reduction schedules to 2050 and a Building Sector Finance Facility program to assist developing countries in planning, designing, building, and financing low-carbon and zero-carbon built environments (Architecture 2030, 2014). Other US initiatives such as green building (US Green Building Council 2014) and well-being (Well Building Institute PBC and Delos Living LLC 2018) certification systems aim to promote the design and construction of human-centric, high-performance, and resource-efficient buildings.

On a global level, the 2030 Agenda for Sustainable Development (United Nations 2015) defines a set of Sustainable Development Goals (SDGs) that aim to address climate change. Relevant SDG 11 proposes to “Make cities and human settlements inclusive, safe, resilient, and sustainable”. Enhancing accessibility and capacity to use data for decision-making is strongly advocated in the New Urban Agenda for sustainable urban/territorial development (United Nations 2016). Cohesive and synchronized data generated through collective, participatory processes are crucial

to planning and monitoring cities in the twenty-first century and empowering citizens. Intersectoral partnering to harness the explosion of available data, technologies, skills, and opportunities to connect multiple data sources is essential to unlocking data for evidence-based decision-making (U.S. Department of State 2016). However, as recognized by the Global Partnership for Sustainable Development Data (GPSDD), interoperability across the data lifecycle and value chain needs to be addressed to support evidence-based decision-making to achieve the SDGs (Morales and Orell 2018).

## 2 Active and Passive Lightweight Design Strategies

### 2.1 *Historical Overview of Active and Passive Design Strategies and Technologies*

To understand these challenges and propose possible scenarios for an increased impact, it is worthy to remind ourselves of some essential design strategies that shaped the progress of environmental architecture throughout history, especially concerning the world crises. It is widely known that passive design strategies have been an integral part of vernacular architecture. Traditional builders used an experience-based approach that relies on extensive knowledge of local climate generated through personal and collective experience over long periods. Building technology and material scarcity have usually imposed limitations on locally available materials and comfort strategies based only on passive methods. The building and urbanization process was extremely slow compared to the current urbanization, usually taking decades of experience and knowledge of local materials and climate habits to shape buildings and cities. *Genius loci* and respect for the landscape and climate were unavoidable due to the lack of tools to change and adapt environments to people's needs.

Furthermore, due to the limited and locally bonded knowledge sharing and knowledge diversity across cities, competencies were scattered among individuals and relatively small groups of builders and craftsmen, a general characteristic phenomenon for the pre-industrialization period. Knowledge was connected and applicable almost exclusively to the local climate and culture, firmly rooted in a place that could not be transferred to another climate. Variability of climatic conditions made it very difficult and impractical to scale the same traditional concepts regionally and globally without available technologies that could manage comfort in any climatic conditions—Fig. 1.

In the late nineteenth and early twentieth century, especially in the pre-electricity times with increased urbanization, passive strategies such as daylighting were employed extensively as there were no practical alternatives to light up substantial indoor spaces such as early factories. Daylight prisms were a solution to increase daylight and improve user comfort and therefore worker's productivity. There were many applications and companies that produced these prisms, and even Frank Lloyd

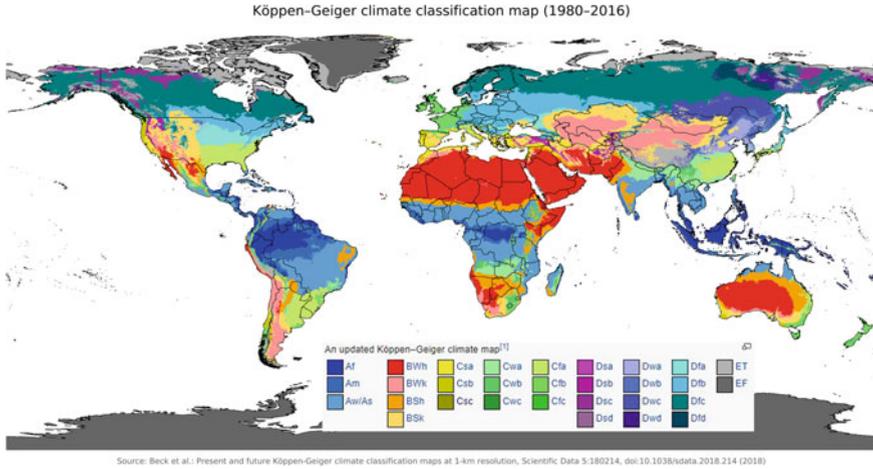


Fig. 1 Köppen-Geiger climate classification map. Reproduced from Beck et al. (2018)

Wright had designed those tiles and developed more than 40 patents in this field for the Luxfer brand—Fig. 2.

Globalization, industrial revolutions, and a rise in standard and comfort have imposed numerous challenges on the applicability of passive strategies universally. Passive strategies have lost their momentum primarily due to the technological revolution. Technologically advanced, active design strategies have offered a plethora of advances across many domains, including temperature and humidity control via mechanical ventilation, solar radiation control via spectrally selective glazing, to name a few. The process of electrification that accelerated after the Chicago world fair in 1893 and the rise of alternating current, combined with the abundance of the relatively cheap energy, almost marginalized only daylighting passive strategies at first. Electrification has enabled the development of many technological systems in

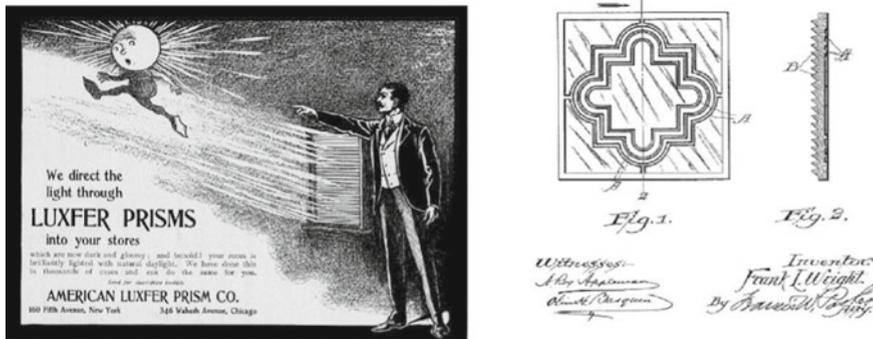


Fig. 2 Luxfer prisms by Frank Lloyd Wright. Reproduced from [www.glassian.org](http://www.glassian.org)

the following decades that caused neglecting the benefits in energy savings and user comfort during building operations.

Currently, the experience-based approach is mainly used in developing countries with limited access to new technology and in rural areas with limited access to electricity distribution networks. One of the rare exceptions is the example of architect Glenn Murcutt. As a Pritzker prize laureate, he contributed to the environmental architecture embedded in his buildings. His approach to design with Sun, wind, water, landscape, soil, and trees as building materials has helped him create comfortable spaces within self-sustaining buildings, even in the harshest conditions of highly remote areas of Australia. He capitalizes only on passive natural resources on every location by carefully observing and analyzing climatic conditions, Sun movement, shadows, tree leaves together with their seasonality, water, and wind flows. His buildings relate to the surrounding nature and work with the climate, not ignoring it.

However, the impact of the architect is quite limited for worldwide adoption for multiple reasons. Firstly, he usually designs one-family residential buildings in rural areas. Using the same approach for multi-family residential and office buildings in urban zones would not be easily replicable. Secondly, his buildings are scattered across similar climates, usually hot and dry. Working for a building in other climates, such as hot and humid, would require either complete change in passive strategies, upgrade the skills, or extensive learning of local techniques over long periods. Thirdly, the concept relies on frequent site visits for personal observation of site-specific microclimate over long periods. This approach is quite impractical nowadays with the increase of architectural practices working worldwide in a very time-constrained manner. Furthermore, as the process is personalized, it is impractical to scale and work in groups on large projects in different parts of the world. Figure 3 shows one of his buildings that uses several passive strategies such as solar shading, wind for natural ventilation and night flushing, and rainwater collection.

With rapid technological progress in the early twentieth century, architecture was reshaped through exciting experimentation with two new materials: reinforced concrete and glazed walls. Despite their numerous advantages in an architectural



**Fig. 3** Glenn Murcutt—Arthur and Yvonne Boyd Education Centre, Riversdale, Australia. *Source* Photos by Anthony Browell

design domain, their environmental footprint, both in embedded carbon and thermal behavior, has paved the way for the energy and carbon-intensive construction sector. Moreover, new aesthetics proposed by famous architects, such as Mies van der Rohe in the form of glass skyscrapers, has focused on elegant, bright, and transparent glass curtain walls that presented a breakthrough and completely new direction in international architecture. These ideas have opened new possibilities, especially for tall buildings, and defined modern international style, and in that terms, their influence on architecture is immeasurable. However, besides outstanding aesthetics, their poor thermal performance brought very inefficient solar heat gain control and energy loss that caused a great need for mechanically controlled cooling and heating. Consequently, energy-intensive mechanical ventilation, heating, and especially cooling caused a dramatic increase in energy consumption. Moreover, full glazing without the efficient coating that we have today created excessive glare that resulted in closing these transparent and elegant glass surfaces with curtains and making buildings less appealing—Fig. 4.

Since then, energy inefficiency and user discomfort of the glass curtain walls have struggled with engineers and architects trying to find solutions in the form of solar shading, dynamic shading systems, electrochromic windows, low-e glazing, microstructured shading, etc. Even when technological progress accelerated after WWII, especially in the US, and performance gradually increased, it was still far from



**Fig. 4** Mies van der Rohe’s proposals for glass skyscraper (left and center) and Lake Shore Drive skyscrapers (right). *Source* Mies van der Rohe Archive Fund

optimal. When mechanical ventilation and heat-resistant glazing were introduced on the market, first through theaters and later in Belluschi's Equitable Building in 1948—Fig. 5, the modernity and convenience of the solutions have provided unprecedented possibilities for architects to explore mechanically ventilated airtight solutions further. Furthermore, one-system-for-all made it possible to detach from and ignore the local climate and neglect performance losses as long as the energy is supplied.

Parallely to this development, the Olgyay brothers have been setting up and defining what would be known as the first global modern environmental architecture or bioclimatic approach to architectural regionalism (Olgyay et al. 1963). In their full-scale labs, they started testing the effect of wind, daylighting, and solar effects on buildings. Empirical data were processed, and results were presented in bioclimatic charts and timetable of climatic needs—Fig. 6. This helped establish a rule-based approach to environmental architecture that can be applied globally to arbitrary bioclimatic conditions.

One of the most significant advances of this approach was the rules of thumb for the solar design that defined how shading devices should be designed according to latitude and orientation (Olgyay and Olgyay 1957). The concepts were quickly adopted by some of the most prolific architects at that time, Le Corbusier and Oscar Niemeyer, in the form of *brise-soleil*. It soon became a defining architectural element for that era and is still present today in various forms. Furthermore, Olgyay's graphics may be considered a foundation for the integrated graphic charts for passive design strategies that followed. This standardized visualization framework represents a great way to interpret any specific climate with its characteristics.



**Fig. 5** Belluschi's Equitable Building in 1948 (left). Reproduced from Leslie et al. (2018) and United Nations HQ in New York in 1952 (right). *Source* Photo from wikiarquitectura

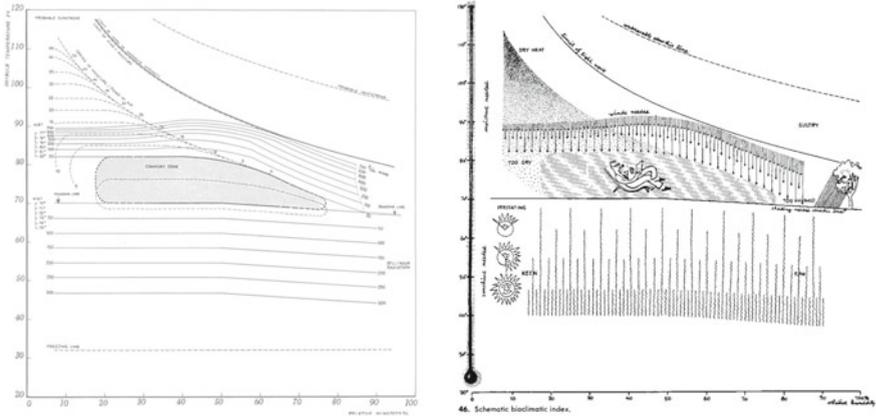


Fig. 6 Olgay brother’s bioclimatic charts. Reproduced from Olgay et al. (1963)

The progress from early enthusiasm for solar radiation by any means and in every circumstance toward awareness of the traps of single-glazed facades is visible in the example of Le Corbusier’s Cité de refuge building in 1933. The original fully glazed design was revised after WWI due to the highly uncomfortable indoor conditions caused by overheating. Window-to-wall area and brise-soleil were introduced to mitigate excessive solar heat gains on the south-facing façade—Fig. 7.

Although very direct, prescriptive, and reasonably accurate, the rule-based approach has proposed geographical scalability and internationalization of styles. However, over time, the method using repetitive concrete shading elements has been regarded as redundant and limited in customization and local interpretation. The competition for the new United Nations HQ in New York in 1952 revealed the consequences of direct competition between modern heat-absorbing glass façade and more



Fig. 7 Le Courbusier Cité de refuge building in 1933. Source Photos by Olivier Martin Gambier, FLC/ADAGP

performing brise-soleil solutions—Fig. 5. The defining moment for modern architecture and international style envisioning fully glazed buildings has shown a preference for modernity and technological supremacy over architectural regionalism, the trend that still prevails.

From a historical perspective, even a substantial OPEC oil crisis in 1973 has not been enough to revolutionize energy-intensive modern and post-modern architecture. During that time, efforts in environmental architecture were epitomized through “rediscovered” bioclimatic charts by Baruch Givoni (1969). While Olgyay’s bioclimatic chart simplifies the climatic characteristics by displaying and identifying the climatic needs related to human comfort, it still does not effectively connect and communicate what building strategies to apply at certain conditions. Moreover, these charts refer mainly to the outdoor conditions and do not account for building effect on indoor comfort. Givoni aimed to overcome these apparent limitations by defining design strategies related to identified climatic needs. He plotted design strategies on a conventional psychrometric chart identifying comfort zone boundaries in the center and boundary regions for design strategies as “expansion” of the comfort zone. He applied graphic calculations to an extensive range of passive, passive-active, and active strategies for achieving human comfort for all regions. In decades that followed, Murray Milne and others have been refining and adding more calculations on the chart (Milne and Givoni 1979) and extended this approach daylighting design (Milne and Zurick 1998) and many other strategies, including carbon footprint (Milne et al. 2009).

This approach evolved over time through constant adaptations into a tool with the most extensive set of passive measures so far—Climate Consultant (Milne et al. 2009). The tool works as an expert system that automatically interprets each location’s climate data to create a unique set of the “Top 20 Illustrated Building Design Guidelines.” The most up-to-date bioclimatic chart representing the most important passive and active design strategies of the design tool is presented in Fig. 8.

This graph is still used nowadays in architectural and HVAC engineering to estimate the potential and limits of passive and active strategies. Except for strategies 1, 12, and 13, conventional heating and air conditioning without and with dehumidification, respectively, all of the strategies are considered passive and, in theory, may be used to provide comfort for those hours of the year representing a set of conditions fall within boundary areas of some of the passive strategies.

A similar tool, BcChart, that uses Olgyay’s bioclimatic chart, instead of Givoni’s one, is also developed to define a set of the most effective strategies for any given climate in a quick and straightforward process—Fig. 9. Contrary to other bioclimatic tools, the main advantage of the tool is that it highlights the influence of solar radiation, which is factored through substitutive daily comfortable dry-bulb air temperature (Košir and Pajek 2017). The tool evaluated bioclimatic potential analysis against heating and cooling demand results from simulations of a generic building model using Energy Plus in five selected locations within the Alpine-Adriatic region characterized by a large diversity of contrasting climates inside a relatively small area (Pajek and Košir 2017). The results showed that BcChart tool could identify

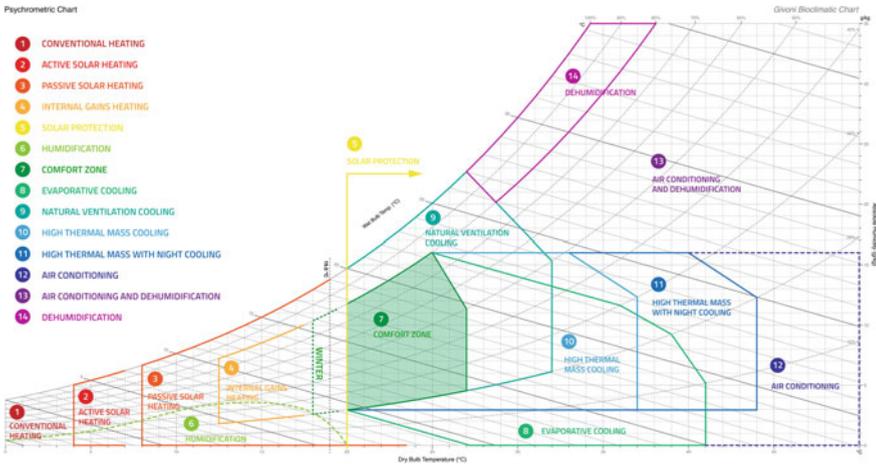


Fig. 8 Updated Milne-Givoni building bioclimatic chart (edited by the authors.)

appropriate passive strategies to be applied in building design at a specific location, resulting in smaller energy usage and higher indoor comfort.

Furthermore, the tool was used to assess the bioclimatic potential of European locations using GIS to acquire typical meteorological year (TMY) data comprised of climate characteristics, such as air temperature, air relative humidity, and received solar irradiance (Pajek et al. 2019)—Fig. 10.

However, all these assumptions are based on generic shoebox room models that may not reflect exact matching with the specific buildings proposed by architects. Paradoxically, with every new specific criterion, a new set of assumptions have to be made, which consequently leads to genericism. While increased resolution alone may uncover previously hidden climatic data, it alone has a minimal influence on

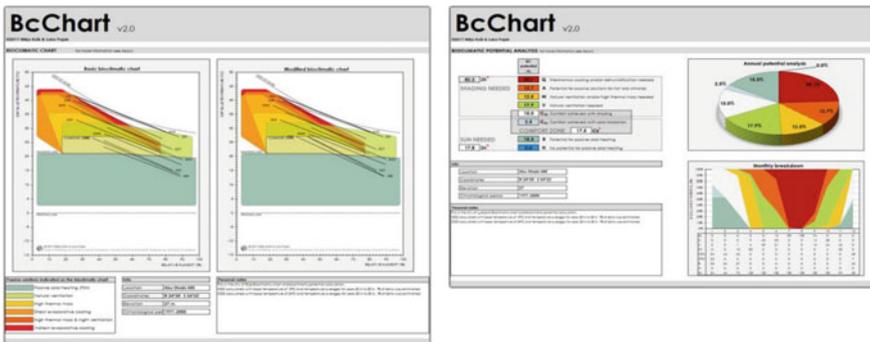
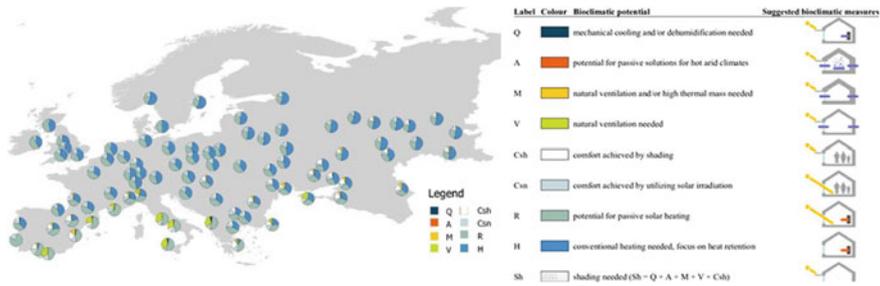


Fig. 9 BcChart v2.0 user interface screenshots: left—bioclimatic chart (basic and modified bioclimatic charts), right—bioclimatic potential analysis (yearly cumulative and monthly values of bioclimatic potential). Reproduced from Košir and Pajek (2017)



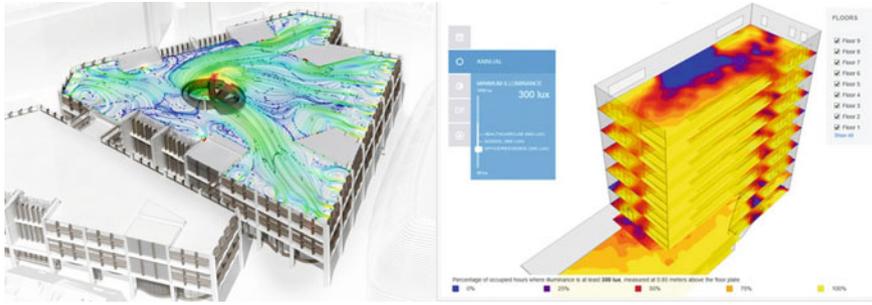
**Fig. 10** Bioclimatic potential of European locations using BcChart. Reproduced from Pajek et al. (2019)

architects’ specific design response to the architectural brief. While the approach succeeds in identifying bioclimatic building strategies, it does not adequately address the needs of architects in quest of creating new or adjusting existing strategies for a custom design. A fundamental limitation may be seen in the dual purpose that such tools deliver in the design process.

On the one hand, they must provide standardized quantifiable data for a location, while on the other hand, they must enable customized responses for the authored design position. Only generic visualizations tend to create generic design responses or altogether unrelated responses posed as a solution to fill the void of generic processing (Steinfeld et al. 2010). Furthermore, most of the users find these types of tools helpful to understand an unfamiliar climate. Concerns are commonly expressed in the lack of flexibility with software output that is not engaging and supportive in the later design stages (He and Passe 2015). Therefore, the rule-based approach remains limited to the early design stages in current practice. The expectancy of a set of passive strategies to direct the design process, neglecting the context of a building-specific program due to the technical constraints of their era, has become a primary characteristic of the rule-based approach.

After decades of adjustments and iterations, the rule-based approach seems to have reached its peak in terms of design guidance. Complexity and mass scale of the construction market demand much more than generalized bits of advice. This is especially true in the later design stages, where custom design strategies with higher accuracy are demanded. Rule-based tools for these purposes have been upgraded to simulation-based tools that provide much more possibilities to verify the performance of the proposed design strategies. However, thoughtful understanding of the climatic data through informative and holistic bioclimatic charts has been and hopefully remains at the core of the environmental architecture strategies.

From the early days of environmental architecture, it has become clear that climatology is highly data-intensive with all of its factors. Due to the limitations of that time, rule-based approaches were an excellent fit to extract meaning from data abundance and represent it straightforwardly. However, with the increase of computational power came the ability to work on much more extensive data points. Previously unfeasible without making assumptions, it has become possible to simulate natural



**Fig. 11** CFD airflow model for Bloomberg HQ by Foster and Partners (left). Reproduced from CIBSE (2017) and Sefaira raytracing simulation for daylighting (right). Reproduced from Sterner (2021)

phenomena such as air movement, daylighting, heat flows with advanced computer-driven methods of Computational Fluid Dynamics—CFD, raytracing, Finite Element Method—FEM, respectively—Fig. 11.

The simulation-based approach also breaks away from lengthy personal observations on-site and organizes the whole observation process through climatic data in weather files. This not only allows faster insights but allows working for distant locations worldwide without ever going on-site. It is not uncommon for large projects, budgets, and companies to organize groups of people working remotely for a site they have never experienced in person. These practices usually rely on local support in cross-checking design strategies and adjusting them to the local tradition and available technologies.

For achieving accuracy, a necessary framework in all domains has enabled the development of design strategies to extend to any area and detail as far as design strategy needs it. On the other hand, the technological development of tools and experimental testing has allowed customization of the workflows to the design strategies concerning climatic conditions. Furthermore, customized workflows have enabled customized solutions that can be simulated with higher confidence. The complexity of the climatic conditions seems to be matched with the complexity of the tools to provide accurate assumptions of it.

However, the complexity of the tools, strategies, and processes does not necessarily lead to better results. Assessing single performance alone may produce reasonably accurate assumptions only when knowing what type of phenomena could be simulated. Furthermore, results greatly depend on the boundary conditions and parameters that define the problem. Given these constraints, a designer must understand all factors influencing design performance to deliver a more performing solution. With the increase of simulated performances, the complexity rises and often exceeds the capacity of an individual to handle efficiently. Usually, teams are required to work on improving solutions where every member takes responsibility for one domain. However, the complexities of domain-specific problems bring integrative design strategies at a challenge. Orchestrating and integrating groups of people

working in various fields with different software may represent an equal challenge they need to solve. Interoperability, timing, computational capacity, organization structure, flexibility to change, and communication efficiency are just limitations of the simulation-based approach that heavily relies on data-intensive processes. Furthermore, these digital design processes are susceptible to numerous simulation parameters, thus requiring excessive knowledge.

On the other hand, constant performance simulation may distract from the design process, break the flow, or even constrain creative spark. Potential traps may also occur when one of the crucial strategies is not recognized and is consequently neglected. Unfortunately, in these cases, buildings will expose all the overlooked parameters much more costly.

## ***2.2 Toward Active and Passive Lightweight Design Strategies and Technologies***

### **Technological Development and Scarcity**

We have previously discussed how technological development has influenced environmental architecture strategies and how active strategies have slowly become dominant over passive ones. Technical systems have enabled building even in areas with extremely harsh conditions at much higher density and comfort than would be possible with passive designs. As long as there are an available energy supply and adequate budget, buildings can emerge in any size and material. Practically, active only, one-size-fits-all strategies offer comparatively more straightforward solutions and the potential to respond to climatic complexity than passive strategies that require careful planning and are limited to climatic potential.

It seems that in periods of prosperity, technology can push the very limits of the human imagination and possibility. Glass skyscrapers, fully glazed facades, and mechanically ventilated airtight city districts, all are possible even in extreme hot and cold climates. Such severe cases raise the famous dilemma: Technology is the answer, but what was the question? Yet, crises reveal the full potential of such solutions to sustain their operation from time to time. Such concepts struggle to run whenever there is an energy blackout, rise, or shortage of energy and oil supplies and prices. In these scenarios, society always turns to alternatives, or in other words, turns to passive strategies. Various factors such as politics, economy, and branding, among others, may still drive demands for iconic buildings that neglect context and climate at any cost.

Hopefully, such examples will slowly diminish as society worldwide defines new sustainable strategies to implement passive measures while successfully integrating active systems. Inspiration may come from communities with technological scarcity and a lack of conventional energy sources, where solutions are much more bonded to the local resources used efficiently. The energy captured from Sun and wind and water extracted from the air are just examples of smart usage of natural resources. With the current climate and biodiversity crises, the construction community must

learn to work with fewer materials, use less energy, produce less waste, and emit less carbon.

Subtractive manufacturing techniques would eventually be replaced by additive manufacturing, which may produce customized on-demand solutions at custom quantities, with zero waste and minimal logistics. Smart energy management, including reduced consumption and local generation, will supplement existing centralized networks to provide more resilient systems capable of withstanding extreme weather and demands. Decentralization and localization of energy use that match temporal and spatial demands represent a promising strategy for personalized comfort and needs.

The potential for integration of active and passive strategies seems to grow bigger with every technological advancement. With ever-increasing technological progress under the umbrella of the new 4.0 industrial revolution, building systems have undertaken radical improvements in terms of material development, system efficiency, connectivity, and interactivity over the last decades. Lightweight versions of traditionally energy-intensive materials, such as glass, concrete, and crystalline PV cells, have emerged and uncovered their potential to replace old ones. Materials such as ETFE and thin-film PV have already shown that they can be reliable energy and carbon-efficient alternatives.

It has also become clear that we do not necessarily have to rely only on hardware components to achieve higher energy efficiency. Instead, greater efficiency may be achieved with software solutions that use available and installed equipment that responds to occupant demands in real time. Improving building smartness with building management systems that respond to the personalized comfort of the occupants may cause dramatic improvements in the available system's efficiency. Human-centric design with personalized comfort models is receiving more attention worldwide as high-tech companies expand their offer in other markets. Internet-of-Things (IoT) integrates all devices and creates ubiquitous systems capable of sensing, processing, and optimizing performance. Recent rapid developments in machine learning and artificial intelligence will provide various tools to augment all design and operation processes. The main question that remains is how fast society is capable of making a shift.

### **3 Solar Lightweight Design**

Technological advancements of active systems have allowed people to harvest natural resources and allocate them spatially and temporally to suit their needs, mitigate climate peaks and lows, and create balanced environments throughout days, seasons, and years.

Advances in solar technologies have been dramatic over the past decade. First, struggling with the efficiency ratio and high price, solar depended on government subsidies until it became self-sufficient. As a milestone of dropping the cost per Wp installed below \$1 has been passed (Jäger-Waldau 2019), solar has been put in

the spotlight for reaching another, even more, an important one—grid parity. This breakthrough point has already been achieved in some countries, and as this trend continues to grow, it will disrupt the energy sector. The current production rate of solar power out-passes installed power, which leads to the conclusion solar needs more creative ways of implementation (IEA PVPS Task 15 Subtask E 2019b).

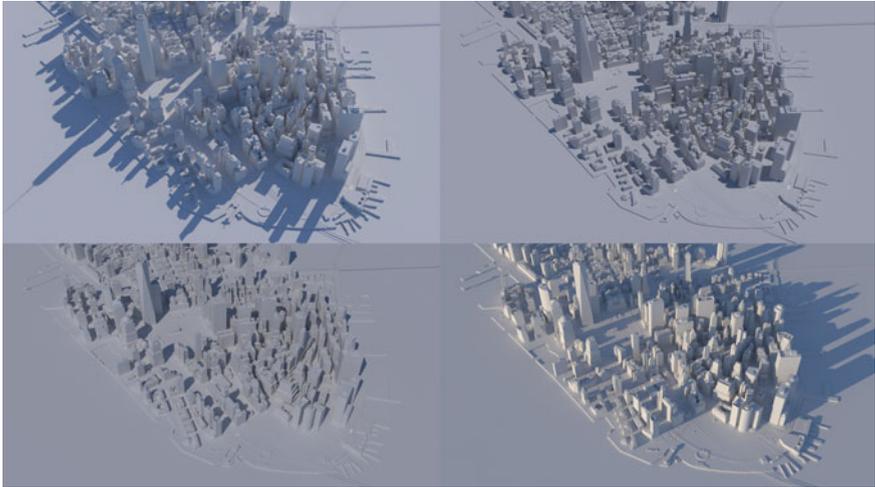
So far, integrating solar power in buildings has mainly focused on rooftop solar, being flat or pitched. In most cases, PV panels were just mounted or attached on top of building constructions without considering the design and aesthetics of integration. Such an approach has created a very negative perception among architects that solar power, although rational and sustainable, in most cases decreases design value. Adding strict technical requirements of c-Si as the most adopted PV technology and relatively high price, it is clear why PV has not played a more significant role in the building sector.

However, all these main barriers seem to be outdated nowadays. Novel PV technologies, single or multi-junction, allow much more design freedom as they are less Sun angle-dependent, meaning they work almost equally efficiently under cloudy conditions or even north facades Fig. 12. PV cells have become thinner and, therefore, more suitable for being integrated with various rigid and flexible substrate materials and curved surfaces. Spectrally selective foils have allowed playfulness of colors to be explored in a range of solutions from partial to fully covering PV cells, even with a low impact on PV performance, as with the latest announcement of Tesla rooftop solar that PV energy comes at no additional price and, in that sense for free, the classical rational approach of calculating the return of investment will become obsolete. This price drop had closed the innovation and improvement cycle and set a perfect ground for PV to thrive and be more competitive with other building materials and solutions. Since design possibilities have become endless, we can expect much more innovative ways of building-integrated photovoltaics (Jakica and Zanelli 2017).

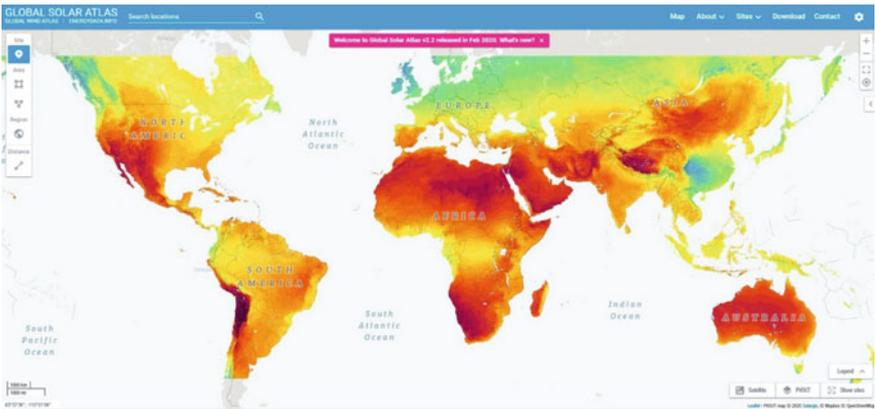
One of the necessary steps for increasing and accelerating BIPV adoption would be to quantify the energy generation potential in high-density urban areas considering all building surfaces (IEA PVPS Task 15 Subtask E 2019a). The extent of the majority of current simulation approaches is limited to rooftop solar as the most rational way of placing and orienting solar panels. However, this approach becomes very limited with the increase of floors and therefore height, so the total floor to roof ratio reaches high values. Consequently, the potential of solar power to cover energy loads becomes extremely low.

### ***3.1 Energy Potential of Lightweight Solar Skins***

As documented numerous times, worldwide solar energy potential is enormous, and it is theoretically the largest and the most abundant energy resource on the Earth (De Castro et al. 2013). The theoretical potential embodies the foundation for all assessments of photovoltaic potential—Fig. 13. Estimates are that counting only



**Fig. 12** Shadow and sunlight availability studies of Manhattan Downtown (edited by the authors.)



**Fig. 13** Global Solar Atlas. *Source* Global Solar Atlas 2.0<sup>1</sup>

the landmass alone and ignoring coastal water areas, one hour of insolation is the equivalent to more than the world’s energy consumption for an entire year (Tsao et al. 2006). Even with the current energy conversion rates of around 20%, it is still an enormous energy potential. It is estimated that the share of PV by 2050 could be three times as large as previously assumed, between 30 and 50% worldwide, and not as current estimate of between 5 and 17% (Creutzig et al. 2017).

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<sup>1</sup> [Data/information/map] obtained from the “Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group,

Therefore, taking only Sun from all of the available natural energy sources can, in theory, be more than enough to supply energy across the globe by a high margin. So, the question is why we have failed to exploit it so far? An even more relevant question would be what action we should take to fulfill at least a fraction of its full potential and make a substantially more sustainable society?

However, the cumulative solar energy parameter does not reveal the whole nature of solar radiation. When considering discrete instead of cumulative behavior, solar irradiation is very inconsistent over time and space. A myriad of factors such as latitude, altitude, atmosphere, sky cover, solar angle, wind patterns, and humidity, among others, influence fluctuating ratios between constant extra-terrestrial solar radiation and inconsistent solar irradiation on Earth's surface. Furthermore, urban zones introduce complex shading patterns that challenge PV system connection types and lower energy output. On the other hand, from the demand side, people simultaneously require constant indoor comfort during operational time within relatively narrow domains across a combination of parameters. By comparing highly oscillating temporal behavior and dynamics of solar irradiation and consequently heterogeneous cumulative solar irradiation over the Earth's surface, it becomes evident that solar energy does not represent a perfect fit throughout time and for every place on Earth. Therefore, for every place on Earth, a specific solar design strategy should be created to respond to microclimatic and urban conditions.

### ***3.2 Temporal Potential of Lightweight Solar Skins***

A temporal strategy is based on mitigating solar heat gains that may fluctuate extensively throughout the day and potentially have substantial seasonal oscillations. These oscillations may cover a wide range of scenarios, from the absence of energy during nighttime to the harmful radiation, usually during the afternoon. Mitigating solar radiation is commonly referred to as passive solar design. In contrast, shading systems performing this task are static and dynamic, depending on their adaptive properties to change over time.

On the other hand, active solar design implies that solar technology extracts energy from solar radiation. While over radiation periods may be mitigated via passive design strategies, periods without solar radiation have to use other energy sources to meet the demand. Secondly, during the last decades, rapid urbanization has brought many people to live in high-density urban areas and therefore intensely concentrating energy demand. Since cumulative solar radiation on landmass produces a much more uniform distribution than energy demand, it imposes a challenge on how to fit the energy demand in urban areas by using natural resources, particularly solar energy, and how to achieve self-sufficiency ultimately. Therefore, careful balancing of solar radiation throughout days and seasons represents the ultimate goal in solar design.

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*utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: <https://globalsolaratlas.info>*

This is important for the building energy balance and visual comfort defined through daylighting and glare and thermal comfort that affect occupants' well-being and productivity.

### ***3.3 The Spatial Potential of Lightweight Solar Skins***

While temporal potential is theoretically the same for building-integrated and stand-alone PV systems, assuming the same angle settings and shading environment, the spatial potential is significantly reduced in the urban zone compared to stand-alone PV. Stand-alone PV uses the best tilt angle and orientation to produce cumulatively maximal energy output. On the other hand, PV in the urban environment is exposed to non-optimal settings at various scales Fig. 14. Traditionally, solar studies for PV potential in the urban environment have been focused only on rooftop areas. This included flat roofs with a possibility for the optimal PV angle settings and pitched roofs with variable angles and rotations. In the majority of cases, these studies were conducted for relatively less dense urban zones, predominantly single-family residential buildings. In such cases, the usable floor to roof ratio is more than enough to provide energy for achieving the zero-energy target in the majority of climates. However, with the increased density and average height of buildings, this ratio decreases. Therefore, it is viable to consider even non-optimal surfaces such as facades to provide additional energy to reach the same target. Although not ideal in terms of angle settings, the solar area of facades may potentially be orders of magnitude more significant than those of roofs. Therefore, when considering solar potential, the granularity of the urban matrix determines the feasibility of BIPV facades.

The spatial potential has another component related to the proximity of the PV energy source to the place where energy is used. Figure 15 shows the global urban footprint mapping of human settlements. Urban zones cover a relatively small world area, while more than half of the human population lives in these areas. Therefore, spatial energy management has an enormous impact on energy efficiency. Traditional energy systems are centralized, meaning that energy is produced off-site at a much lower cost per Wh at one place and then distributed to the energy users via energy grids. However, BIPV challenges that model by introducing the potential for on-site energy generation, thus eliminating the need for energy grids. This strategy has already been proven in the areas with a lack of other natural energy sources and where the Sun was the only remaining option. However, such cases have shown that the decentralized energy concept is more resilient to external events than a centralized one. Therefore, this chapter aims to demonstrate the potential for on-site solar energy harvesting for any type of spatial complexity and location.



technology, resulting in a massive increase in industrial production capacity. Therefore, all these parameters create a general tendency to decrease levelized cost of electricity (LCOE) and achieve energy parity with other energy sources. Some countries with high solar potential have already reached that parity, even with relatively low fossil fuel prices.

What is more interesting for the building sector is economic projections considering the building lifecycle. It is a common notion that better-performing buildings are usually more costly. This cost difference relative to the baseline is considered through ROI. Therefore, every investment in building performance, in this case in BIPV, can be evaluated and multiple alternatives compared. A study (Ferrara et al. 2018) showed that nZEB buildings represent a cost-optimal solution over the building lifecycle of 20 and 25 years, depending on the building function.

Figure 16 shows a hypothetical case that demonstrates the economic optimality of nearly zero-energy and plus-energy buildings considering the building lifecycle. While ROI always focuses on short-term payback, when considering the building lifecycle of even 25 years, the majority of BIPV systems will become much more interesting investments. Moreover, the graph shows economic potential for plus-energy building that theoretically may provide financial income. No other building material may be a candidate for such an opportunity.

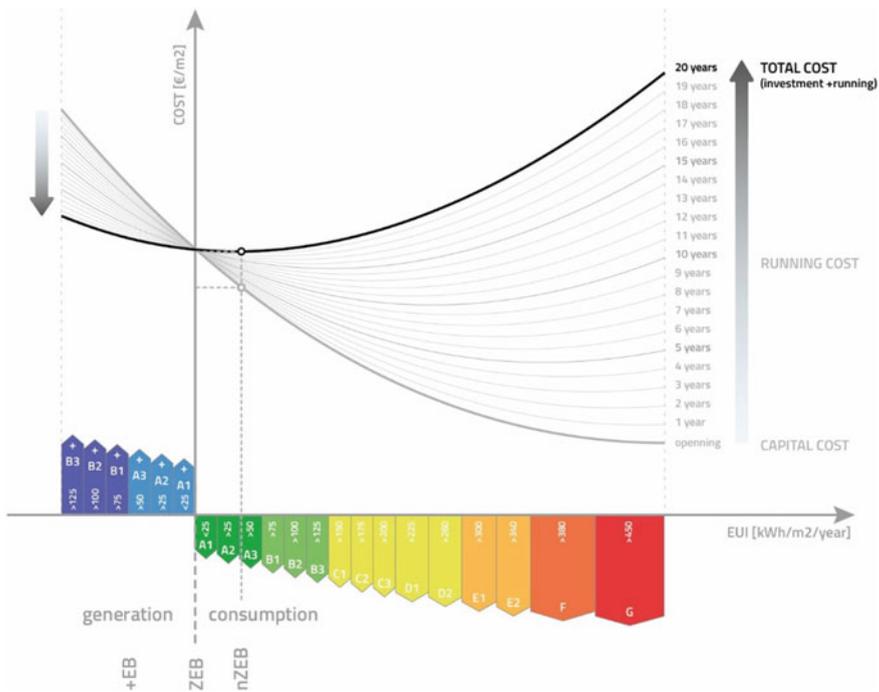


Fig. 16 Cost-optimal zero and plus-energy buildings (eited by the authors.)

### 3.5 *Material Potential of Lightweight Solar Skins*

Very often, active systems are coupled with passive ones to maximize efficiency. The solar design represents such a case where solar energy can be harvested passively through solar heat gain. At the same time, it can be used to generate power from solar radiation. Balancing these two approaches may be challenging, especially in the case of facades where multiple performances, including architectural and engineering disciplines, occur. Placing any type of solar device, whether shading or solar panels, on facades requires the delicate work of architects and engineers. Not rarely, these systems may be defining elements of buildings and even architectural styles. Original brise-soleils of Le Corbusier have defined modernism in the same way as roller-blinds have defined international style fully glazed skyscrapers. Material rigidity and durability have traditionally determined the placement of shading elements inside or outside.

While external shading elements were usually rigid and durable, interior shading was reserved for flexible and lightweight materials that were replaceable. However, technological progress in lightweight materials has enabled materials resistant to UV-light, chemicals from the air and rain, thermally and mechanically resistant to thermal cycling during years of operation. ETFE, PTFE, woven, and non-woven fabrics, among others, have become an attractive material choice due to the multiple advantages over rigid and opaque material counterparts. Flexibility, variable transparency, clarity, color, and texture have provided countless possibilities for exploiting architectural aesthetics. More importantly, these material properties have also enabled numerous options for adaptation to the local climate, culture, and built context. Today, we can find lightweight exterior shading across many climates and in many forms. For example, transparency and coating selectiveness could vary from opaque in Riyadh, Saudi Arabia—Fig. 17 (right) up to the highly translucent ETFE in London, the K—Fig. 17 (left).

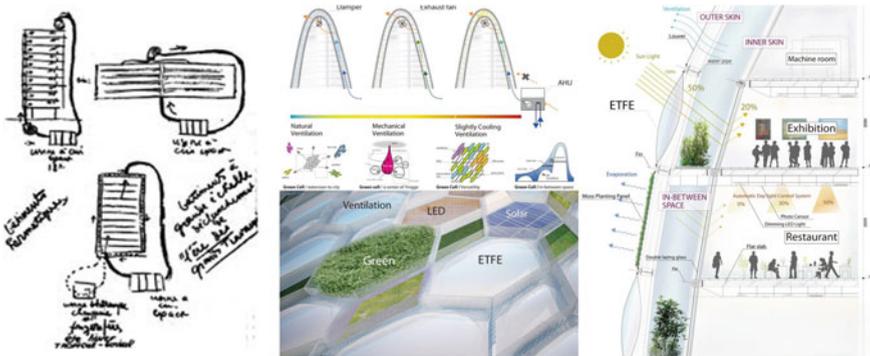
Moreover, multilayering of the building skin with both ventilated and non-ventilated cavities has drastically increased the number of effects and solutions. Since Le Corbusier proposed *Mur Neutralisant*—Fig. 18 (left), double-skin envelope systems that use the cavity to create a buffer environment and provide comfort have



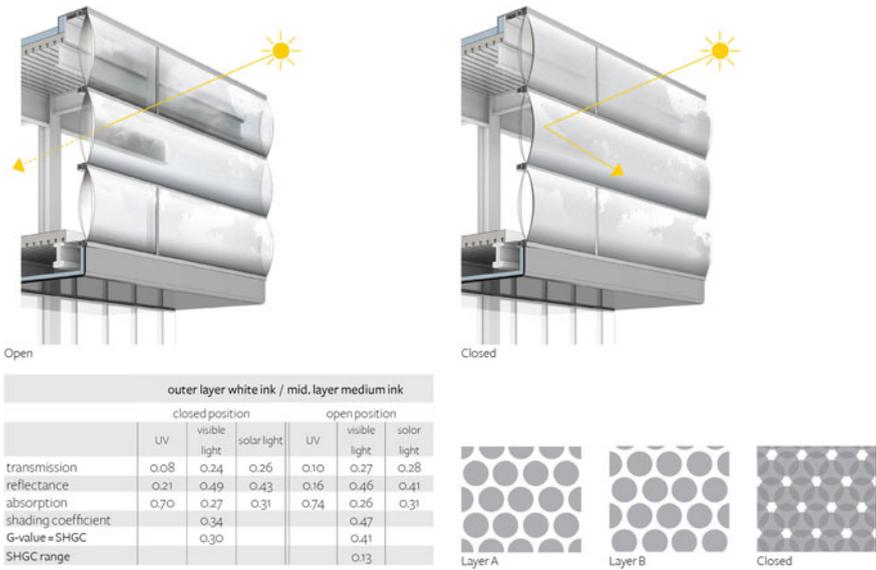
**Fig. 17** American Embassy in London (left). *Source* Photo by Richard Bryant/arcaidimages.com), King Fahad National Library in Riyadh (right). *Source* Photo by Christian Richters

triggered attention. Yet, only technology such as solar coatings and HVAC systems allowed the efficient cavity and drove implementation. Double-skin facades using only glass have been a promising façade concept in ‘90. They have never achieved their full potential mainly due to the high maintenance costs and volume/space they require, usually used only as a service corridor. However, recent biophilia concepts have started to emerge with lightweight external skin in ETFE. Some of them used flexible skin in ETFE to create a microclimate for the group of buildings—Fig. 18 (right). The concept utilizes a full range of natural resources within the external skin, creates a solar chimney effect, and induces natural ventilation through the cavity in the same way as Mur Neutralisant imagined.

However, probably the unique advantage of flexible envelopes lies in adaptability. Since Sun movement combined with sky cover creates a highly dynamic luminous environment, none of the static systems can fully exploit all passive solar design strategies. Trade-offs have to be made to balance harmful solar radiation during summer and beneficial solar radiation during winter. Seasonal behavior is usually non-symmetrical, meaning that the spring season may have different behavior than autumn. When defining a fixed shading size and position, architects and engineers must prioritize some performances, such as heating or cooling energy, lighting energy, or carbon emissions. Adaptive façade systems, on the other hand, respond to the environment and allow higher efficiency of the system. However, adaptability achieved via mechanical actuation of rigid elements requires high maintenance and low durability. Alternatively, a flexible multilayered ETFE system can respond to daily and seasonal changes at no additional cost by simply controlling inner foil placement. With a combination of shading patterns on all three membranes, it is possible to achieve a highly variable solar heat gain coefficient—Fig. 19.



**Fig. 18** Mur Neutralisant by Le Corbusier in 1930 (left). Reproduced from Le Corbusier (2004), a proposal for a New Taipei City Museum of Art by Kengo Kuma in 2011 (middle and right). *Source* Photos by Kengo Kuma + associates



**Fig. 19** Achieving highly variable solar heat gain coefficient with the kinetic movement of skin layers. The Ed Kaplan Family Institute for Innovation and Tech Entrepreneurship at the Illinois Institute of Technology in Chicago. *Source* Photos by John Ronan Architects

## 4 Wind Lightweight Design

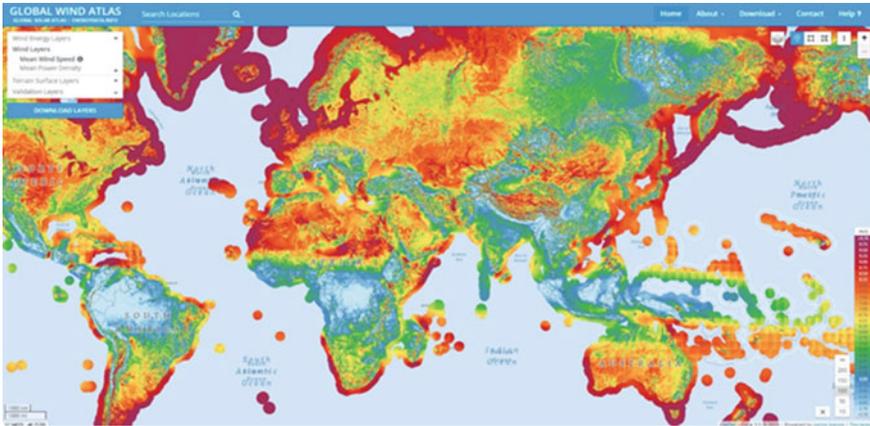
Nowadays, the need to have low-polluting energy resources and the necessity of alternative sustainable solutions have led to the exploitation of wind. Wind is an abundant, inexpensive, inexhaustible, and widely distributed resource, and most importantly, its exploitation is sustainable.

Historically, populations have taken advantage of wind passively in vernacular architectures, more recently, actively using wind turbines for energy production.

### 4.1 Wind Potential Use in Lightweight Skins

Since ancient times, the wind has been exploited for energy production, with the sailing boats in navigation and windmills to perform mechanical work. At the beginning of 1900, wind generators capable of directly producing energy were developed electrically, moving to a second step the use of windmills.

Wind is a natural and renewable resource, with the potential of energy production over 22 times the current world energy needs, according to the studies of the University of Harvard (Lu et al. 2009).



**Fig. 20** Wind speeds. *Source* Global Wind Atlas 3.0<sup>2</sup>

Moreover, if global temperatures reach 1.5 °C above pre-industrial levels, the temperature that refers to the most ambitious goal of the Paris Agreement, large areas of northern Europe could become windier. To reveal, it is the study “European wind generation within a 1.5 °C warmer world” (Hosking et al. 2018) which highlights that this phenomenon has implications in wind energy production. The results suggest that “Wind could be a more important source of energy production than previously thought, with stronger winds.”

The advances in the design of wind turbines over the last ten years allow them to operate even at lower wind speeds, harnessing a greater volume of energy, increasing the amount exploitable by collecting it at higher heights. Costs have also fallen and are now even more favorable.

Wind energy is notoriously irregular (Fig. 20). The wind speed depends on orography (roughness, forests, and residences reduce wind speeds), temperature, and the fluid-dynamic regimes of the troposphere.

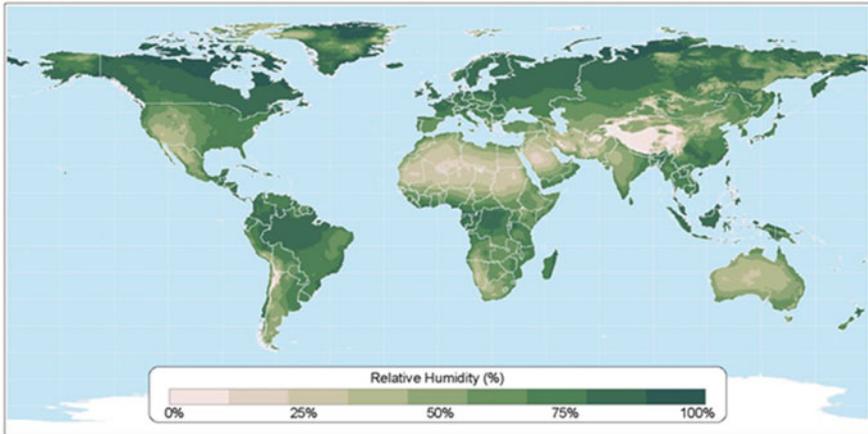
Wind formation is related to air masses moving from areas of high atmospheric pressure to adjacent areas of low pressure, whose velocity is proportional to the pressure gradient.

The intensity and direction of the wind depend on a large number of factors. Among these, the more significant is the solar radiation of the areas closer to the equator than the poles. Air moving at the bases of the three major convection cells in each hemisphere north and south of the equator creates the global wind belts.

Generally, prevailing winds blow east–west rather than north–south. This happens because Earth’s rotation generates what is known as the Coriolis effect. The Earth

<sup>2</sup> [Data/information/map] obtained from the “Global Wind Atlas 3.0, a free, web-based application developed, owned, and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: <https://globalwindatlas.info>.”

## Average Annual Relative Humidity



Data taken from: OIU 0.5 Degree Dataset (New, et al.)

**Atlas of the Biosphere**  
Center for Sustainability and the Global Environment  
University of Wisconsin - Madison

**Fig. 21** Relative humidity. *Source* Atlas of Biosphere, Center of Sustainability and the Global Environment, University of Wisconsin<sup>3</sup>

contains five major wind zones: polar easterlies, westerlies, horse latitudes, trade winds, and the doldrums. Each of these areas is influenced by a type of wind with a prevalent direction; the doldrums are also known as the zone of the equatorial calm; and also in the horse latitudes, the winds are less intense. In fact, many of the world’s deserts fall close to the average latitude of the subtropical ridge, where the descending currents reduce the air mass’s relative humidity (Fig. 21). The strongest winds are in the intermediate latitudes, where cold polar air collides with warm tropical air.

As shown in Fig. 20, wind speed varies depending on geographical conditions and humidity. Therefore, the exploitation of wind as a productive resource is conditioned by the location. Firstly, the presence of strong winds is essential. Secondly, the area’s characteristics are crucial. Therefore, wind turbines are more likely to be installed in rural areas, because the massive device structure makes its integration difficult in urban areas. Urban constructions are more feasible to integrate passive wind systems for cooling and internal well-being since they do not require strong winds to function.

The exploitation of wind to guarantee building internal well-being has ancient origins. In arid areas, the exploitation of wind, through chimney effect, is combined with massive walls for its cooling properties; on the other hand, in humid regions, ventilation is helpful to prevent mold formation and preserve the structure. Nowadays, these vernacular systems are being re-evaluated and adapted to the new technologies, and this integration is particularly challenging in lightweight structures. As a matter of fact, membrane architectures are commonly known to not ensure thermal mass

<sup>3</sup> <https://nelson.wisc.edu/sage/data-and-models/atlas/maps.php?datasetid=53&includerelatedlinks=1&dataset=53>.

or even insulation. Exterior temperature variations are reflected inside the building almost instantly, and heating and cooling gains are quickly lost through the building envelope.

### Passive wind systems.

Ancient populations used various construction techniques to ensure excellent livability conditions even where the natural environment was less favorable. One of these techniques involves the exploitation of the natural wind for passive cooling.

The expression “passive cooling” refers to all those processes of heat dispersion that occur naturally, without the adoption of mechanical tools or energy consumption. The widespread use of air conditioning systems involves significant energy consumption and contributes significantly to air pollution. On the other hand, integrating the passive cooling technique, consuming renewable energy, and designing buildings with low environmental impact would dramatically reduce the usual dependence on traditional plants.

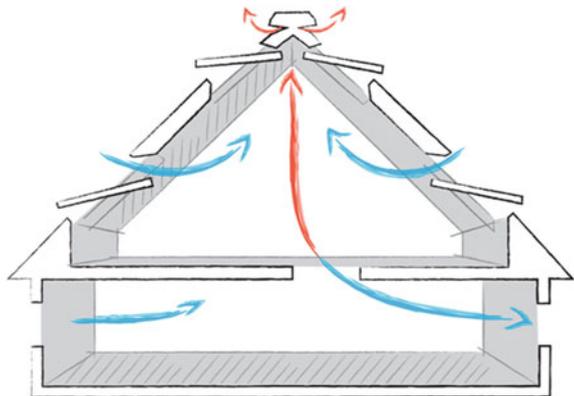
Favoring natural ventilation leads to passive cooling, insulation, or heat dispersion solutions. The movement of the air will be more significant with the increased difference in temperature and pressure of the air between two areas, that can be inside and outside, or lower parts and higher parts of the same building. These thermal convections subtract heat, and the airflow renews the air’s purity and its freshness.

### Chimney Effect

See Fig. 22.

The chimney effect is the movement of two masses of air of different temperatures. The chimney effect can be created by providing the building with openings at the bottom and the top. In this way, the hot air will rise naturally and exit from the openings at the top, while the cold air will enter through the openings at the base. This system is advantageous to avoid the stratification of hot air in the upper part of indoor environments. The chimney effect can be also applied to the ventilated cavity

**Fig. 22** Chimney effect.  
Source [edilportale.com](http://edilportale.com)



in the building envelope; in this way, the cooling effect is obtained thanks to a layer of flowing air that becomes part of the membrane skin.

### **Membrane Structures**

Membrane architectures are composed of a thin layer, which often is less than 1 mm thick. Therefore, the poor insulation properties of the base material, which often is plastic based, and the lack of insulating layers (or air gaps) may cause the creation of warmer layers of air close to the membrane. The result is an envelope characterized by high dispersion of heat due to excessively high transmittance values; this favors heating of the upper air layers (in the vicinity of the cover). This phenomenon tends to amplify during the day when the Sun's rays hit the covering membrane, so much so that it is possible to find differences in temperature between the highest point and the floor even of 14 °C (Harvie 1995).

Membrane structures can generate vast and high spaces: The different elevations of the intrados of the textile roofs favor the accumulation of hot air at the highest points of the structure, resulting in colder layers of air in the lower areas, just where people are expected to stay. If the building is wisely designed, it should present openings at the base and in the upper part, in order to favor the chimney effect, and obtain internal comfort (Fig. 23).

## ***4.2 Conventional Wind Techniques***

Internal courts, wind towers, and thick walls are just some of the systems devised for the passive cooling of the built environment. In the Middle East, for example, in unfavorable areas, several stratagems were needed to improve the livability of living spaces; this is because of the high temperatures reached in summer (over 40 °C), hot winds, and the great temperature range between day and night.

### **Courts**

In Iran, since 3000 BC houses have been built with very thick walls to accumulate thermal energy during the day and re-emit it during the night. Further measures adopted in these buildings are the opening located almost exclusively toward the inner courtyards and the use of the dome, so the hot air tends to move to the upper part of the same, thus refreshing the low zones occupied (Aryan et al. 2010) (Fig. 24).

In any case, the climatic conditions in those internal yards are severe, especially during the hottest hours of the day. Some technical solutions can be applied to improve the hygrothermal behavior of those spaces, as in the project of umbrellas in the Holy Mosque of the Prophet in Medina. The umbrellas are designed to guarantee optimal climatic conditions both during summer and winter. In the open position, they offer shading during the day, and in the closed position, they permit heat dissipation during the night, allowing heat loss by wind convection (Fig. 25).

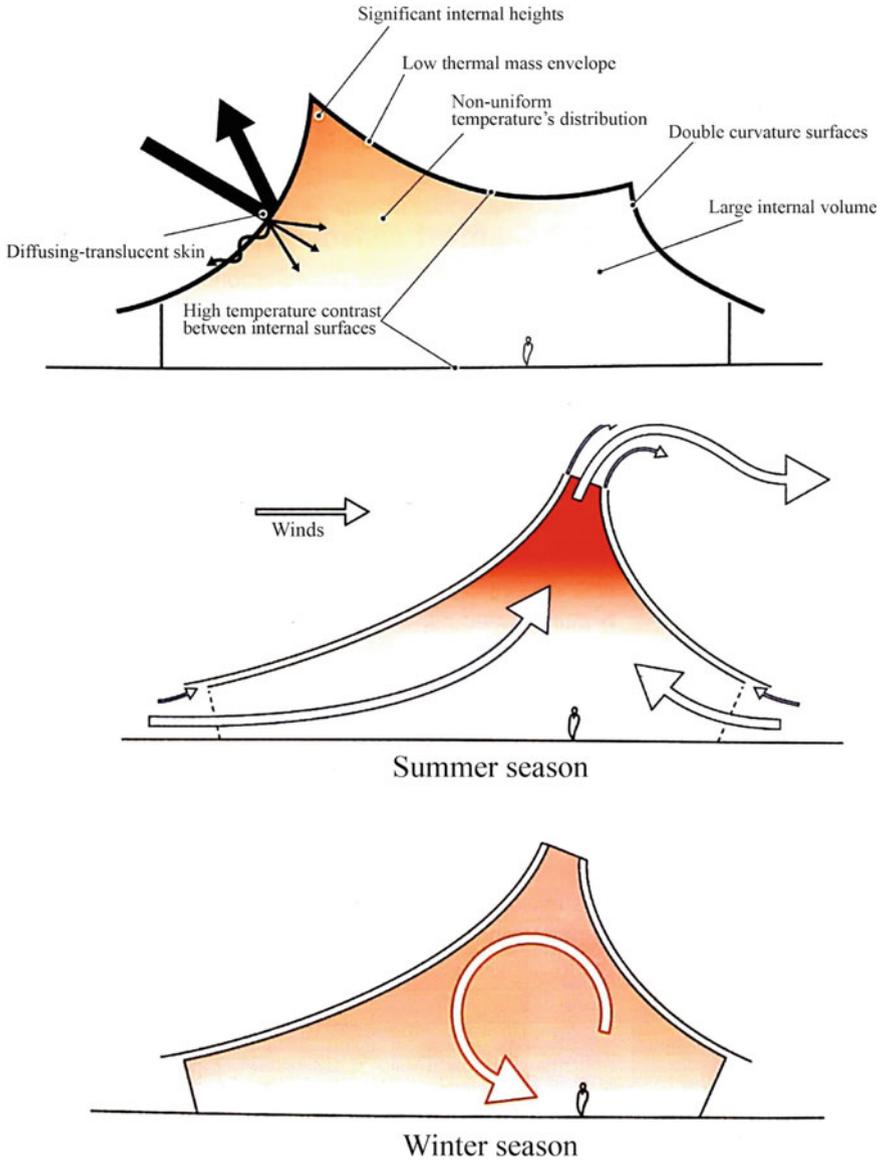
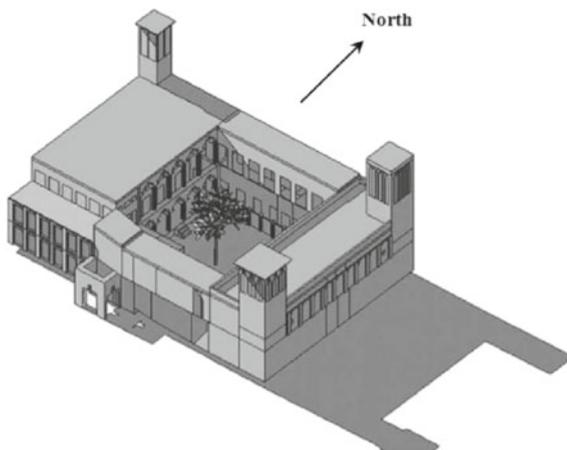


Fig. 23 Thermo-hygro-metric behavior of a membrane structure. Source Tensinet (2004)

### Wind Towers

Wind towers are an architectural solution used in ancient Persia to exploit wind, based on the principle of convection to mitigate the summer heat through ventilation and passive cooling of indoor environments, thus making homes more livable

**Fig. 24** Image of the Bukhash house—internal courts. *Source* McCabe and Roaf (2012)



**Fig. 25** Umbrellas in the Prophet's Holy Mosque square in Medina, SA. *Source* Wikimedia, Sekretärin

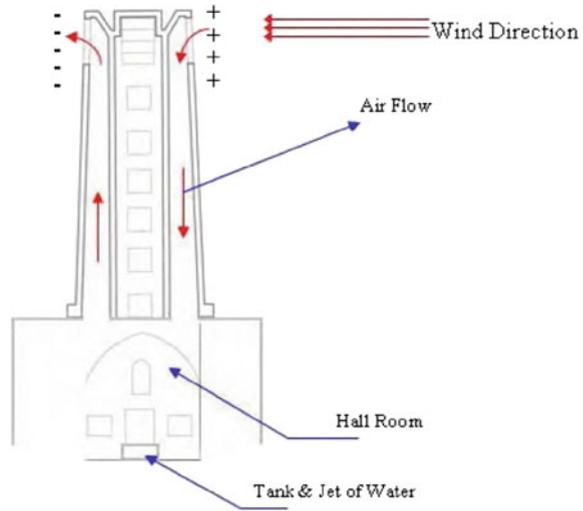


and comfortable. Wind towers are still today the most sophisticated passive cooling systems in the world.

The wind towers present openings facing the main wind direction; if there is more than one, it can present openings on more sides, but the internal column must be divided in order not to lose the air that is getting in. They work thanks to the wind speed or forcing wind movement creating areas of different pressure. The chimney is designed to create a low-pressure zone at the top of the tower, and the pressure drop triggers an air current toward the chimney. Then, during the day the tower warms up, the masonry releases heat creating a stream of air descending toward the tower (Aryan et al. 2010).

The walls of the towers are very thick to have a high thermal mass which creates a difference in pressure between inside and outside. In addition, communications between the tower and the building can be closed and opened as needed with particular doors that close and open the ducts.

**Fig. 26** Wind tower-wind flows. *Source* Maleki (2011)



During the construction of the wind towers, many factors were taken into account, such as the building's wind direction, height, and organization. Therefore, there are different types of towers depending on the external and internal conditions and goals. Moreover, the presence of masses of water in the building makes the cooling effects increase thanks to the humidification of the environment (Fig. 26).

In membrane architecture, the thickness of the envelope layer is much more reduced concerning the traditional massive walls; for this reason, the passive cooling effect must just take advantage of wind speed. However, the refreshing and humidification can also be obtained thanks to a wet textile, obtained through its periodic immersion in water. In this way, due to Sun exposure, the textile warms up and releases the water present in it in the form of water vapor. This study was conducted by Butera et al. in 2017. In Fig. 27, three methods to wet the curtain are shown.

### 4.3 Wind Design Strategies

Membrane architecture can be designed with the application of a multilayer envelope, where the internal flow of air improves interior comfort. Usually, each layer fulfills a specific function, and the combination of two or more layers results in a clear improvement in the thermal performance of the entire envelope.

The design of this ventilation cavity depends on different factors, such as climate, function, and location. Therefore, the configuration, the material combination, and their distance result in various performances.

Although the subject is complex, two fundamental and radically opposite approaches can be defined. The first tends to isolate the structure as much as possible by exploiting the air between the layers of fabric, which does not transmit heat

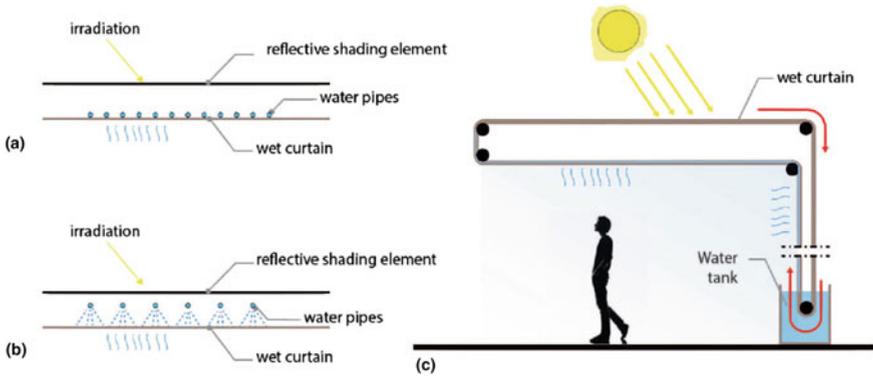


Fig. 27 Cooling effect on web curtain envelope. Source Butera et al. (2017)

between one layer and the other. The opposite strategy prefers using the cavity to ventilate the structure, stimulating natural convective motions or forced ventilation, with fresh or hot air depending on the seasons and the need. Careful design must be able to choose the best combination of waterproof or breathable, transparent or opaque materials, coupled to insulating mats and/or ventilation cavity to ensure the project's thermal comfort.

An example of isolation in membrane architecture through air masses between the layers of fabric is using a multilayer cushion of ETFE.

The use of membranes in ETFE, such as tensile structures or as pneumatic elements, guarantees a certain level of thermal insulation, which can be increased thanks to other layers of different materials. It is possible to use insulating layers, reducing the transparency of the envelope. In the case of tensile structures or pneumatic elements, it is possible to insert additional layers that create separate air chambers. However, when using structures with multilayer membranes, paying close attention to the fasteners is necessary to avoid draughts or thermal bridges. A connecting element typically consists of several thermally separated parts. Moreover, the printing of the outer layer of the membrane can reduce the incoming energy of the Sun's rays, thus ensuring shelter from excessive heat. The additional lower insulating layers can solve the problem of condensation, which prevents the cushion from coming into contact with damp air. A drainage system must also be arranged inside the cushion to drain the water created by condensation inside the two layers. It is also essential that the air injected into the cushion is dehumidified (Campioli and Zanelli 2009).

### Cushions and Ventilated Cavity

See Fig. 28.

The Beijing National Swimming Center was built for the 2008 Olympics.

The water cube consists of a 200 m square-plan volume whose surface is composed of a double layer of structural packages shaped by a steel space frame whose application is an absolute novelty. It is not the traditional tetrahedral mesh but a structure born from observing soap bubbles aggregation in foam composition.

The watercube



Fig. 28 Watercube, PTW Architects, Beijing, 2008. Source PTW apud Gonchar (2008)

The structural package consists of two parts: The first is generated by a system of rods and nodes that reproduce the spatial geometry of the foam; the second is real bubbles, ETFE cushions that equip the swimming system with a double protective barrier, inside which the air is pumped; and the plumbings that connect cushions and inflate them are divided into areas.

This architectural example combines the two cooling approaches previously examined: ventilation of the cavity and pneumatic cushions. The bubble envelope tends to isolate the structure thanks to the heated air between the layers of fabric, forming a greenhouse effect during winter. During summer, printed dots on the ETFE surface reflect the radiation outside, preventing the heat, and at the same time, some fresh air is pumped into the cavity between the two bubble layers (Orr 2007) (Figs. 29 and 30).

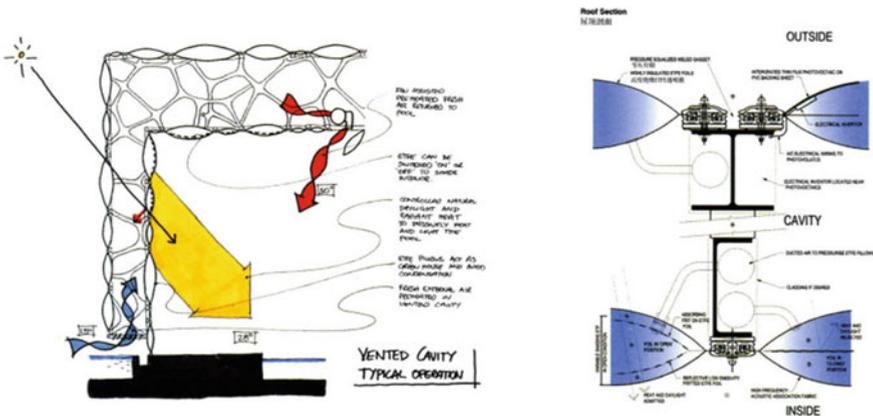


Fig. 29 Watercube airflows and cushion details. Source Gonchar (2008) and Architecture Australia archives



*Bellegrade railway station*

**Fig. 30** TGV station, AREP group, France, 2010. *Source* AREP group

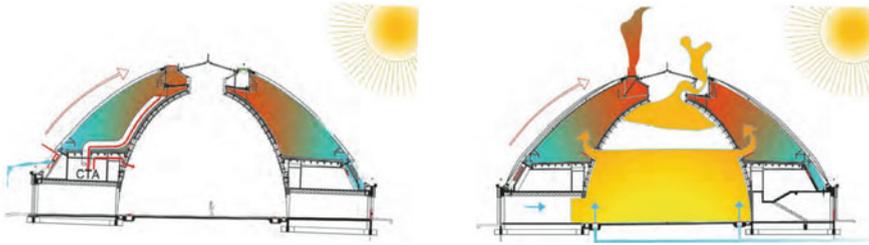
The Bellegarde central railway station has been constructed following an innovative approach to bioclimatic design. The aim of energy control has allowed a combination of environmental sustainability objectives and financial sustainability ones while maximizing the savings of energy use to reach comfortable temperatures. The building has been designed to pursue precise bioclimatic performances and adopt three primary technical and construction devices.

The construction consists of a double dome: one opaque, which limits the usable space, and an outer one, transparent, which controls the energy balance of the building during summer and winter. Geothermal probes inject air to pre-heat the hall during winter and inject naturally cooled air during the summer from vents integrated into the floor. The creation of a plenum system allows for a pre-heating of the channeled air. The duct system distributes the air treated by the heat pumps at an adequate temperature for internal comfort depending on seasons (minimum temperature is 12 °C). They are covered by a protective dark elastomeric membrane due to the solar overheating caused by the outer transparent dome. A double motorized vent system, attached to the windows at the base of the drum and the top of the central lantern, allows to inject fresh and clean air in the plenum's mezzanine levels and to extract exhaust air coming from the intermediate space between the two domes but also directly from the main vaulted space (Zanelli 2011) (Fig. 31).

### **Wind Protection**

See Fig. 32.

The building was one of the first in the city to be awarded the Hafencity Gold environmental label, introduced in 2007. Criteria for this certification include low primary energy consumption (less than 100 kWh/m<sup>2</sup>a) and permeability of public space. The company has set up a ground floor accessible to the public, where a spa, a cafe, and a shop are located. To reduce the reverberation frequencies of the sound and thus obtain an acceptable level of noise, the inner facades are made up of chipboard and metal grating panels.



**Fig. 31** Scheme of the building's energy use during winter (left) and summer (right). *Source* AREP group archive



**Fig. 32** Unilever Headquarters, Behnisch Architekten, Germany, 2010. *Source* Behnisch archive

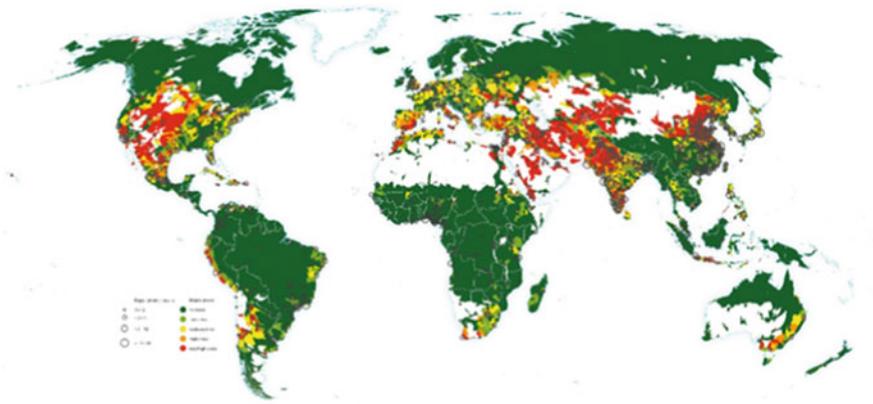
Peculiarity notable is the membrane facade, doubly essential for the strategy of ventilation and temperature regulation. The skin is used to protect the automated solar protection system from strong wind and other weather factors. The obtained cavity can thus be used for the natural ventilation of the building. The outer skin of the building consists of frames individually covered with ETFE sheets mounted before the insulating glazing, which forms the innermost layer of the facade. To provide even more wide surfaces with the necessary resistance to wind force, ETFE sheets have a curved pattern. The facade specialists have chosen a saddle-shaped profile: horizontally convex and vertically concave. In order not to limit too much the transparency of the facade, the sheets are stabilized with a network of ropes (Zanelli 2010) (Fig. 33).

## 5 Water Lightweight Design

The hydric emergency is one of the most relevant effects of the climate crisis (EEA 2012). Water supply generally derives from underground water; however, even if it is natural and renewable, this resource is constantly threatened by the temperature rise,



**Fig. 33** Unilever headquarters second skin. *Source* FormTL archive



**Fig. 34** Variability in the Water Stress Indicator across the globe. *Source* Aqueduct Global Map, European Commission, Joint research center, world Atlas of desertification, Water stress and urbanization<sup>4</sup>

the growing population, and the ascent demand for anthropic purposes; therefore, it is overexploited; and the basins cannot be recharged (Corona et al. 2009). Moreover, it is not equally distributed on Earth, as shown in Fig. 34; this factor determines drastically different levels of availability between the various areas of the globe, particularly between the states that make up the international system. A summary analysis of water concentration and distribution shows that 60% of the world’s resources are located in nine countries.

The discrepancy in water supplies is often the result of poor management of water resources; this would be confirmed by the fact that many inhabitants suffer from water scarcity precisely within countries with good freshwater availability.

Due to climate change, we live in a scenario of unpredictable water provisions; for this reason, it is essential to develop the research focused on sustainable water

<sup>4</sup> <https://wad.jrc.ec.europa.eu/waterstress>.



**Fig. 35** Global location of Big Cities (population >300,000), highlighting dryland versus non-dryland distribution. *Source* United Nations Department of Economic and Social Affairs—Population Division, *World Urbanization Prospects: The 2014 Revision*

use, and new ideas tailored to this particular issue should be pursued (Domen et al. 2014).

The latest update of the *Aqueduct Water Risk Atlas* states: 17 countries in the world, which contain about a quarter of the world’s population, are facing extremely high water shortage stress. In these areas, the agricultural, industrial, and municipal systems consume more than 80% of the water available from the surface and underground resources in an average year. The “Water Risk,” explains Andrew Steer, President of the WRI, is one of the most unspoken global crises, and risks are food production and consumption, conflicts and migration, and financial instability (Fig. 35).

In this scenario, many arid and temperate areas worldwide, which present the more critical hydric conditions, are defined as fog oasis because intense fog phenomenon characterizes them. This water vapor can be considered as an alternative water resource, which nowadays remains unexplored. The device used to collect water from fog is the fog collector, also called *atrapaniebla*. This technology can be a solution to water stress in many territories.

### 5.1 *Atrapaniebla as a Passive System*

Passive systems are essential for eco-sustainable development, and they can be applied in many sectors to save energy without consumption. Water on Earth exists in three states: liquid, in underground basins, which are currently being exploited and are no longer sustainable; solid, in the glaciers, which should not be considered as a water resource for apparent reasons; and finally, gaseous water present in the

air, in particular conditions, in the form of tiny droplets suspended in the air (Fuzzi et al. 1997).

The *atrapaniebla* is an ancient device for fog harvesting. It is a non-conventional, passive, low cost, and low maintenance system that permits the acceleration of the condensation process for water production. It works thanks to the natural fog phenomenon, where the droplets of water dispersed in the air accumulate on the *atrapaniebla*'s mesh surface, transported by the winds. The use of fog water as an alternative source has been studied and used for many purposes in different countries, such as agriculture, reforestation, and farm breeding. Efficient collection of fog water depends on various factors, such as phenomenon characteristics (frequency, water content, wind speed, etc.), and on the participation and involvement of local communities (Klemm et al. 2012: 226–227). Studies have estimated it to be an abundant and under-exploited resource (Larraín et al. 2002; Cáceres et al. 2007; Cereceda et al. 2008).

### **Biomimetics**

Living nature provides many lessons for water harvesting. In this case, the study of passive systems for fog harvesting is linked to the investigation of the same system in nature. Many plants and animals around the world already use the condensation process for their self-support. Bioinspired water collectors can be designed for improving their efficiency, “Everything you can imagine, nature has already invented it.” So said Albert Einstein. Biomimicry is the science that studies the transfer of biological processes from the natural world to the artificial world. Architect Buckminster Fuller suggests: “We do not seek to imitate nature, but rather to find the principles she uses” and do not limit yourself to copy nature but to derive from it an oriented inspiration to transfer its biological principles and logics.

All living creatures need water to survive. Due to this, in 3 million years of evolution, many species have demonstrated efficient solutions to secure supplies of water (Bhushan 2016). These solutions concern species with unique chemical characteristics or those whose bodies can regulate the movement of water. For example, many plants and animals in arid areas rely on exploiting fog water regarding gain, preservation, transport, and water loss. Therefore, through the observation of these organisms' systems and structures, it is possible to create *atrapanieblas* for providing an additional water source for communities in regions where fog is common (Klemm et al. 2012); some examples are the spider-web, the beetle surface, and the spines of some cactus or succulent.

## **5.2 Lightweight Fog Harvesting Technology**

In various parts of the world, there are similar fog formations. These places are defined as fog oasis or *oasis de niebla* (Cereceda et al. 1999). Since ancient times, several techniques have been developed to exploit the natural phenomenon and produce water in these oases.

In its primordial forms, the *atrapaniebla* was a simple accumulation of stones to form a pit under “natural monuments” such as the Garoe tree at Canary islands or a dolmen erected by the indigenous communities on the north coast of Chile. In the most advanced forms, the Inca produced a primordial tensile structure with fishing nets. The modern *atrapaniebla* model does not differ much from this version (Pascual et al. 2011).

As regards the construction of an *atrapaniebla*, the knowledge at the base is strongly interdisciplinary; for example, the Desert Centre of the Atacama, which deals with the study and realization of *atrapanieblas*, is a research department of the Pontificia Universidad Católica de Chile, and it unites the lines of investigation of energy, water, biodiversity, architecture, design, landscape, and geography.

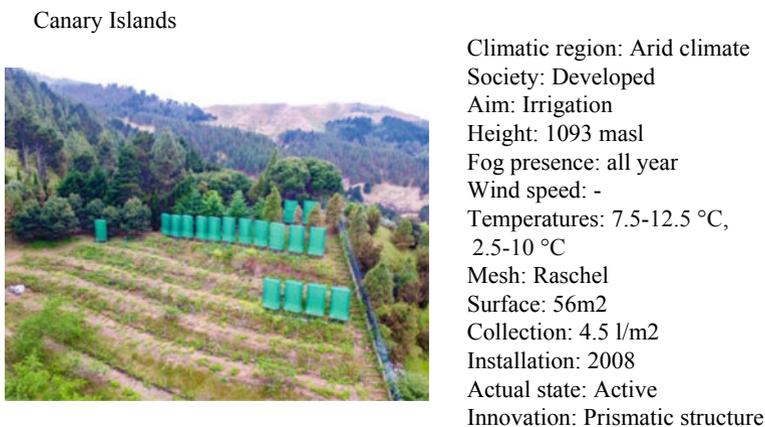
The study of the landscape and geography is significant because these structures must adapt to various environments. They can be installed and dismantled without a trace on “virgin” soil. It is, therefore, a straightforward construction system composed of a limited number of pieces, designed to last as long as necessary, usually about ten years. It is constituted to be easily disassembled so that only the deteriorated parts can be renewed and replaced (Cereceda et al. 2011).

Most of the *atrapaniebla* (especially the two-dimensional ones, which will be illustrated later) are designed to be utterly self-constructed with prefabricated pieces, which can be commonly found in DIY shops, therefore cheap, easily transportable, and workable.

This innovative climate is no longer a question of saving rural communities in extreme climates but of working to safeguard all the areas threatened by desertification, including those inhabited by more developed societies (Cereceda et al. 2011).

## Case Studies

See Fig. 36.



**Fig. 36** Canary island: *Huerto hidrico* of Nieblagua enterprise. Source [nieblagua.com](http://nieblagua.com)

## Chile



Climatic region: Arid  
 Aim: Aquaponics system  
 Height: 550 masl  
 Fog presence: Tutto l'anno  
 Wind speed: 9 Km/h  
 Temperatures: 15 °C  
 Mesh: Double Raschel 35% shadow  
 Surface: 10 atrapanieblas x 48m2  
 Collection: 1.5 l/m2  
 Attività: 2002  
 Stato attuale: Active

**Fig. 37** Chile, Chañaral: Falda Verde, Fog Quest. *Source* Marca Chile

The main characteristic of this collector is its volumetric and multilayer shape, which allows it to collect much more water than traditional collectors called planes or Chilean type. Its design makes it resistant to strong winds, and it does not depend on their direction for water collection. Moreover, it occupies a minimum floor area of 1.60 m<sup>2</sup>, and in one year, it can provide between 11,000 and 20,000 L of freshwater. The water quality is good because it does not touch the soil, so it cannot absorb any minerals from the subsoil. Its low mineral intake is obtained from the salt particles that contain the drops that form the clouds/mists transported from wind by the ocean (Ritter and Regaldo 2008) (Fig. 37).

The project started in 2001, intending to provide water to the coastal communities. The location is about 5 km north of the city of Chañaral. The Atacama Fog Collection Group carried out the construction work. The six initial prominent fog collectors have a surface of 48 m<sup>2</sup> each and are located at 550 slmn. The fog collectors used are the Chile type, a bi-dimensional structure designed by Fog Quest. The pipeline takes the water to a greenhouse. The daily average collection rate of 1.5 L m<sup>2</sup>/d is the lowest among the six sites studied in northern Chile (Larrain et al. 2001) (Fig. 38).

Warka Water fog collector's is 10 m high, weighing only 60 kg, and it is built with ecological materials readily available as nylon, bamboo rushes, and bioplastics. The device is based on the principle of air condensation, taking advantage of the huge temperature range between day-time and night-time, that in Africa is very accentuated. The structure captures dew, fog, and tiny particles of moisture, turning them into drinking water. This prototype, able to produce up to 100 L of water per day, takes advantage of the humidity of the atmosphere, was designed by the Italian architect Arturo Vittori, developed with Kickstarter, and realized directly on the Ethiopian territory thanks to the support of the Italian Cooperation (Vittori 2017).

## Ethiopia



Climatic region: Arid  
 Aim: Drinking and irrigation water  
 Height: -  
 Fog presence: -  
 Wind speed: -  
 Temperatures: 20 °C  
 Mesh: Raschel 35%  
 Surface: 90m<sup>2</sup>  
 Collection: 1 l/m<sup>2</sup>  
 Activity: 2015-  
 Actual state: Active  
 Innovation: Structure

**Fig. 38** Ethiopia, Warka Water. *Source* [warkawater.org](http://warkawater.org)

## 6 Lightweight Design Strategies for Combined Use of Natural Resources

The climate-based design is mainly related to natural resource exploitation, like Sun, wind, and water. Moreover, in the design process, these strategies can be combined and integrated into a building structure to significantly increase comfort, reducing fossil fuel dependence and relative emissions.

The combination of wind and water resource harvesting can be noticed in Dadong arts and education center. It is an excellent example of a modern lightweight architecture that integrates two natural elements for passive well-being (Fig. 39).

In Taiwan, on an area of over 24.000 m<sup>2</sup>, the architecture studio CIE, in collaboration with MAYU studio of Taiwan and Arup Amsterdam's advice, has designed a multifunctional center. The designers have developed a series of independent volumes connected by the porch and a covered square. Slender steel columns support a theory



**Fig. 39** Dadong Arts Center, Architekten Cie + MAYU Architects, China, 2016. *Source* De Architekten Cie



**Fig. 40** View of the main covered square facing north. *Source* De Architekten Cie and Yu-Lin Chen

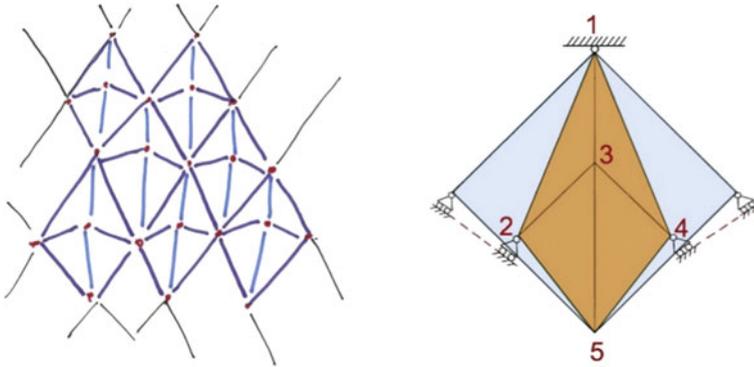
of eleven gigantic inverted metal-textile cones that signal from far away from the presence of the Dadong Arts Center.

The ancient Chinese lanterns are slender structures in colored translucent paper whose presence of a brazier at the base ensures that, for temperature difference, trapped air inside the irregular polygonal volume allows the lantern itself to soar high, fluctuating in the air. Observing the trunk-conical membrane textile and steel structure forming the space system outside the Dadong Arts Center, we notice that the reference to such ephemeral structures is explicit. The relation with the ground floor of the inverted cone depends on the location. It can be a pool or a fountain, a protected enclosure of seats and playground enclosure, or still, filled with Earth for plants and flowers. This retelling of the brazier of the ancient lantern makes it possible to anchor to the ground, in the lightest way possible from a visual point of view, large textile cones and equally imposing primary steel structures that support them (Zanelli 2016) (Fig. 40).

The relationship between the lantern and the pools is essential because water can refresh the air through cooling and evaporation. Air naturally contains water, and the sensible heat of the air is transferred to the water in the form of latent heat and allows it to evaporate.

Another possible combination explored in the residential buildings Università di Salerno consists of a façade that integrates the exploitation of Sun and wind. In this case, the technical elements that compose a smart *façade* take advantage of the natural resources of Sun and wind both passively and actively. It consists of a series of interconnected tensegrity modules that react to external conditions, providing energy from wind speed and solar radiation for the building functions; moreover, this façade also works as a sunscreen. This novel dynamic design can change its technological configurations and energy performances during the day.

This adaptive architecture is designed like a set of blinking sails. Each module of the system is shaped like a rhombus and is controlled by regulating the elongations of selected cables. The design of the elementary module depends on two angular aspect variables, which define the node coordinates (Fig. 41).



**Fig. 41** Blinking sail modules. *Source* Cimmino et al. (2016)

These smart skin sail screens are composed of foldable origami fitted with bendable, composite photovoltaic modules in correspondence with the perimeter bar elements and fiber-membrane sails.

The blinking sail wind energy harvester works thanks to the motion of the membrane attached to the generic module. In this case, the module is formed by all stretchable elements (strings) attached to a rigid truss. Moreover, additional cables are linked to a generator rotor. In this way, the wind flow provokes elongations of such cables that rotate the generator, creating power for immediate use of the served building, such as to operate solar façades (Cimmino et al. 2016) (Fig. 42).



**Fig. 42** Façade structure. *Source* Cimmino et al. (2016)

## 7 Conclusions

This chapter showed a plethora of lightweight solutions for energy harvesting from nature, including Sun and wind. Multiple case studies demonstrated temporal, spatial, and geographical potential for single or multiple-source harvesting in various climates and technological advances, ranging from low-tech solutions in developing countries to high-tech solutions in developed countries. The chapter argues that environmental design should be embedded into the building design process to use visible and invisible natural resources that surround us. Moreover, doing so is possible with lightweight technologies that produce minimal environmental impact and can reach net or plus-zero targets. Therefore, only a careful balance of energy harvesting and lightweight solutions could make a successful and accelerated transition toward a sustainable future.

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# Flexible Photovoltaic Solar Design



Zhengyu Fan, Alessandra Zanelli, Carol Monticelli, and Qingxiang Li

**Abstract** The advancement in material science has enabled enormous developments of photovoltaic technologies. From an architectural integration viewpoint, the mechanical flexibility of the photovoltaic products represents another key consideration, rather than cost and energy conversion efficiency only. This chapter presents descriptions of flexible substrates and thin-film photovoltaic, deepening the two key choices for the flexible photovoltaic in buildings, the thin film, as well as the organic one. This chapter includes the investigation of the main flexible substrate materials for PVs as well as the flexible PV module products. Considering the two important requirements for building applications, the higher transparencies upon visible lights, as well as the multiple color choices, the corresponding potentials and limits are highlighted. Additionally, the state of the art over the manufacturing and market of flexible photovoltaic are introduced. And a frame has been defined regarding the environmental impact assessment of organic photovoltaic technologies and flexible skins.

**Keywords** Photovoltaic · Flexible PV · Organic PV · Thin film

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# 1 Technologies

## 1.1 Rigid and Flexible PVs

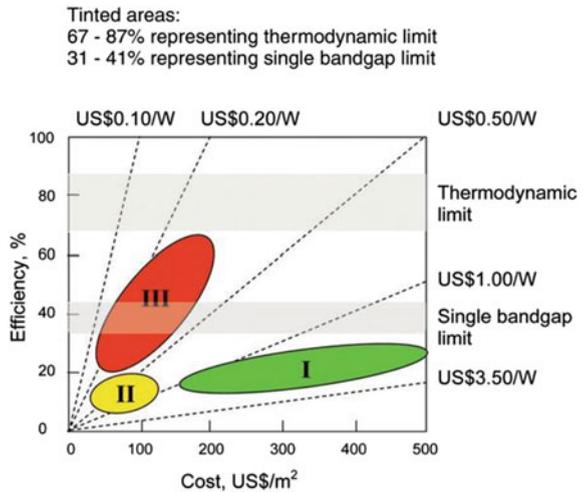
The advancement in material science has enabled enormous developments of photovoltaic technologies. Generally, the various kinds of photovoltaic technologies can be classified into three generations according to their cost and energy conversion efficiency (Fig. 1).

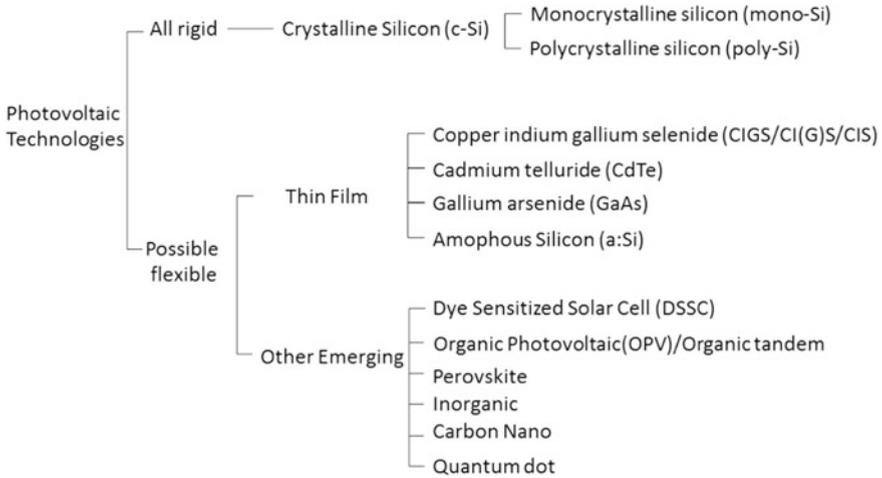
However, from an architectural integration viewpoint, the mechanical flexibility of the photovoltaic products represents another key consideration, rather than only cost and energy conversion efficiency. Based on the mechanical flexibility of all examined substrates and composites of existing technological approaches, they can also be grouped as shown in Fig. 2.

Corresponding to the product application scenarios of the two main groups of photovoltaic technologies, featured substrate and functional layer materials should be robust enough to fulfill the mechanical property requirements. The different mechanical performances of the rigid and flexible substrate, therefore determine the mechanical flexibility of the encapsulated photovoltaic module or products eventually, lead to the so-called rigid or flexible photovoltaics.

Currently, rigid substrate materials, most commonly glass, are employed for crystalline silicon (c-Si), including both the monocrystalline silicon (mono-Si) and polycrystalline silicon (poly-Si) photovoltaic modules. Meanwhile, various types of flexible substrates have been adapted by thin film, organic, and other cutting-edge photovoltaic technologies. More descriptions of flexible substrates are presented in later chapters.

**Fig. 1** Efficiency and cost projections for first-(I), second-(II), and third-generation (III) PV technologies (wafer-based, thin films, and advanced thin films, respectively). *Source* Green (2003)





**Fig. 2** Classification of main photovoltaic technologies in the aspect of mechanical flexibility (edited by the authors)

## 1.2 Main Flexible PV Technologies

As shown in Fig. 2, up to now only thin film and several emerging PV technologies could be possibly realized in flexible forms. Therefore, two key choices for the flexible PV in buildings, thin film, as well as organic PV, are briefly introduced in this section.

### 1.2.1 Thin-Film PVs

Due to comparatively lower mass and volume, higher flexibility, homogeneity as well as increased efficiency, thin-film PV has been long dominating the second largest market share since its invention. Although quite many novel cutting-edge PV technology could also be manufactured into thin-film form, the generally considered category of “thin-film” PV normally include amorphous silicon (a:Si), cadmium telluride (CdTe), copper indium gallium di-selenide (CIS/CIGS), and gallium arsenide (GaAs). Due to their material property and photovoltaic mechanism differences, the four types of thin-film technologies still demonstrate distinguished features. An overview of their strengths and weaknesses is summarized in Table 1.

### 1.2.2 The Special Role of Organic PVs in Flexible PV Development

As an emerging third-generation PV technology with a wide range of active material candidates as well as comparatively lowest unit price, organic PV had received high

**Table 1** An overview of thin-film PVs regarding their strengths and weaknesses

Category	a-Si		CdTe		CIGS		GaAs	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Materials	Limited cost by using silicon alloys rather than crystalline silicon No feedstock limitation as silicon is common materials on Earth Multiple materials can be deposited to capture a wider spectrum of light Reliable energy output even at low daylighting levels	Comparatively low efficiency Exhibits efficiency degradation over time Multiple layers are required for higher efficiencies and increased photo-stability	Uses very little Cadmium material Relevant research started earlier in 1970s	Cadmium (Cd) in elemental form, poses a health risk telluride (Te) as a rare-earth material may have a supply bottleneck Manufacturing needs to control exposure to the compound Wastes need to be properly recycled	Highest PCE efficiency among thin-film technologies) CIGS compound is robust and defect-tolerant Does not exhibit efficiency degradation over time	Indium (In) as a rare-earth material may have a supply bottleneck Cadmium (Cd), as a rare and toxic material	Comparatively high efficiency with higher theoretical upper limit Good performance at high temperature Less sensitivity to low daylighting levels	High cost due to higher price of raw materials Gallium (Ga) as a rare-earth material may have a supply bottleneck Arsenic (As) as toxic material

(continued)

**Table 1** (continued)

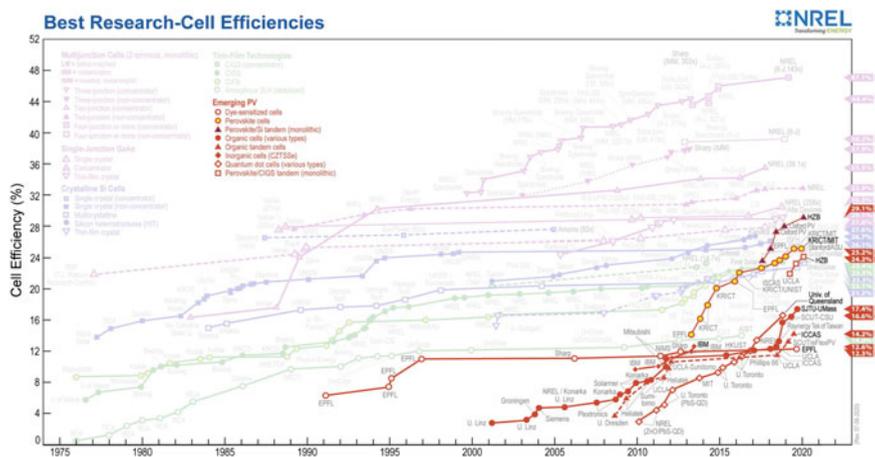
Category	a-Si		CdTe		CIGS		GaAs	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Substrate and flexibility	<p>Could use rigid or flexible substrates</p> <p>Glass and stainless-steel substrate-based modules can be warranted for 20 years</p> <p>Can be deposited as both superstrate and substrate configurations</p>	<p>Generally does not use very thin substrates so the flexibility is limited</p> <p>Plastic-based modules have shorter lifetime</p>	<p>Uses glass as a superstrate</p> <p>Lifetime of glass-based module can reach 20 years</p>	<p>Can only use glass as a deposition surface thus with very limited flexibility</p> <p>Module very sensitive to breaks or cracks of glass substrate or superstrate</p>	<p>Could use rigid or flexible substrates</p> <p>Can be deposited on very thin plastic substrates using low-temperature processes with roll-to-roll capability</p> <p>Glass and stainless-steel substrate-based modules can be warranted for 20 years</p>	<p>Only substrate configuration flexible</p> <p>substrates are less durable</p>	<p>Could use Ge deposited metal foil as substrate</p> <p>With specific substrate, the production process could be roll-to-roll compatible</p>	<p>More brittle even than silicon</p> <p>Higher encapsulation and installation damage rate</p>

Source: Sorin (2007)

expectations and exponential development since its invention. Its power conversion efficiency had also seen steady improvements (Fig. 3) over the past decades.

Different from c-Si and thin-film PV technology, OPV employs various organic materials to realize its photovoltaic effect. Up to now, the mainly investigated materials include conjugated molecules and conjugated polymers. Table 2 lists the main features of investigated OPV material types.

Through the past decades, the huge potential of realizing high throughput production of cheap solar cells has driven the research of organic PV in full swing. Its



**Fig. 3** Best emerging PV research-cell efficiency chart. *Source* National Renewable Energy Laboratory (2021)

**Table 2** Main features of investigated materials for OPV research (edited by the authors)

Main types of OPV active materials	Typical molecular structure of OPV active materials	Features
Small molecule/conjugated molecules	<p>Perylene, M<sup>+</sup>2Di or M<sup>0</sup>Di, Phenylperylene, Subphthaloperylene, Corroles</p> <p>Porphyrins, Porphyrin derivatives, C<sub>60</sub></p>	<p>Research start in early age</p> <p>Mainly thermally evaporated</p> <p>High vacuum deposition</p> <p>More expensive</p>
Conjugated polymers	<p>PA, PPV, MDMO-PPV</p>	<p>Ease of processing</p> <p>Mechanical flexibility</p> <p>Environmentally safe</p> <p>Inexpensive</p>

**Table 3** Comparison of cost estimates for OPV to projected cost estimates for other thin films and mc-Si

Tech.	Materials active (\$/m2)	Inactive (\$/m2)	Total (%)	Process costs (\$/m2)	Overhead costs (\$/m2)	Module manuf. Costs <sup>a</sup> (\$/m2)	Module cost <sup>b</sup> (\$/Wp)
OSC	6.7–10.0	16.70–27.48	(27–48)	9.30–69.60	13.78–25.21	48.80–138.80	1.0–2.83
DSSC(1)*	10.3–16.0	5.22–5.51	(22–23)	7.69–10.88	11.6	36.55–46.19	0.75–0.94
DSSC(2)#	23.54	97.59	(80)	18.07	1.23–10.95	157.66	3.22
CdTe†	6.84	58.86	(53)	30.11	27.38	129.33	1.65
mc-Si‡	150.57	57.49	(57)	95.81	23.27	343.50	2.34

Source: Kalowekamo and Baker (2009)

characterized strength in solution processing, low cost, high transparency, and high flexibility entitle it with a critical role in future PV product development.

(a) **Lower cost**

One chief advantage of organic PV refers to its low unit price. Table 3 lists the cost estimates of organic, DSSC, CdTe thin-film, and mc-Si photovoltaic technologies in each breakdown. It can be clearly identified that organic photovoltaic demands unbeaten superiority over other emerging PV technologies.

(b) **High transparency**

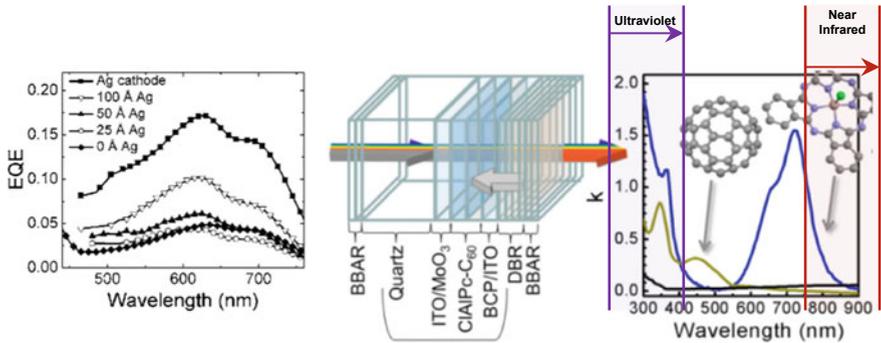
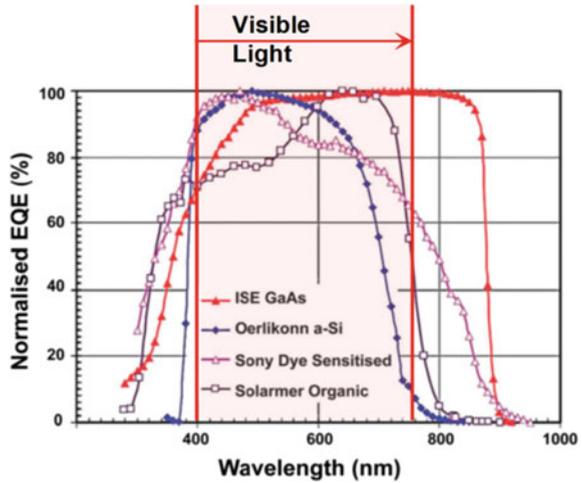
Another important merit of organic PV considering building applications is its higher transparency upon visible lights. Figure 4 shows the differences among amorphous silicon, thin film, and organic photovoltaic. According to the graph, while OPVs comparatively exhibit much lower absorption through the visible light range compared to other emerging PV technologies.

Some more recent research has further improved the active material property and enlarged the absorption region from the visible part centralized to a wider range with more ultraviolet and near-infrared (NIR) spectrum parts absorbed (Fig. 5) (Source: Huang et al. 2013). Figure 5 also illustrates the different novel active materials developed to tune visible light absorption curves for better transparency perception (Source: Bailey-Salzman and Rand 2006; Lunt and Bulovic 2011). Figure 6 shows the novel prototype of transparent organic photovoltaic developed at MIT (Source: Lunt and Bulovic 2011).

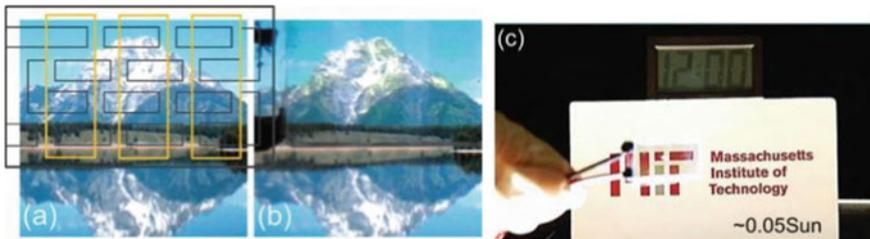
(c) **Multiple color choices**

Compared to other third-generation PV technologies, organic PVs have a wider range of active materials choices in various colors. Therefore, they have much more possibilities of final cell appearance in color than in their campaigns. Figure 7 shows this with different embodied colors of various conjugated polymers due to their unique

**Fig. 4** External quantum efficiency of light spectrum of a-Si, GaAs, dye-sensitized PVs, and OPVs. Source Huang et al. (2013)



**Fig. 5** Modified light spectrum absorption of OPV. Source Bailey-Salzman and Rand (2006), Lunt and Bulovic (2011)



**Fig. 6** a “Teton mountains” displayed on an LCD, b with transparent OPV in front, c picture of the OPV powering an LCD clock while allowing for high transparency. Source Lunt and Bulovic (2011)



**Fig. 7** Various conjugated polymers with different embodied colors due to their unique band gaps. Source Janssen (2010)

band gaps, which therefore results in their reflected external coloring appearances, which bring them competitiveness for architectural integration needs.

### 1.2.3 Perovskite Photovoltaic—The Most Promising Technology in Flexible PV Development

Flexible perovskite solar cells (FPSCs) have been the most promising PV material over the last decade, mostly due to the combination of the high efficiency and a huge economic potential. Perovskite absorber film with excellent requisite properties can be processed under low-temperature conditions, which makes this wonder material an ideal choice for next-generation low-cost high-performance flexible solar cells. Its advantages like high power-to-weight ratio and compatibility with irregular surfaces are suitable for portable power sources, lightweight drones, building façade, reflectors, etc. (Fig. 8). However, the technology is still not mature and most of the research and development is still at the laboratory stage.

#### (a) *Extremely low cost*

Compared to other flexible photovoltaics, both material and production are at low cost. A cost analysis of perovskite solar cells was performed with two typical models (Molang et al. 2016). One was a moderate-efficiency module made of cheap materials, and the other was a high-efficiency module made of expensive materials. It showed that the costs of both models are lower than other PV technologies. The levelized cost of electricity (LCOE) was performed to be 3.5–4.9 US cents/kWh with a PCE of 12% and 15-year lifespan, below the cost of traditional electricity sources.

#### (b) *High power conversion efficiency*

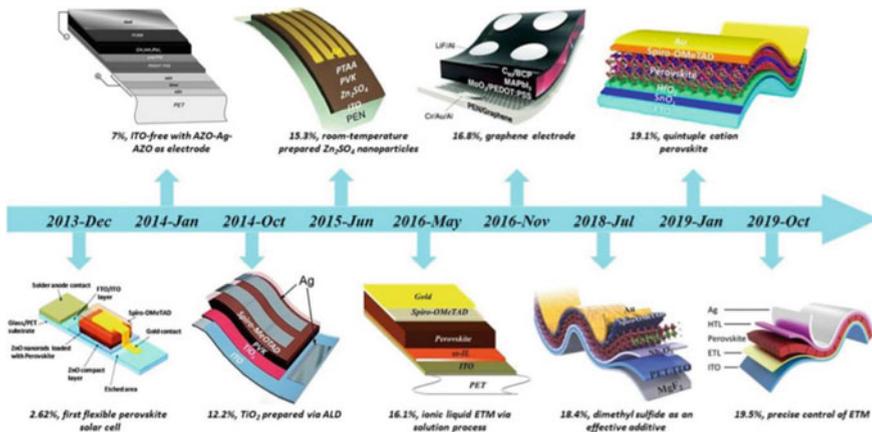


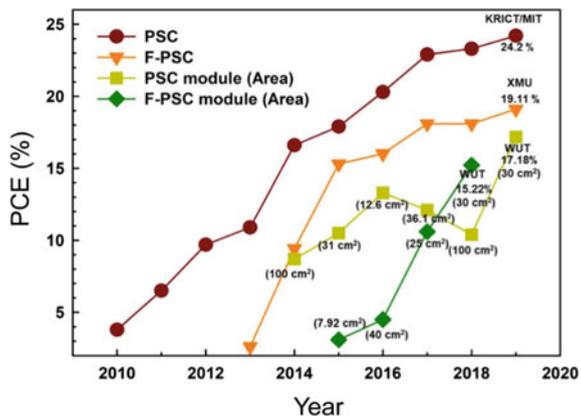
Fig. 8 Year-wise advancements of flexible perovskite solar cells. Source Zhang et al. (2020)

Perovskite PV has a leap forward promotion from 2012. With only a couple of years, it has achieved great progress in power conversion efficiency and shows its enormous potential. The cell power conversion efficiency of FPSCs has reached up to 19.5% in laboratory-scale fabrication (Fig. 9). Huang et al. (Source: Huang et al. 2019) developed a structure of PEN/ITO/SnO<sub>2</sub>/perovskite/Spiro-OMeTAD/Ag, showing PCE and a steady output of 19.01%. Furthermore, the FPSCs exhibit a robust bending resistance and present an outstanding long-term stability without encapsulation.

(c) **Rapid fabrication**

Rapid fabrication potential is also an essential advantage. In 2020, Stanford team firstly tried to manufacture scalable and fast open-air perovskite PV modules at continuous inline production speeds > 10 m/min without any perovskite post-annealing (Source: Rolston et al. 2020). It is the highest reported throughput of any

Fig. 9 Progress of PCEs in rigid-type cells and FPSCs for unit cells and modules. Source Jung et al. (2019)



solar technology. This fabrication system can make significant progress in reducing manufacturing costs to the level that can compete with incumbent Si-based PVs in the energy market. Then the perovskite module will be deployed in a wider scale to support the development of distributed energy systems with the lowest levelized cost of energy for any form of PV production. Kim et al. (Source: Kim et al. 2020a, b) demonstrate the production of FPSCs with a manufacturing of 100-m-long roll and a high PCE exceeding 16 and 13% by a full R2R gravure printing method. This work has provided a new way for high throughput of FPSCs at larger scale via R2R processes in the near future.

#### (d) *Applications*

Building vertical envelopes provide a large-scale platform for the application of the FPSC technology because of its good electrical performance under the low-irradiation condition. Kim et al. (Source: Kim et al. 2020a, b) used InZnSnO (IZTO) as top cathode to produce semitransparent PSCs that are suitable for building-integrated photovoltaics. Wang et al. (Source: Wang et al. 2020) showed that the diverse colorful tunability and superb bifacial PV performance of CuSCN-based PSCs could be extremely beneficial for BIPV applications to design esthetically attractive buildings.

FPSCs possess a revolutionary potential for space applications. Reb et al. (Source: Reb et al. 2020) tested the electrical characteristics of different PSCs during a sub-orbital rocket flight. Under strong solar irradiation conditions, the PSCs showed considerably efficient performance and reached power densities. The long-term operation in the space environment has been the next emphasis toward space applications.

## **1.3 Manufacturing**

### **1.3.1 Fabrication Technologies of PV**

Corresponding to the three main phases of technology development, the fabrication of photovoltaic panels has also experienced three main developing phases (Fig. 10) due to the material breakthrough of photon-active layers:

- (1) the direct pseudo-square crystal or ingot slicing for the wafer-based modules (Fig. 11);
- (2) the physical/chemical vapor deposition or sputtering for thin-film-based modules (Fig. 12);
- (3) the direct printing (e.g., roll-to-roll printing technology as shown in Fig. 13) of photon-active and functional layers onto the substrate for various cutting-edge Photovoltaic technologies.

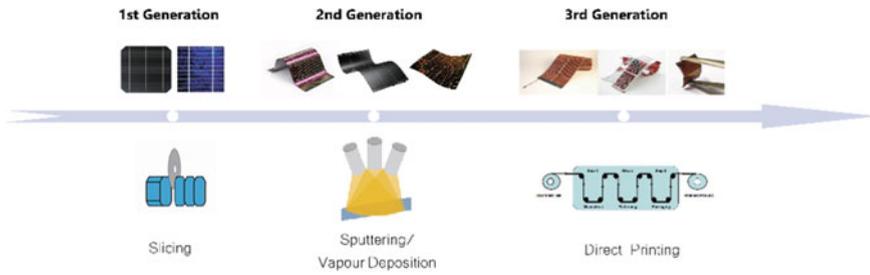


Fig. 10 Three phases of photovoltaic panel production processing (edited by the authors)

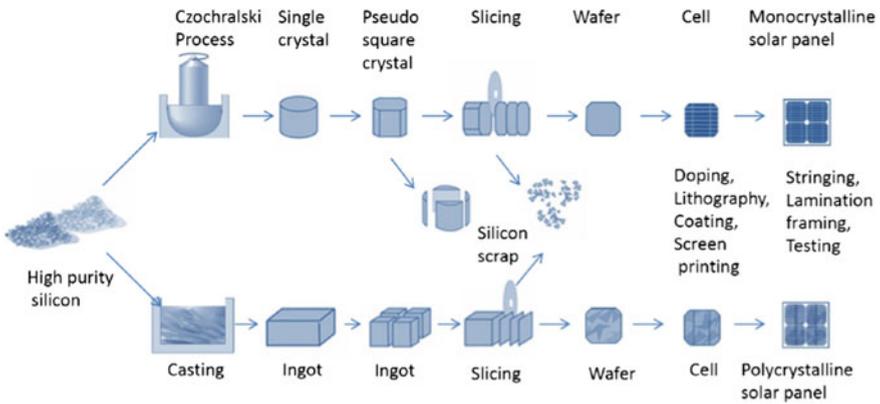


Fig. 11 Production processing of crystalline silicon photovoltaic panels (edited by the authors)

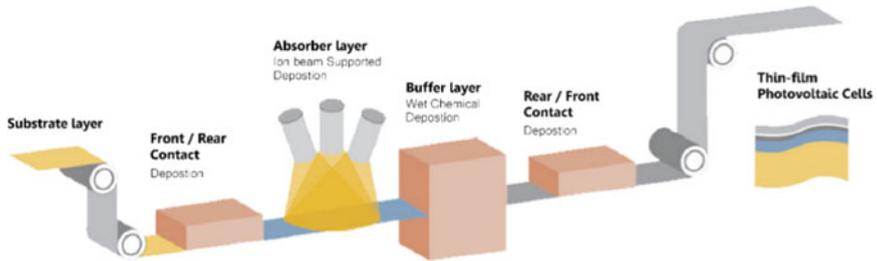
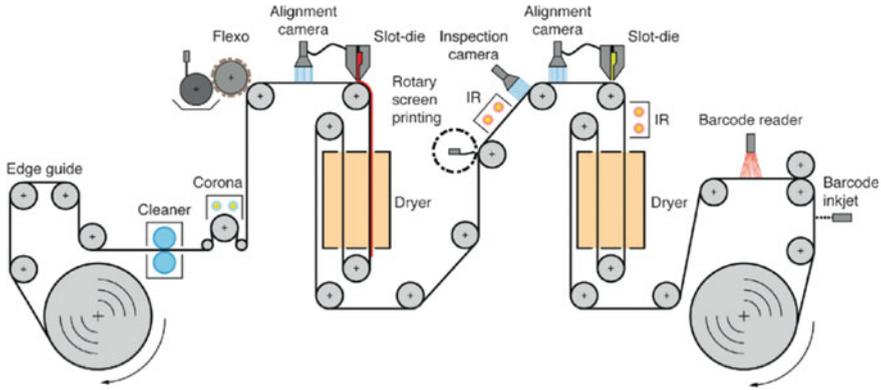


Fig. 12 Illustration of thin-film photovoltaic cell production line. Source Bundesministerium für Wirtschaft und Energie (2019)



**Fig. 13** Schematics of a large-scale R2R machine with multiple printing and coating units. *Source* Hösel et al. (2017)

### 1.3.2 Direct Printing as a Promising Flexible PV Fabrication Technology

Normally, the direct cutting and slicing production is employed by crystalline (monocrystalline or polycrystalline) silicon wafer production. Only vapor deposition and direct printing are compatible with layer formation on flexible substrates. So, they can well exert the high potential of emerging photovoltaic technologies. Despite this, sputtering and vapor deposition processes in many cases demand a critical working environment, especially high-vacuum and high-temperature conditions, compared to direct printing. The complexity of the associated setup and processing configurations, higher cost as well as its lower processing speed, induce the lower popularity of vapor deposition than direct printing for future photovoltaic products. The high output, relatively more ambient-alike processing environment, together with its processing and operation simplicity makes direct printing to be probably the most promising technical pathway for the fabrication of future flexible photovoltaics. A wide range of terms have been adopted to describe the layer formation processes, including deposition, coating, and more recently printing. The clarification of their difference is critical for understanding the high potential of direct printing technologies for flexible PV manufacturing. The term printing initially refers to a contact or pressing process through which the ink is reversely transferred from a stamp to a substrate, while all other terms are used to describe the process through which the ink is transferred to the substrate through pouring, spraying or painting and so on. In this sense, the utilization of printing highlights its simplicity and effectiveness of mirroring complex pattern, as well as its high compatibility with rolling printing processing. To meet the desired mass production need toward the target of global energy supply, a continuous and industry-compatible direct printing manufacturing process is highly wanted.

#### (a) *Application of Direct Printing Technology with Flexible PVs*

The direct printing, especially roll-to-roll (R2R) printing technology, has been proved to be highly compatible with various types of emerging photovoltaic technologies:

### **Amorphous Silicon (a:Si) Photovoltaic**

Hiroko et al. have proved that liquid-Si printing (LSP) fabricated hydrogenated amorphous silicon (a-Si:H) has better power conversion efficiency (PCE) than a conventional plasma enhanced chemical deposition (plasma-CVD) fabricated one (Source: Hiroko et al. 2014). Huang C-P., et al. developed a continuous roll-to-roll (R2R) VHF PECVD for high-efficiency amorphous silicon thin-film solar cells on flexible stainless-steel substrates, with a cell efficiency within 4.3–5.8% (Source: Huang et al. 2012).

### **Dye-Sensitized Solar Cells (DSSC)**

Kati M. et al. have investigated the effectiveness to improve the R2R manufacture ability of counter electrodes for dye solar cells by using a carbon gel catalyst layer on plastic substrates at low temperatures (Source: Kati et al. 2011). Jean-Claude T., Renata S., Artur B., et al. have proposed a new low-temperature R2R coating procedure for the large-scale production of flexible photoelectrodes for dye-sensitized solar cells (DSSCs), through comparison of different coating procedures with respect to their PCE (Source: Jean-Claude et al. 2011). Ghufuran et al. have found that the transferring to the employment of simple R2R production methods is the key issues for the upscaling and commercialization of dye-sensitized solar cells (DSSC) technology (Source: Ghufuran et al. 2011). Baker et al. have developed a semitransparent catalytically active graphene nanoplatelet (GNP) ink for catalytic layer on a DSSC solar cell electrode, which is suitable for R2R printing. They achieved a comparable PCE with chemical reduced or sputtered platinum catalyst (Source: Baker et al. 2014). Paolo et al. have then evidenced that the printing techniques fit very well with the intrinsic characteristics of the DSSC technology, through the reviewing of large-area printing/coating technologies underlining the process parameters and applications (Source: Paolo et al. 2015).

### **Cu(In,Ga)Se<sub>2</sub> (CIGS) Photovoltaic**

Susan et al. have investigated in general the possibility of employing printing technology to fabricate inorganic thin-film solar cells, mainly Cu(In,Ga)Se<sub>2</sub> (CIGS) and cadmium telluride (CdTe) technologies (Source: Susan et al. 2010). David et al. from US Photovoltaic Manufacturing Consortium (PVMC) have validated their process and cost model for the manufacture of CIGS solar cells through the R2R process (Source: David et al. 2016). Muhammad et al. have validated the effectiveness of “roll-on” printing as a layer formation process for nano-CIGSe powder applied over ITO electrode, when compared with spin coating (Source: Muhammad et al. 2014). Lih-Ping et al. have fabricated CIGS cells on flexible stainless-steel substrates with the absorber layer prepared using ink-printing technique and selenization process (Source: Lih-Ping et al. 2013). Yanmin et al. have proposed the R2R compatible “one-stage process” for the production of CIGS cells at low temperature on the polyimide (PI) (Source: Yanmin et al. 2011).

### Perovskite Photovoltaic

Youn-Jung et al. have proposed organic cation additives in lead iodide solutions as a practical approach for printing-friendly sequential deposition, and R2R production of perovskite solar cells (Source: Youn-Jung et al. 2017). Pei et al. have achieved a champion efficiency of 14.04% with a novel kind of highly conductive, low-temperature, and perovskite-compatible carbon paste, through its application in fully printable perovskite solar cells (Source: Pei et al. 2018). Francesco et al. have demonstrated the possibility of fabricating a high-efficiency perovskite module through scalable sheet-to-sheet slot-die coating processes (Source: Francesco et al. 2018). Chuantian et al. have demonstrated a maximum PCE of 19.48% for perovskite solar cell through a facile spin coating-free and R2R compatible blowing-assisted drop-casting (BADC) method to prepare  $\text{CH}_3\text{NH}_3\text{PbI}_3$  films, and then an applied one-step R2R air processed prototype on flexible substrate, yielding record PCEs of 11.16% (Source: Chuantian et al. 2018) and both exhibit as important milestones in the development of upscalable manufacturing technologies for perovskite PV modules. Other than these, Yaoguang et al. and Wei et al. have examined in detail the application potential of current printing technologies for flexible perovskite photovoltaic production (Source: Yaoguang et al. 2018; Wei et al. 2018).

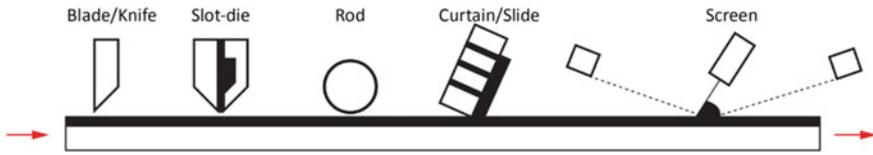
### Organic Photovoltaic (OPV)

Frederik et al. have spared a large amount of work investigating the feasibility and technology pathways of fabricating organic photovoltaic through full R2R processing. His group has proved the high potential of fabricating OPV through the R2R processing and the promising methodology for upscaling (Source: Frederik and Kion 2009; Frederik et al. 2010a, b; Suren et al. 2011; Thue et al. 2012; Roar et al. 2012). Yulia et al. have also investigated the technology development for R2R production of organic photovoltaics (Source: Yulia et al. 2011; Yulia and Ronn 2012).

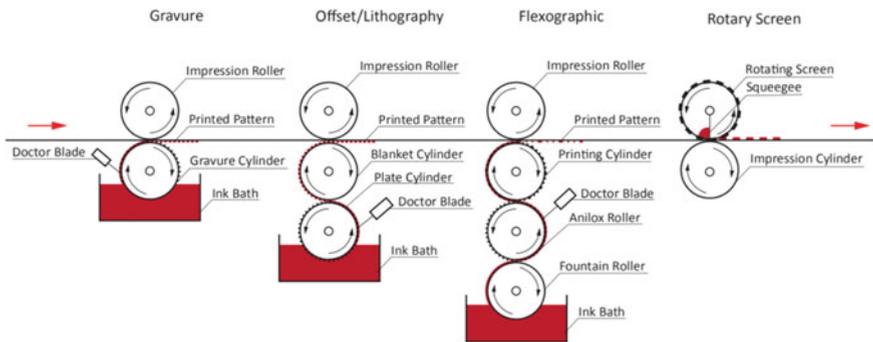
#### 1.3.3 Printing Technologies of OPV

Generally, the high solution processability of OPV's photon-active and functional materials makes it the best candidate for the effective production with direct printing methods in high volumes. A great many of OPV prototypes have been fabricated through research in laboratory scale, but most of them are facing the huge challenge of industrial upscaling. To enable the industry-compatible fabrication, more work should be devoted to "make it happen" of printing processing onto various flexible substrates.

In this section, the main existing printing technologies have been reviewed to serve as a reference for addressing the above-mentioned unification challenge (Figs. 14, 15, and 16). It will also bring attention to the hitherto little explored area of enabling integration of OPV onto flexible substrates to realize flexible PV by means of industrial compatible fabrication methodologies. Currently, mostly investigated layer fabrication technologies include:

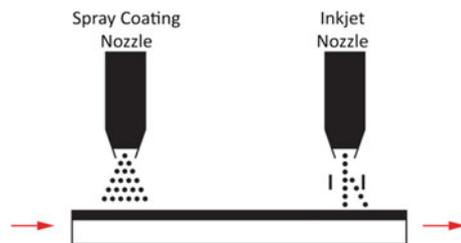


**Fig. 14** Schematics of main coating heads for flexible PV printing technologies (edited by the authors)



**Fig. 15** Schematics of main rotational type printing technologies for flexible PV (edited by the authors)

**Fig. 16** Schematics of printing mechanism of inkjet printing and spray coating technologies for flexible PV (edited by the authors)



*Casting*

Through casting films are formed in good quality by casting a solution onto a substrate followed by a drying process. Even though the process exhibits high simplicity, it strongly suffers from a lack of control over the film thickness and frequent occurring picture framing effects (Source: Frederik 2009; Roar et al. 2012).

*Spin Coating*

The typical spin coating operation is applying feeding liquid to a substrate followed by the acceleration of the substrate to a chosen rotational speed, or applying the liquid through the spinning of the substrate layer. The technique is highly questionable whether to be competitive when it comes to upscaling, as it requires the substrates to

be handled individually through the process and thus not intrinsically R2R compatible (Source: Frederik 2009; Roar et al. 2012).

### *Doctor Blading*

This technique forms the film by means of a sharp blade limiting the coating ink at a fixed distance above the substrate surface. It demands the same level of instrumental cost and operational complexity compared to spin coating, but is relatively slower with the film formation speed (Source: Frederik 2009; Roar et al. 2012).

The three above-mentioned layer formation techniques are not truly “printing” technologies and also not R2R compatible. But they are still of high value through the OPV development work in the laboratory. Below some more techniques supposed to be real “printing” will be introduced. These techniques are extremely interesting as future candidates for OPV processing industry.

### *Knife-Over-Edge and Meniscus Coating*

It is a quite similar layer formation technique to doctor blading, but reversely to keep the substrate moving while the knife to be stationary, making it R2R compatible. Due to the printing mechanism, it cannot form a multi-dimensional pattern but only an evenly smooth flat layer. Another upgraded technique of it is meniscus coating, where the ink supply and layer control is done with another roller at a certain distance from the substrate (Source: Frederik 2009; Roar et al. 2012).

### *Slot-Die Coating*

This is a similar technique to the above one but with the coating head more complex. The ink is simply transferred to the substrate at the direction perpendicular to the substrate moving direction. As the ink is directly fed down through the slot, the feeding process needs to be controlled with either a pump, pressure system, or patterning mask in the coating head (Source: Frederik 2009; Roar et al. 2012; Frederik et al. 2010a, b; Wengeler et al. 2011).

### *Gravure Printing*

This is today’s most widely employed printing technique in high volume printing like magazines, press publications, and so on, but it is still being explored as a printing technology for organic solar cell development. Through this technique, the ink is transferred from a gravure cylinder with engraved ink carrying cavities to the surface web to be printed. The web is tensioned with surface tension and meanwhile super pressed by the impression cylinder to the gravure cylinder (Source: Frederik 2009; Roar et al. 2012; Jinsoo et al. 2011; Koidis et al. 2011; Mark et al. 2011).

### *Flexographic Printing*

Flexography is similar to gravure printing except that it is a four roller rather than two roller systems. It employs an extra anilox roller and a final printing cylinder or flexo roller in contact with the substrate to print. The flexo roller surface is typically made from rubber. The substrate roll is also guided by the impression roller-like gravure printing. Flexographic printing is still a relatively new technology and so far

not been employed so much. It has been used with some cases of the PEDOT:PSS and electrode grids processing (Source: Frederik 2009; Roar et al. 2012; Frederik et al. 2010a, b).

#### *Offset Lithography Coating*

This is another appealing technique based on the hydrophobicity of the roller. The roller selectively got wetted with the hydrophobic area but excluding the ink with the hydrophilic area. Afterward, the inked roller passes to the substrate to print to form the desired pattern. It will need specific requirements of the ink hydrophobicity and special development of ink systems (Source: Frederik 2009; Roar et al. 2012).

#### *Screen Printing*

Screen printing involves a screen of woven material (i.e., synthetic fiber or steel mesh) that has been glued to a frame under tension. The area of the printed pattern is kept open (without emulsion) through the process while the areas where no print should appear are kept impervious to the coating solution. Through the printing process, the squeegee moves relative to the screen and forces the ink paste through the opening of the screen mesh to form the desired pattern. Screen printing includes both the flat-bed screen printing and rotary screen printing. Flat-bed screen printing demands an intermittent printing mode and a much lower cost of the mask, while the rotary screen printing consumes higher cost with mask and is with superior speed. The rotary screen printing has a rotating cylinder ink container with internal squeegee to achieve the continuous process and therefore more promising for R2R printing (Source: Frederik 2009; Roar et al. 2012; Frederik et al. 2010a, b).

#### *Inkjet Printing*

Conventionally utilized for convenient graphic printing and common organic electronics like organic light-emitting diodes (OLEDs), organic thin-film transistors (OFETs), inkjet printing exhibits as a quite different film-forming way. It prints the two-dimensional pattern of the film by specifically addressing each pixel onto the substrate. The layering principle refers to the typical low-cost inkjet printer for the home office. Currently, there are also two types of droplet controlling mode employed for the film formation in inkjet printing. The piezoelectric inkjet ejects the ink droplet on demand from the nozzle to the moving substrate while in continuous inkjet the ink droplets are continuously generated but selectively deflected onto the moving substrate when one pixel is desired to form the two-dimensional layer pattern. Afterward, it forms the three-dimensional layer structure by means of multi-layer printing. The process has the advantage of quite high resolution and processing capacity of complex patterns, but also has limitations of relatively low printing speed and restrictions of ink formulations (Source: Frederik 2009; Roar et al. 2012; Mark et al. 2011; Berend et al. 2004).

#### *Spray Coating*

Similar to inkjet printing, this technique forces the ink to pass through a nozzle to form a fine aerosol, where after the aerosol was directed to arrive at the coating

**Table 4** Classification of common PV direct printing technologies (edited by the authors)

Printing technologies			
	Film formation with contact	Film formation with micro-contact/meniscus	Film formation without contact
Non-R2R compatible	–	–	Casting, spin coating
R2R compatible	Gravure Offset/lithography Flexographic Pad	Doctor blading Knife-over edge Slot-die Rod Screen Curtain/slide	Spray coating Inkjet

surface with the aid of a carrier gas and electrostatic charging. Although principally R2R compatible, as a zero-dimensional coating technique, it has restricted ability to precisely control the two-dimensional pattern and layer thickness (Source: Frederik 2009; Roar et al. 2012).

#### *Roll-to-Roll (R2R) Printing*

A key term in today's OPV research is R2R printing which could be realized with substrate sheet wound on rolls. It has been commonly agreed to be the current most promising route for the manufacture of OPV. The strength of R2R processing is the potential of high printing speed to realize high throughput at ambient temperatures while its current weaknesses lie in the technology maturity. Ideally in a R2R production line, the raw substrate is unwound from a roll and passed through the printing or coating machine and once completed the flexible polymer solar cell should emerge on the other end and is rewound on a roll. This is the so-called integrated R2R process that is highly compatible with industrialized production manner with high throughput and reduced damaging risks. As the process currently still faces many difficulties like the synergized processing speeds and intermittent calibration needs in practical terms. More practically the discrete processes are more employed at the moment, where each layer is processed individually in between each printing step. In Table 3, the compatibility with the R2R process of main printing technologies is summarized. And the printing mechanism and competence are also listed in Tables 4, 5, and 6 (Source: Frederik 2009; Frederik et al. 2010a, b; Yulia et al. 2011; Roar et al. 2012; Frederik et al. 2010a, b; Jinsoo et al., 2011; Mark et al. 2011; Frederik 2009; Suren et al. 2011; Cheng-Hsin et al. 2011).

### **1.3.4 Printing Technologies of Perovskite Photovoltaic**

The perovskite solar cell is another most promising technology for industrial production in the method of R2R printing processing. Up to now, blade coating, slot-die

**Table 5** Printing mechanism summary of common flexible PV printing technologies

Printing technologies	Ink feed method	Ink feed tool	Layer thickness control method
Casting	Dropping	Ink outlet	Self-leveling
Spin coating	Dropping	Ink outlet	Angular accelerated and air-blowing self-leveling
Spray coating	Spraying	Nozzle	Spray distribution quality
Doctor blading	Dropping	Ink outlet	Blade
Knife-over edge	Dropping, bathing	Ink outlet, ink bath	Knife/blade
Slot-die	Slot-dropping	Slot-die	Meniscus
Rod	Dropping	Ink outlet	Rod distance + positioning
Screen	Screen slot-dropping	Screen, Rotating screen + squeegee	Screen distance + positioning
Pad	Transfer/deposition	Pad stamp	Gravure motif thickness Impressing Force
Curtain/slide	Slot-dropping	Multiple Slot	Meniscus
Gravure	Impressing	Ink bath + Gravure cylinder	Cylinder distance + positioning Impressing force
Offset/lithography	Impressing	Ink bath + plate cylinder + Blanket cylinder	Cylinder distance + positioning Impressing force
Flexographic	Impressing	Ink bath + Anilox roller + plate cylinder	Cylinder distance + positioning impressing force
Inkjet	Projection	Nozzle + Electric Field	Ejection times

Source: Frederik (2009), Roar et al. (2012), Frederik et al. (2010a, b), Wengeler et al. (2011), Jinsoo et al. (2011), Koidis et al. (2011), Mark et al. (2011), Berend et al. (2004), Frederik (2009), Suren et al. (2011), Cheng-Hsin et al. (2011), Ciro et al. (2017)

coating, spray coating, and inkjet printing have been applied to the fabrication of FPSCs mostly.

### *Slot-Die Coating*

The research on producing FPSCs by slot-die coating is at an early stage. As mentioned above, Francesco et al. have demonstrated the possibility of fabricating high-efficiency perovskite modules through scalable sheet-to-sheet slot-die coating processes (Source: Francesco et al. 2018). Recently, Ciro et al. (Source: Ciro et al. 2017) showed FPSCs can be fabricated in ambient conditions by a slot-die coating processing in a mini roll coater, achieving a PCE of 2.9%. Their results further suggest

**Table 6** Printing competence comparison of common flexible PV printing technologies

Printing technologies	Printing dimension	Printing speed (m/min)	Printing resolution ( $\mu\text{m}$ )	Maximum printing layers	Reproducibility
Casting	0	–	–	1	Very low
Spin coating	0	–	–	1	Very low
Spray coating	0	–	–	1	Very low
Doctor blading	0	0.001–0.1	–	1	Very low
Knife-over edge	0	1–100	–	1	Very low
Slot-die	1	5	200	3	High
Rod	0	–	–	1	Very low
Screen	2	33	100	1	Low
Pad	2	5	10	1	Low
Curtain/slide	Pseudo/quasi 2/3	1–1000	–	17	High
Gravure	2	90	60	1	High
Offset/lithography	2	80	30	1	Medium
Flexographic	2	50	50	1	High
Inkjet	Digital master	13	30	1	Medium

Source: Frederik (2009), Roar et al. (2012), Frederik et al. (2010a, b), Wengeler et al. (2011), Jinsoo et al. (2011), Koidis et al. (2011), Mark et al. (2011), Berend et al. (2004), Frederik (2009), Suren et al. (2011), Cheng-Hsin et al. (2011), Ciro et al. (2017)

that flexible perovskite solar cells are compatible with slot-die coating in ambient conditions to achieve low production costs and scalable PV technology.

### *Inkjet Printing*

Inkjet printing has been applied to deposit perovskite thin film and grid electrodes using both one-step and two-step processes. Gheno et al. fabricated  $\text{WoO}_x$ ,  $\text{MAPbI}_x\text{Cl}_{3-x}$ , and Spiro-OMeTAD on the ITO substrate by inkjet printing, which was conducted under ambient conditions and at low temperatures ( $<90^\circ$ ), with a PCE of approximately 10% (Source: Alexandre et al. 2018).

### *Spray Coating*

Spray coating seems like a promising approach to produce industry-scale FPSCs with nearly no precursor wastage. Jiang et al. (Source: Jiang et al. 2018) achieved a PCE of approximately 15% with a depositing of ETM/HTM and perovskite layers by spray coating. Furthermore, the operating condition of the whole processes was below  $150^\circ\text{C}$ .

### *Blade Coating*

Blade coating has a promising prospect to commercialize large-area FPSCs because of its operation under relatively low temperature. Recently, a record efficiency flexible

perovskite solar module (19.7%) is presented on flexible Corning Willow Glass in the method of blade coating (Source: Xuezheng et al. 2020).

### 1.3.5 Encapsulation

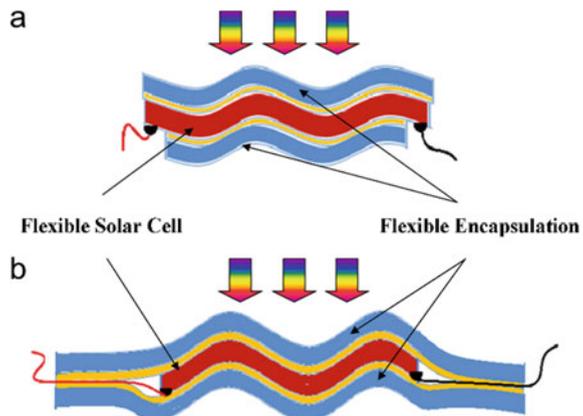
Keeping sufficiently long operating lifetimes of OPVs and PSCs is a major challenge for facilitating the commercialization of flexible PV technologies, because these two kinds of solar cells are extremely sensitive to external environments. The encapsulation that can limit the exposure of solar cells to moisture and oxygen is a very important process to maintain their stability.

One is for the protection from external environment, including water vapor transmission rate (WVTR), oxygen transmission rate (OTR), and resistance to ultraviolet (UV). The other is to keep the performance of the solar cells, like light transmission, mechanical flexibility, chemical inertness, and strength.

To date, there are two encapsulation forms, partial encapsulation and complete encapsulation as shown in Fig. 17. Partial encapsulation links electrical connections and devices directly. And complete encapsulation uses thin copper wires to contact these two parts.

Single-layer and multiple-layer encapsulations are two mainstream techniques for the encapsulation of flexible PV technologies. Multiple-layer encapsulation employs both inorganic or organic materials to make up for the shortage of single-layer encapsulation which appears pinholes on its surface. The depositing of inorganic materials is through atomic layer deposition (ALD), which is suitable for flexible electronics but with high-cost processing. Another way is to use polymer encapsulants for heat sealing. The polymer sealants are listed in Table 7.

**Fig. 17** a Partial encapsulation, b complete encapsulation (edited by the authors)



**Table 7** Summary of polymer encapsulants for flexible solar cells

Name	WVTR (g/m <sup>2</sup> /day)	Comment
Ethylene-vinyl acetate (EVA)	15–30	EVA has a high light transmission up to 91%
Ethylene methyl acrylate (EMA)	N/A	EMA is chemically and thermally stable and performs good flexibility under low-temperature conditions
Polyvinyl butyral (PVB)	40	PVB has a high light transmission and favorable heat resistance
Thermoplastic polyurethane (TPU)	40	TPU is resistant to oil, grease, and abrasion
UV-cured epoxy	16	This film has high optical transparency and is thermally conductive
Polyisobutylene (PIB)	< 0.001	PIB is a synthetic rubber
Cyclized perfluoro polymer (Cytotm)	N/A	It is easy to be deposited through solution-process at low cost

Source Zhang et al. (2020)

**Table 8** Comparison of physical and chemical characteristics of common plastic materials

Properties	Unit	PET (Melinex)	PEN (Teonex)	PC (PureAce)	PES (Sumilite)	COC (ARTON)	PI (Kapton)
Provider		Dupont	Dupont, GE Teijin	Dupont Teijin	Sumitomo	JSR	Dupont
Density	g/cm <sup>3</sup>	1.4	1.36	1.2	0	1.08	1.43
Water absorption	%	0.3	0.3	0.2	1.4	0.4	–
Refractive index		1.4	1.74	1.59	1.65	1.51	1.7
Total light transmission	%	89	85	90	90	94.4	< 30
Glass transition temp. (°C)	°C	78	121	155	223	171	410
Using temp.	°C	105	180	125	180	150	240
CTE	ppm/°C	15	13	75	54	62	20
Chemical resistance	Methanol	○	○	○	○	○	○
	Ethanol	○	○	○	○	○	○
	Acetone	○	○	X	○	○	○
	MEK	○	○	X	○	○	○
	Cellosolve	○	○	X	X	○	○

Source Bundesministerium für Wirtschaft und Energie (2019), Industrial Technology Research Institute (2020)

**Table 9** Typical product specification of ETFE films

Thickness	[ $\mu\text{m}$ ]	50	80	100	150	200
Weight per unit area $\acute{\alpha}$	[ $\text{g}/\text{m}^2$ ]	87.5	140	175	262.5	350
Minimum tensile strength $\acute{\epsilon}$	[N/5 cm]	64/58	58/54	58/57	58/57	52/52
Fracture strain $\acute{\epsilon}$	[%]	450/500	500/600	550/600	600/650	600/600
Tear resistance $\acute{\eta}$	[N]	450/450	450/450	430/440	450/430	430/430

Source: Leslie (2004)

$\acute{\alpha}$  According to DIN 55 352, (DIN = German Institute for Standardization)

$\acute{\epsilon}$  Warp/weft, according to DIN 53 354 or DIN EN ISO 527

$\acute{\eta}$  Warp/weft, according to DIN 53 363

## 2 LCI of a Novel Concept of Skin

This part is focused on the LCA approach related to the ETFE technology and to the PV/OPV technology, by an investigation of the literature references of the last years, thanks to which some important steps were found out. The outline of the LCA method to be applied to OPV, referring to a codified European method, is explained.

### 2.1 Environmental Profile of Organic Photovoltaic Technologies

A frame has been defined regarding the environmental impact assessment of PVs. The International Energy Agency has developed and defined into the collaborative R&D Photovoltaic Power Systems Programme the “Methodology guidelines on life cycle assessment of photovoltaic electricity” (Source: Anselma et al. 2009) and published the guidelines (Fthenakis et al. 2011) (Source: Fthenakis et al. 2015), which represent a consensus among PV-LCA experts in North America, Europe, and Asia, for assumptions about PV performance, process input and emissions allocation, methods of analysis and reporting of the findings. The document offers guidance on photovoltaic-specific parameters (e.g., life expectancy, irradiation, performance ratio, degradation) that are the inputs of the LCA, on choices and assumptions in analyzing the life cycle inventory (LCI) data, and on implementing modeling approaches.

A first target is to quantify the environmental profile of electricity produced with PV systems (in comparison with that of electricity from other sources of energy), a second one is to show the improvement trends of the PV environmental profile, and, last but not the least, to assess the environmental profile of PV electricity with the help of “external” costs and other life cycle impact assessment methods. The methodology guidelines lead to the life cycle inventory analysis and life cycle impact assessments of grid-connected photovoltaic electricity, according to the ISO standards 14040 and 14044 (Source: EN ISO 14040:2006/A1:2020; EN ISO 14044:2006/A2:2020; EN ISO 14044:2006/A1:2018; EN ISO 14044:2006). Into the document, the life

expectancy of PV systems is declared as a reference. Regarding the LCA, some specific indications of the functional unit and the reference flows (*kWh electricity* or the *m<sup>2</sup> laminate*) of the system boundaries are recommended in the guidelines.

The structure of the environmental impact analysis is also defined through four steps: (a) Description of the aim of the analysis; (b) Description of the involved materials and components; (c) Methodology with—Life cycle inventory LCI of the materials and energies,—Energy payback time (EPBT),—Emissions of the Global Warming Gases in the life cycle; d. Analysis of sensibility and interpretation of the experimental results between laboratory and industrial production.

Specific category indicators are suggested to be defined in relation to audience: greenhouse gas emissions (GHG, to be identified by specifying the underlying time horizon either 20, 100, or 500 years), cumulative energy demand (CED), acidification potential (AP), ozone depletion potential (ODP), or volume of radioactive waste.

The study of Marco Raugei, Paolo Frankl on Life cycle impacts and costs of photovoltaic systems resumes the state of the art in the PV technology and drafts three future outlooks, in terms of costs, market penetration, and environmental performance (Source: Raugei and Frankl 2009). They underline how more and more renewable energy sources are developing and evolving in many parts of the world, due to the recent sharp increase in oil prices and the growing concern about global warming. For instance, one of the direct consequences is that the European Commission has set a fairly ambitious target reaching the 20% of renewable energy in the overall EU energy budget by 2020, in order to stabilize greenhouse gas emissions and reduce its contribution to global warming.

The most widespread PV technologies on the market are the multi c-Si types (45.2%) and the mono c-Si (42.2%); the OPV technology, the one of SOFT research, belongs to the category “Other tech” with 0.1%, with their possibilities and potentials slightly growing.

Looking at life cycle energy consumption and environmental impact of PV systems, there has been a marked reduction over the last two decades. As illustrated in the research of Raugei and Frankl (Source: Raugei and Frankl 2009), greenhouse gas emission values of PV electricity in recent scientific literature are already reported to be one order of magnitude lower than those associated with the average electricity mix of the European Union for the Coordination of Production and Transmission of Electricity (UCPTE), and to be less than 5% of those deriving from a modern coal-fired power plant (Source: Fthenakis et al. 2008). The LCA comparison in long-term scenarios (25, 50 years) between selected technologies (representatives of the three big PV families, the ribbon-Si one, the CdTe one and the newest Dye-Synthesized Cells (DSC)), based on peer-reviewed life cycle inventories and compared to that of sc-Si PV today, in terms of global warming potential, clearly suggests that marked reductions in life cycle CO<sub>2</sub> equivalent emissions are expected to take place for both silicon-based and binary thin-film (CdTe) technologies. DSC systems also show favorable results, despite a comparatively shorter service lifetime (Source: Garcia et al. 2010).

Focusing on the developing technology of organic PV, a great contribution in the comprehension of its environmental impact is the research executed by Espinosa N.

et al., regarding the application of the LCA on a full R2R coating procedure used for the manufacture of one square meter of flexible polymer solar cell modules, under environmental conditions (Source: Espinosa et al. 2011). The process employs a polyester (PET) substrate with a sputtered layer of the transparent conductor indium tin oxide (ITO). The ITO film was processed into the required pattern using a full R2R process, employing screen printing of an etch resist and then applying etching, stripping, washing and drying procedures. The three subsequent layers, ZnO, P3HT:PCBM, and PEDOT:PSS, were slot-die coated, and the silver back electrode was screen printed. Finally, the polymer solar modules were encapsulated, using a polyester (PET) barrier material. The life cycle analysis delivered a material inventory of the full process for a module production that constitutes an excellent guideline for the SOFT production inventory, and an accountability of the embodied energy both in the input materials and in the production processes. The results of the embodied energy in the considered input materials to the direct production of one  $\text{m}^2$  processed surface of organic solar modules (with an active area of 67%) identifies the most energetically intensive materials processes: the energy involved in processing the ITO represents about 87% of the total. This is a bottleneck in the fabrication of organic solar modules and intensive research is ongoing to find an alternative transparent conducting oxide or polymeric layer to be used as transparent electrode. As regards the distribution of the energy consumption in the “production steps,” PEDOT:PSS deposition is the more consuming step, accounting for more than one-third of the total energy consumption during the manufacture (35.31%), followed from a short distance by both electrodes processing: silver deposition and ITO patterning (27.89% and 23.23%, respectively). The electron transport layer deposition accounts for almost 10% of the total energy, and active layer is one of the less energy-intensive processes (5.38%). It is emphasized that a more efficient use of the ITO covered substrates has to be addressed and this means a rethinking of the etching process, where 65.2% of the initial amount of the ITO gets lost: a step forward would be to avoid the etching process and substitute it with a directly patterned deposition method for an ITO. In the end, the use of the ITO should be avoided: the share of embodied energy that arises from it as electrode is the highest of all input materials, almost 87%. Also, the economical cost of indium and its scarcity makes this element a bottleneck for a competitive price per watt peak.

Upon assumption of power conversion efficiencies and lifetime for the modules, a calculation of EPBT has been carried out in this paper to compare this R2R manufacturing with other organic and hybrid photovoltaic technologies. The results showed that an energy payback time (EPBT) of 2.02 years could be achieved for an organic solar module of 2% efficiency, which could be reduced to 1.35 years, if the efficiency would be 3% that actually is much lower.

However, this technology has a lower environmental impact in terms of embodied energy, GHG emissions, and EPBT than other more traditional PV modules.

The comparison of the embodied energy between different PV technologies is clearly shown in the research of Garcia VR, Cherni JA, and Urbina A (Source: Garcia et al. 2010), whose study is focused on the life cycle analysis of the laboratory production of a typical bulk hetero-junction organic solar cell and on the

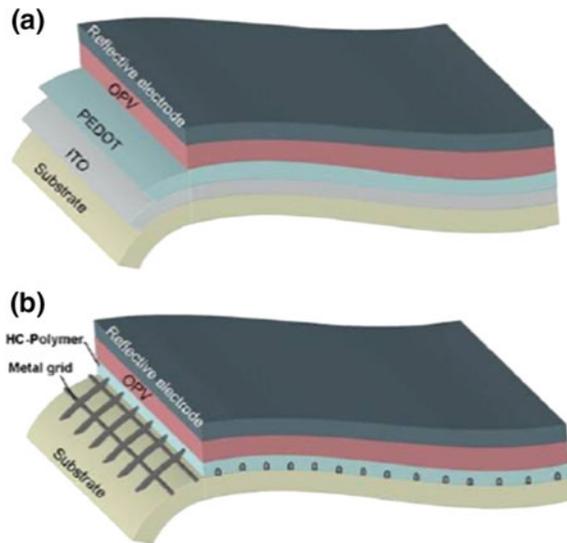
comparison of this result with those obtained for the industrial production of other photovoltaic technologies. Their results highlight how organic photovoltaic technologies in general, and full organic polymeric technology in particular, even if they are far from optimum laboratory fabrication procedure, in terms of embodied energy are more eco-efficient compared to other PV technologies, because not high temperatures are involved in the process. Specifically for their laboratory cell production, the final embodied energy of a square meter module is  $2800.79 \text{ MJ/m}^2$  (the fabrication of the electrodes-ITO accounts for 50.39% of total material embodied energy and Indium is a scarce and expensive material, as mentioned): half of the average value calculated for crystalline silicon technologies, the same order of magnitude of thin-film technologies and slightly higher than dye-sensitized solar modules. However, they can expect bigger reductions for the organic technology in the large-scale industrial process; therefore, giving a clear advantage to organic technologies provided that the efficiency of these industrial modules is similar to that of actual laboratory cells (about 5% now and an expected 10% in the coming years).

The ITO is actually the bottleneck of this OPV technology, and alternative materials for cathodes are therefore needed to make this technology more competitive. An evolution has been contemporary developed in the research ICT 2009 collaborative project HIFLEX (Grant Agreement number 248678) into the EU Framework 7 (Fig. 18) (Source: Galagan et al. 2010); it demonstrated the possibility of excluding the expensive and brittle ITO electrode from organic photovoltaic devices and replacing it by a composite anode containing a combination of an inkjet-printed silver grid and a high conducting PEDOT:PSS layer, prepared in atmosphere, excluding deposition of the cathode, which was evaporated under vacuum. The authors stated that devices with a composite electrode demonstrated a reasonable efficiency, while the integration of a conductive grid significantly decreases the resistance of the anode. This should enable a complete roll-to-roll printing of solar cells on large flexible plastic substrates.

The technology explained in this work corresponds to the process fabrication of the OPV cells developed by the no more existing company Konarka. The life cycle assessment of this last type of polymer solar cells is clearly shown in the paper of Lenzmann et al. (Source: Lenzmann et al. 2011); the software Simapro (version 7.3) and the integrated Ecoinvent 2.0 database were used to assess the environmental impacts. The different environmental quality indicators have been carried out on the basis of the following predefined methods within Simapro and following the ISO 14040 standard: CED V.1.04 (for embedded energy), IPCC 2007 GWP100 (for greenhouse gas emissions).

The work of Lenzmann et al. provided a comprehensive picture of the environmental profile of polymer-OPV technology based on a full-scope embodied energy analysis and it finds that, for power-generating applications, the embodied energy of a module is about  $300 - 500 \text{ MJ/m}^2$ , resulting to a large extent from the encapsulation scheme with a contribution of about  $200 - 400 \text{ MJ/m}^2$  (Source: Lenzmann et al. 2011). They found out a total embodied energy of about  $130 \text{ MJ/m}^2$  for a benchmark system, lower than an approximately factor of 10 (about 130 versus about

**Fig. 18** Schematic illustration of a “standard” ITO-based device and a device with current collecting grids. *Source* Galagan et al. (2010)



1000–1500 MJ/m<sup>2</sup>) compared to averaged values for other current thin-film PV technologies. This value refers to the “average” thin-film PV technology, produced as glass-based laminates (this laminated encapsulation structure brings itself embodied energy values of several hundreds of MJ/m<sup>2</sup>). From this point of view, the comparability of an “average” thin-film PV module and the benchmark polymer-OPV module described here is limited since the encapsulation scheme of the latter only added up to about 10 MJ/m<sup>2</sup> and is most certainly not appropriate for power generation devices in outdoor conditions: It is based on a “cold lamination” procedure using adhesives and thin PET foils with basic moisture barrier coatings (sufficient for relatively short-lived mobile electronics applications, power generation applications). Different encapsulations are expected to require substantially different schemes providing a more stringent and robust protection from humidity and oxygen access as well as mechanical impacts.

The large majority of current thin-film PV modules are manufactured as glass-glass laminates with EVA encapsulations: This structure (glass/EVA/glass) is considered in the study of Lenzmann et al. as a benchmark encapsulation scheme (Source: Lenzmann et al. 2011). Another possible encapsulation scheme considered here is the structure steel foil/EVA/ETFE, in analogy to flexible PV modules manufactured on metal substrates. Such a structure would probably still need to integrate additional components in order to comply with all requirements for outdoor uses, but it is an indicative benchmark here. More specifically, the thicknesses of the materials envisioned for the two possible encapsulation concepts described above are: glass pane: 2.3 mm, EVA foil: 500 μm, stainless-steel foil: 100 μm, ETFE foil: 100 μm. Regarding the process, the lamination with EVA is carried out in vacuum laminators at high temperatures of 140–150 °C for up to about 30 min. The embodied energy values of all three encapsulation schemes were computed, to which the “cold processing” of

the benchmark laminate is referred. It came out that for power-generating devices an encapsulation scheme similar to state-of-the-art rigid or flexible PV modules would amount to additional contributions to the embedded energy of about 200–400 MJ/m<sup>2</sup> and thus become the dominant factor (by far) of the total embodied energy of the polymer-OPV module (of then about 300–500 MJ/m<sup>2</sup>).

Generally, when expressed in a Wp basis or in the ultimately most relevant kWh basis, the competitiveness of new generation OPV cells is (partially) lost due to the lower module efficiency and lifetime expectancy. For polymer-OPV to become an environmentally viable power-generating PV technology, these latter two parameters (module efficiency and lifetime) necessarily need to be further improved. Konarka and Solarmer published references to increased record efficiencies and improved operational lifetimes on a regular basis, reaching values major of 8% and thousands of hours for record devices. It has to be underlined as this research paused around five years ago, with no further developments till now.

## ***2.2 Main Flexible Substrate Materials for PVs***

The key concern for choosing the substrate material for flexible PV includes flexibility, transparency, or conductivity. The flexibility of flexible PV can be classified into three types: conformal, bendable, and roll-able. The property of substrate material plays a key role that determines this flexibility. If the substrate material can be rolled in the size of a handwriting pen, then the fabrication process would be possible to realize in a way of R2R direct printing, which can afterward save a major part of the manufacturing costs. High transparency on one hand can ensure the maximum penetration of photons from solar illumination into the photon-active layer, so as to increase the device power conversion efficiency, on the other hand can promote the daylighting quality of the PV-covered spaces. And high conductivity can make full use of the generated photocurrent while avoiding the outflow through the conductivity. Other property requirements of substrate material include heat resistance, glass transition temperature (T<sub>g</sub>), dimensional stability, coefficient of thermal expansion (CTE), surface smoothness, hardness, chemical resistance, water vapor transmission rate (WVTR), etc.

Currently, the flexible substrate materials used are mainly in the following categories, including mainly plastic film ultra-thin glass, metal sheet, etc.

### **2.2.1 Common Plastic Film**

Due to their high transparency, high flexibility, lightweight, low cost, anti-collision, and high portability, plastic films are more and more favored as the development direction of the flexible PV substrate material. Currently, the main barrier for the real application of plastic films refers to its poor heat resistance and high WVTR. Actually, these are not only the problems for the application in flexible PVs, but also

the common research topic among the flexible electronics. To overcome these difficulties, ambient temperature-based manufacturing processes and ultra-high barrier encapsulation technologies need to be developed. A list of the physical and chemical property comparison for main employed plastic materials is summarized in Table 1.

### **2.2.2 Ultra-Thin Glass**

According to the general understanding, glass is not a bendable material. However, when the thickness of glass reaches the level of 50–100  $\mu\text{m}$ , it will become partially flexible. Its flexibility will even reach the flexibility level of conformal. The advantage of ultra-thin glass is it can follow the traditional manufacturing process of TFT-LCD, since in this case the flexible PV would employ the same material with it. However, even though the thickness of ultra-thin glass is remarkably low, when compared to a plastic film it is still highly fragile. This will result as well as in high difficulty and complexity of the manufacturing process.

### **2.2.3 Metal Sheet**

Various material-based thin metal sheets have also been popular for laboratory research for the flexible PV development. With appropriate thickness, metal sheets could be suitable for layer deposition, and enough flexible for flexible PV needs.

However, even with high flexibility, the intrinsic opaque appearance makes it much less interesting for being utilized as flexible PV substrates.

### **2.2.4 ETFE**

Glass has long been the common choice for quite many building envelope applications including atrium roofs and skylights where materials with lightweight, high strength, and low cost are essential. It exhibits as a nearly perfect can without considering its limited flexibility. To find flexible alternatives, many common plastic materials like polycarbonate have been applied through both research and construction as a substitute. However, their application is still limited due to their inferior durability properties.

An ideal material choice of the substrate should hold the property advantage of both plastic and glass. The common architectural membrane material, ethylene tetrafluoroethylene (ETFE) could coincidentally be a possible candidate. In recent years, membrane structures have been widely adopted and developed, which depends largely on the technological enhancement of the membrane material properties. A great part of this should be attributed to the wide application of ETFE membrane. The high acceptance of the material in contemporary membrane architecture is due to its extraordinary material properties. Hereby some of its key material properties are listed to be a reference:

(a) ***Tensile Strength and Ductility***

Reported ultimate tensile strength of ETFE varies from 40 to 64 N/mm<sup>2</sup> (Source: Galliot and Luchsinger 2011). Generally, ETFE can ensure a tensile strength larger than 40 N/mm<sup>2</sup>. The elongation rate of ETFE foil at tensile failure varies from 250% to more than 600% (Source: Linda 2011). In principle, ETFE will not fail with elongation less than 300%.

(b) ***Stress–Strain Relationship***

ETFE exhibits linear elastic behavior with a low-stress level (<20 MPa) and an elastic modulus from 300 to 1100 MPa. It begins yielding at around 25 MPa and develops into a reinforced plastic stage until the rupture (Source: Linda 2011).

(c) ***Flexibility and Lightness***

Depending on different manufacturers and standards, the finishing thickness of ETFE membrane foil varies from 0.05 mm to 0.25 mm, therefore with super-high flexibility. With increasing thickness, ETFE gets harder and stiffer. ETFE has a density of approximately 175 g/cm<sup>3</sup>. A typical ETFE foil with a thickness of 0.20 mm has a weight of 350 g/m<sup>2</sup> (Source: Leslie 2004).

(d) ***Color and Transparency***

Usually, ETFE is colorless with high transparency. It can also be produced to be white-colored. Transparent ETFE foil demonstrates a light transmittance higher than most other transparent or translucent envelope materials as shown in Fig. 19 (Source: Cremers and Lausch 2008).

(e) ***Fire Performance and Durability***

ETFE is a fire-resistant and retardant material. Even if on fire, ETFE will shrink and show self-extinguishing property rather than generating drips or any other harm to surroundings. It also maintains great durability and very high electrical and chemical resistance. With high stability even when exposed to weather conditions and ultraviolet radiation, ETFE can reach a service lifetime to more than 25 years.

(f) ***Temperature Capabilities and Self-cleaning property***

ETFE shows a very wide service temperature range (-200 °C to 150 °C) and also excellent thermal control properties, therefore can facilitate either multilayer or cushion structures (Source: Galliot and Luchsinger 2011). It has also been widely described to have a good self-cleaning characteristic and demands little needs of wiping and maintenance.

### **Other Properties**

ETFE also has very good tearing resistance, very low gas and water vapor permeability, as well as recyclability. Table 2.2 shows some typical product specifications of ETFE films.

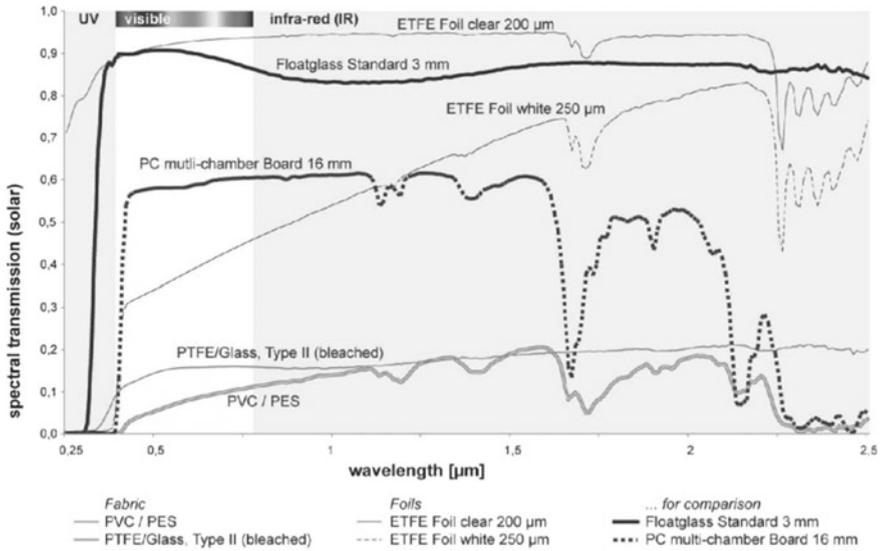


Fig. 19 Solar transmission of different envelope materials. Source Cremers and Lausch (2008)

### 2.3 Environmental Profile of ETFE Cushion Technology

The new tendencies with respect to the fixed panels or hard silica are flexible panels as mentioned. In the past, there was a substantial gap between the two in terms of efficiency. ETFE-based flexible panels have narrowed the gap sufficiently to make the technology extremely attractive. ETFE’s unique features and excellent performance characteristics provide the light transmittance, aging resistance, weight advantage, and performance that could enable it to compete with the photovoltaic glass (Fig. 20).

Considering the possibility of different encapsulation schemes and the use of ETFE for this scope, as explained before, it has to be noted how the Asahi international company developed the employment of the ETFE for the encapsulations, and actually

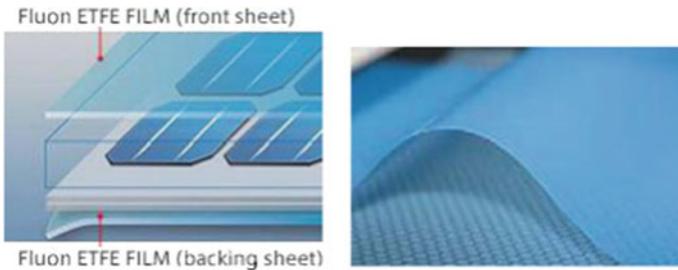


Fig. 20 Use of ETFE for the encapsulation of the PV cells. Source AGC Chemicals Europe (2008)

produces and laminates it as front and backing sheets to improve the durability and reliability of photovoltaic devices.

Because of the 95% of light transmittance from ultraviolet to infrared rays and the excellent weather-ability, ETFE film is used as front sheets for photovoltaic devices and also as backing sheets to contribute to the increasing of the durability and reliability for a range of photovoltaic devices. They are also used as a material for bendable flexible photovoltaic devices, thanks to these features and the high flexibility.

Although these advantages of the ETFE, the environmental impacts of its life cycle have to be considered in order to understand better its contribution to the OPV technology and its role into the building sector: As a result of both the newest chemical synthesis process and the polymeric material working one, the application of technological advanced components related to the ultra-light transparent film production is becoming more and more widespread.

At the material scale, some studies have been carried out, in order to analyze the environmental impacts of the manufacturing process. In the research work of Monticelli C, Campioli A, and Zanelli A (Source: Monticelli et al. 2009), the “state of information” about ETFE environmental performance, besides the assessment of the most energy content stage of the ETFE cushion system manufacturing chain, has been deepened. In the manufacturing chain, particularly in the raw materials’ phase and in the polymerization one, monomers are polymerized thanks to an initiator, a chain transfer agent, and a polymerization medium. ETFE does not contain any additives to enhance its service performance. As maintained by AGC Chemicals Europe (Source: AGC Chemicals Europe, 2008), additives, such as plasticizers, flame-retardants, and antioxidants, could give rise to an increased environmental burden in the future, during the service life or potentially at the end of the life of the products. But something has to be said about the environmental effects of the initiators and the chain transfer agents. The Montreal Protocol (which deals with the control of ozone-depleting substances) recognizes ethylene and chlorodifluoromethane-like substances used as chemical feedstock and, transformed in the process, they are thus removed from the environment. In these cases, their ozone-depleting potential is zero. For this reason, the protocol specifically excludes these substances from its regulation (Source: Society of the Plastic Industry 2005). Other involved substances may represent hazards in the production of the fluoropolymer resin, considering that their manufacturing chain releases damaging gases. The hazardous ingredients, related with the ozone depletion potential, are the processing aid PFOA<sup>1</sup> (perfluorooctanoic acid, also called “C8,” a polymerization emulsifier) and the chain transfer agents. The chemical industries have just improved their manufacturing plants with sophisticated systems, closing the loop of the outputted gases, minimizing their emission, capturing and reusing them in their processes. The main companies have worked to find a substitute of PFOA. In January 2006, the US Environmental Protection Agency asked companies manufacturing fluoropolymers and fluorotelomer to commit to a

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<sup>1</sup> PFOA—is used as a polymerization aid in the manufacture of fluoropolymers and is present in trace quantities as impurities in fluorinated water and oil repellents.

voluntary program with global goals, to be achieved no later than 2015: The goal was to reduce and work toward ultimately eliminating facility emissions and product's content of PFOA, their precursors<sup>2</sup> and related higher homolog chemicals. The state of the art of program was presented in February 2009 in Geneva (Source: US EPA 2009). Reviewing the used raw materials, the manufacturing technologies, and the production processes, some companies have recently developed a new alternative high-performance emulsifier.

AGC, for example, has launched a new range of PTFE products, the Fluon® PTFE E-series (used for wires and cable insulation, hose and tube, and non-stick coatings), whose production process does not use ammonium salts of perfluorooctanoic acid (PFOA) as a polymerization surfactant. Conventional PTFE manufacturing uses PFOA in its process but there have been concerns expressed about its persistence and widespread presence in the environment. AGC announced in 2011 (Source: AGC Chemicals Europe, 2008) a further investment into Fluon® PTFE product development and manufacturing at the Hillhouse site in Thornton Cleveleys (UK), building an ETFE manufacturing plant alongside the existing PTFE production facility. Since concerns about PFOA were raised, AGC has worked to reduce PFOA emissions in the environment and has developed a new high-performance surfactant<sup>3</sup> as an alternative to PFOA. This new surfactant is being registered in the EU under the REACH programme. AGC will convert all its fluorinated products, including the water and oil repellent Asahi Guard®, into PFOA-free products (free of PFOA at or above detection limits) by 2012.

As well as AGC, also Dyneon, a 3M company, one of the major producers of ETFE granules, satisfied in November 2008 the requirements of the USA (Source: 3M Dyneon Company 2021). Environmental Protection Agency introducing a new emulsifier without PFOA from the production of fluoropolymers. Dyneon's stewardship strategy includes sophisticated systems to minimize the release of PFOA into the environment and recapture and reuse PFOA in its processes. 3M Dyneon has offered to license the use of this PFOA containment technology to other companies.

Regarding the environmental impact assessment of the ETFE manufacturing, in order to obtain one kilogram of an extruded ETFE film, a rough estimation of the embodied energy and the other EPD indicators has been carried out in the research work of Monticelli C, Campioli A, and Zanelli A (Source: Monticelli et al. 2009). The embodied energy amount is about 210 MJ/kg. In this study the LCA of an ETFE cushion with its frame (the scale of a building component/system) has also been assessed in comparison with other similar transparent building systems—glass,—PC,—PVC crystal: The results point out the importance to assess these light technical solutions not only considering the material stage (related to their own specific gravity), but also the involved materials in the roof subsystems and, even better, their role in the building. The ETFE system shows as result a great impact bond

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<sup>2</sup> Precursors are substances that change into other substances via decomposition. In this case, they are those chemicals that decompose to generate PFOA and/or related higher homologue chemicals.

<sup>3</sup> Surfactants are wetting agents that lower the surface tension of a liquid. They can reduce the interfacial tension between oil and water by absorbing at the liquid-liquid interface.

with the global warming potential and the ozone depletion (global environmental problems), caused by the emissions and energy content of each product, due to the chemical industry manufacturing chain during the polymerization of monomers to create the granules. The glazing manufacturing causes dangerous output, influencing the acidification and eutrophication of air, water, and soil (regional, local environmental damages), due to the manufacturing process step to obtain the float glass. In the case of a glazing system, much more material for the frame is used.

In January 2014m an Environmental Product Declaration (EPD) in accordance with ISO14025 describing the specific environmental performance of the Texlon System has been published and validated by the Institut Bauen und Umwelt e.V., aiming to support the development of environmentally compatible and “ETFE Construction Element” 2011–05 (Source: Environmental Product Declaration 2014).

Texlon is a system made of cushions in UV transmissive ethylene tetrafluoroethylene copolymer (ETFE) foils welded, stabilized by compressed air, and secured by aluminum profile systems. This building system is offered by the company Vector Foiltec GmbH under the TEXLON® brand name. The complete product chain for the manufacture of the ETFE building envelope elements includes Dyneon GmbH, the ETFE granulate producer, i.e., the raw material for the manufacture of the ETFE foils, Nowofol Kunststoffprodukte GmbH & Co. KG, which from the ETFE granulate extrudes foils of different thicknesses, and Vector Foiltec GmbH, fabricator and builder up of the foil cushions.

This EPD provides the environmental profile of the impacts caused by the production and transportation processes to do the cushions. In detail, this EPD assesses the impacts related to the realization of foil cushions composed of between 2 and 5 layers of NOWOFLON® ET-foil, welded together along the edges and stabilized to approximately 220 Pa (220 N/m<sup>2</sup>) by a low-pressure air system during installation on site.

This declaration refers to the manufacturing of 1 m<sup>2</sup> of a standard foil cushion with a mass per unit area of 0.967 kg/m<sup>2</sup>, and the average quantity of frame material required for the assembly of the roof construction:—ETFE foil cushion 0.967 kg/m<sup>2</sup>,—aluminum profile 4.571 kg/m<sup>2</sup> and—Seal 0.016 kg/m<sup>2</sup>. The quantities of raw materials, energy, auxiliary substances and supplies used in the LCA have been accounted as average values for a period of 12 months for each considered plant. For life cycle modeling of the ETFE construction element manufacture, the “GaBi 4” software system was used. The basic data of the GaBi database have been used for energy, transports, auxiliary substances, and primary products.

The results of the embodied energy (EE) of one square meter of a standard foil cushion and the average quantity of frame material required for the assembly of the roof construction are the following: foil cushion (three layers) 305.7 MJ, frame 413.7 MJ, transport to the construction site 183.1 MJ. This EE value for one square meter of foil cushion is aligned with the results found out in the research work of Monticelli C, Campioli A, and Zanelli A (Source: Monticelli et al. 2009), where the EE value of foil cushion is 315 MJ/m<sup>2</sup>. The production of the raw materials used for the granulate manufacturing and for dyeing and printing requires a high quantity of

primary energy. The impacts of the fossil primary products in the upstream chain of ethylene become apparent as well.

In both the studies EPD of the Texlon System and of the research by Monticelli C, Campioli A, and Zanelli A (Source: Monticelli et al. 2009), the usage stage of the ETFE construction elements was not considered, although its computation is very important for an evaluation in the context of a building assessment and has additionally to be considered in order to understand the potentials and limits of this building component into the whole life cycle assessment.

With a life cycle approach future researches on the environmental impact assessment of the fluoropolymer films will have to weigh the recycling contribution and balance the saved energy and raw material consumption with the huge impact of the first production process. The positive effect of recycling, being considered as a negative or avoided impact, can be expressed by the material's recycling inventory minus its new fabrication inventory.

### 3 Market

#### 3.1 Flexible PV Module Products

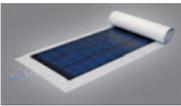
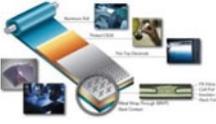
Due to the integration and application demand of flexible PV products, manufacturers had already started the exploration and manufacture of flexible PV module products. As a plastic film and metal sheet are the common economical flexible products available, while in most cases the laboratory research also employs them for flexible PV development, currently most of the available flexible PV products are still based on commercial plastic (PET, PEN etc.) or metal foil (aluminum, steel, etc.) as the base substrate.

Currently, only a few products of this type are available in the market, with the name of PV laminates, PV foils, etc. They normally employ a commercial polymer substrate like PVC or PET, with various types of thin-film PV as the above built flexible modules, out of which the a:Si and CIGS are the most commonly used. And the products are manufactured in various sizes, patterns without a standard specification. A list of currently available products in this type is presented in Table 10.

The key shortage of this type of products lies in two aspects:

Firstly, as almost none of the substrates in these products can be integrated into building envelopes, flexible PV products in this type are still utilized by being attached to building surfaces as BAPV rather than being integrated as BIPV when applied in buildings. As a BAPV, the post-built installation or construction becomes the necessary step for these flexible PV products before being put into service, which will surely result in additional costs. Meanwhile, for various module types, no standard installation or construction configuration can be widely suitable for all products. Figure 21 gives some examples of this kind of product's installation details. As

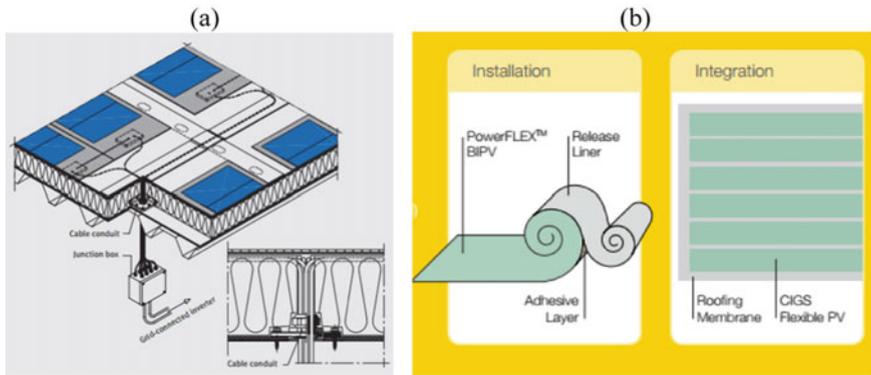
**Table 10** Overview for some of the BIPV foil products

	Manufacturer	Product	Material	Substrate
	Alwitra	EVALON® V-Solar	a•Si & a•SiGe	Stainless steel/polymer coating/Evalon®V membrane/polyester fleece
	Nanosolar	Nanosolar Ultralight	CIGS	Aluminum roll
	Global Solar	PowerFLEX™	TCO/CDS/CIGS	Stainless steel
	Flexcell (Q-cells)	Sunlick solar board/pack/panel	NA	TPO coated metal/TPO membrane
	SoloPower	SoloPanel® Model SP1/SP3S/SP3L	CIGS	Stainless steel
	Ascent Solar	WaveSol™ Light Modules	CIGS	Thin-film plastic
	Phaesun	PN-XFlex	Triple junction of a•Si	Fluoropolymer

SourceCythelia Energy (2021), Nanosolar Company (2021), Globalsolar Company (2021), Solarc Company (2021), Solopower Company (2021), Sunload Company (2021), Solar-Bazaar Company (2021)

a result, the incremental cost and construction complexity significantly reduce the appeal of the product.

Secondly, the material durability of most applied common plastic substrates is not reliable in a long term. Their mechanical, optical, fire, and thermal properties



**Fig. 21** BIPV foil product's installation detail from **a** Alwitra. *Source* Cythelia Energy (2021), **b** Flexcell. *Source* Solarc Company (2021)

like strength, ductility, transparency, flammability, and insulation is inferior to architectural membrane materials like ETFE or PTFE in general (Source: Cremers and Lausch 2008).

These reasons intrinsically determined their serviceability and hindered their market share increase. The market popularity of this type of PV products was seriously impeded by the huge gap between its integration design requirements and current product pattern of the industry, as summarized in the below points:

1. The rigid PV modules still occupy the mainstream market, and the direct utilization of this type of products is quite limited due to the lack of integration design.
2. The mechanical imposing of PV products in invariable color and texture often results in a loss of aesthetics or historic value of buildings.
3. Flexible PV products did not give full play to its soft features, and a considerable part of flexible PV products is still simply used just as BAPV.
4. Either the conventional rigid PV modules or flexible PV products can hardly facilitate a high variety of application scenarios.

### 3.2 Market Segments of Flexibles PV

Due to common superior flexibility, the novel flexible PV products and conventional membrane materials share quite similar market segments. In addition, the utilization of flexible PV can generate extra power through solar energy harvesting, which would be highly favorable by most buildings. It could therefore be well-forecasted that, once well-designed, a great many of conventional membrane applications will be substituted with flexibles PV under certain circumstances (Klaudia and Miljana 2012). The most potential application scenarios, meanwhile also main market segment directions for flexible PV in the future could be summarized as follows:



**Fig. 22** Typical projects of membrane used as roofs/shelters for large span needs (edited by the authors)

The most common employment case is to be utilized as roofs/shelters for large span needs, such as stadium, archeological excavating site, and large public open spaces (Fig. 22). These structures exhibit the same needs of either light roof structure to ease the construction difficulty, or a temporary site with subsequent movable locations. This utilization scenario is usually applied with newly built or temporary architectures.

Another case, widely applied, could be added as a secondary outer sink fo existing buildings (Fig. 23). This scenario of application commonly happened with regeneration design projects like add-on shelter for listed historical building conservation or refurbishment design of existing old buildings.

Other than the outer skin, flexible PV could also well serve the specific needs of internal sheltering of buildings. It is especially favored to be employed as internal garden and courtyard coverings due to their light and semitransparent characteristics. This intrinsic feature enables hard-won light channels within the building’s within building’s inner space. The idea could be adopted for both existing and newly built buildings.

Another quite similar application scenario more and more popular for flexible PV is to add it as a joint roof for building aisle and atria spaces (Fig. 24). These spaces were usually uncovered and unilluminated. The application of flexible PV can well cope with the unsatisfied weathering conditions and may provide self-powered illumination if needed. This application typology of flexible PV could soon be one of the most important sectors for the rehabilitation of existing buildings.



**Fig. 23** Typical projects of membrane used as second outer skin for existing buildings (edited by the authors)



**Fig. 24** Typical projects of membrane used as a joint roof for building aisle and atria spaces (edited by the authors)

Last but not least, flexible PV could be a superior substitute of conventional façade materials, due to its unique appearance and properties. More and more architects choose to adopt membrane-based materials through contemporary architectural design practice (Fig. 25).

There are also other application possibilities including entertainment/touristic landscape, public assembly points and transportation stop/platform, etc.

Based on the above-mentioned utilization typologies, Fig. 26 summarizes and illustrates the five main categories of application scenarios for flexible PV in buildings.



**Fig. 25** Typical projects of membrane used as a building facade (edited by the authors)

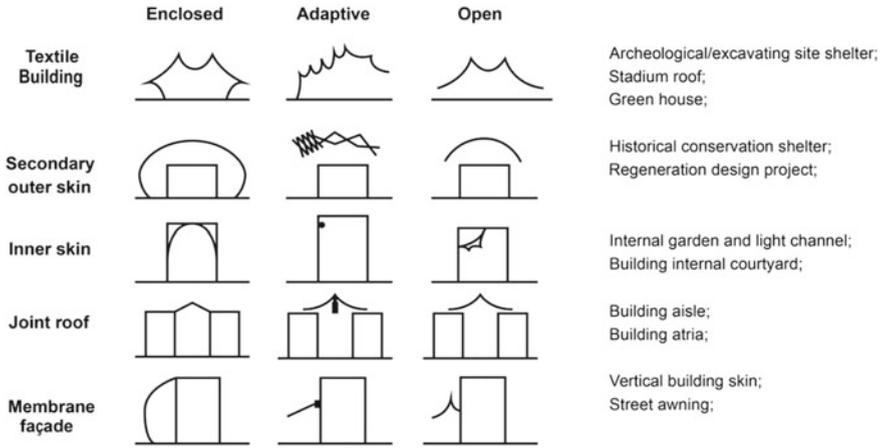


Fig. 26 Typical application scenarios for flexibles PV (edited by the authors)

In viewpoint of upon which building type the flexible PV is being applied, its application could also be classified into four main scenarios as follows:

1. Application with important historic buildings (listed buildings)

In this category, the application mainly refers to regeneration design of historical monuments and sites. The application can also engage also other materials like steel and glass with both structural and envelope upgrading.

2. Application with ordinary existing buildings

This category includes all types of refurbishment around ordinary built buildings such as inner or outer skin upgrading, aisle and atria covering, and so on.

3. Application with new buildings

This category mainly corresponds to the design of contemporary architectures excluding temporary ones.

4. Application with temporary architecture and landscape

This category contains all the other utilization excluding above. Mainly they are in the form of temporary architectures, landscapes, and awnings.

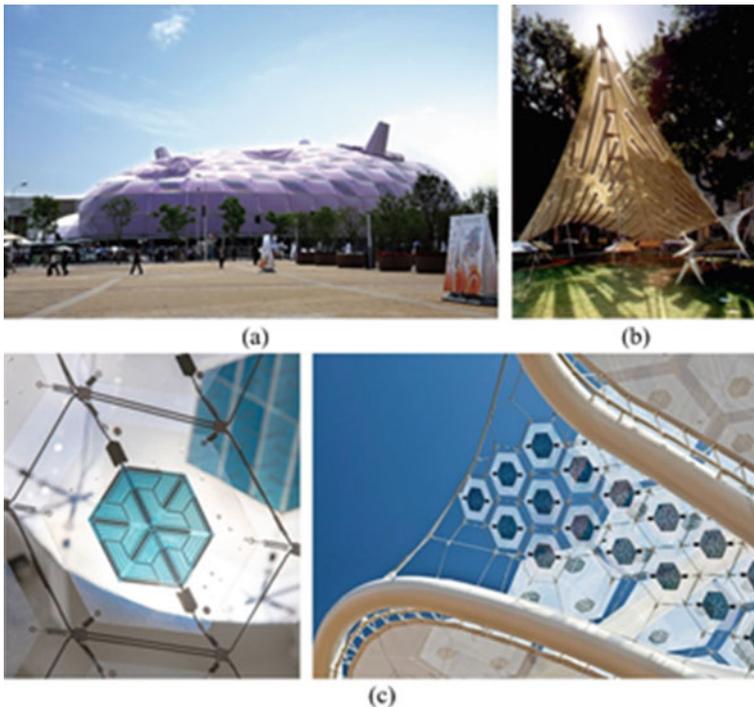
### 3.3 Architectural Application of Flexible Photovoltaic Skins

We recently published a paper that has a specific description on this topic. Some of the contents will be introduced here.

In contrast with a project only utilizing conventional PV panels, more and more architects have opportunities to do more instead of just incorporating existing technology. They have free rein to design TE-FPV systems to match their own novel ideas and to integrate them into the overall design of the building. The projects with TE-FPV systems have been applied in a series of building types.

### 3.3.1 Pavilion

In 1998, the first trial in terms of membrane fabrics incorporating FPV was exhibited in a national design museum in New York as Fig. 27 (Source: Ftlstudio Company 2021). It was a 9.7 m high tensile fabric pavilion entitled “Under the Sun,” which was made of FPV laminated on the transparent PVC membrane material designed by Nicholas Goldsmith from FTL studio (Source: Mather and Wilson 2006). While providing shelter and contributing to shadow, the pavilion was capable of generating electrical energy. However, the power output was limited due to undeveloped FPV technology (Source: Cremers and Felix 2009).



**Fig. 27** a Japan pavilion of Shanghai Expo. *Source* Ohno (2010), b Under the Sun. *Source* Ftlstudio Company (2021), c German Pavilion of Milan EXPO. *Source* Berny et al. (2016)

In 2010, at Shanghai World Expo, Japan pavilion also used membrane cushions integrated PV as the envelope, as shown in Fig. 27a (Source: Ohno 2010). In the project, the a-Si PV was fixed on the bottom-layer internal surface of a two-layer ETFE cushion. The components were capable of generating the electrical power for the LEDs lighting at night. At the same time, the air in the cavity of the cushion could be heated and collected as thermal energy.

The German Pavilion for EXPO Milan 2015 was one of the first projects to demonstrate the potential of flexible OPV in the fabric-architecture context, as shown in Fig. 27c, d (Source: Berny et al. 2016). In order to meet the aesthetics requirement of architecture, the shelters were covered by expressive transparent membrane in the shape of sprouting plants to show the “Idea Seedlings.” On the other hand, the printed OPV cells were laminated between two ETFE membrane sheets and fixed by a net of delicate steel cable, which acted not only as a part of the structure but also as an electrical conductor for the power output. Moreover, the electrical energy produced in the daytime could be collected and stored for the light-emitting diode (LED) ring at night to light the tree-shaped body of the pavilion. The whole system created a close energy cycle to reflect the central idea. At the end of the Expo, the manufacturer reused the OPV modules and other components recycled them.

### 3.3.2 Carport

Carport is also the main building type applied to the technology (Source: Pvilion company, 2021; Volvo Car Corporation Company 2021). Completed in 2011 in Munich, the roof of the Waste Management Department carport (Fig. 28a) is the first case to show a perfect integration method of thin-film PV and membrane structure applied in a large-size building but not facilities. The 8000 m<sup>2</sup> roof contains 220 air-supported three-layer ETFE cushions whose middle layer FPV modules are embedded in. As for the energy part, highly transparent UV-resistant protects the front and back surfaces of PV cells. In order to replace the faulted PV modules easily, the upper layer of the cushion was designed as a separate part from the other two layers fixed by a clamping profile, which can be opened. Every year, 140 MWh electricity that can fulfill the requirement of two local apartments is generated. Some of the energy is fed into the grid, other energy supports the power of the air pressure system. Furthermore, the lower layer of the cushion is printed with the PV modules together to block out excess sunlight.

In 2014 in Milan, Italy, Volvo Car Italia released the Pure Tension Pavilion (Fig. 28c) that was a tailor-made, solar-powered tensile membrane structure for the charging of its plug-in hybrid electric car (Source: Mather et al., Volvo Car Corporation Company 2021). The product can be disassembled within one hour to be a flat-pack facility with the suitable size for the trunk of the car. The skin is made of PVC mesh membranes with precision cutting to exacting specifications. 252 lightweight FPV cells are embedded into the fabric structure. The configuration of PV cells is based on the result of solar irradiation analysis on the structure by Rhino software. Additionally, the power output of PV cells is controlled by a maximum power point



**Fig. 28** a Waste Management Department carport, b Carport in Google company, c Volvo Car Italia released the Pure Tension Pavilion. *Source* Volvo Car Corporation Company (2021)

tracking (MPPT) device that can eliminate the mismatch impact because of non-uniform radiation. A fully exhausted car can be charged only in 12 h under good environment conditions. For Pure Tension, the balance of solar energy technology and aesthetic presents a vision for transportation in the future.

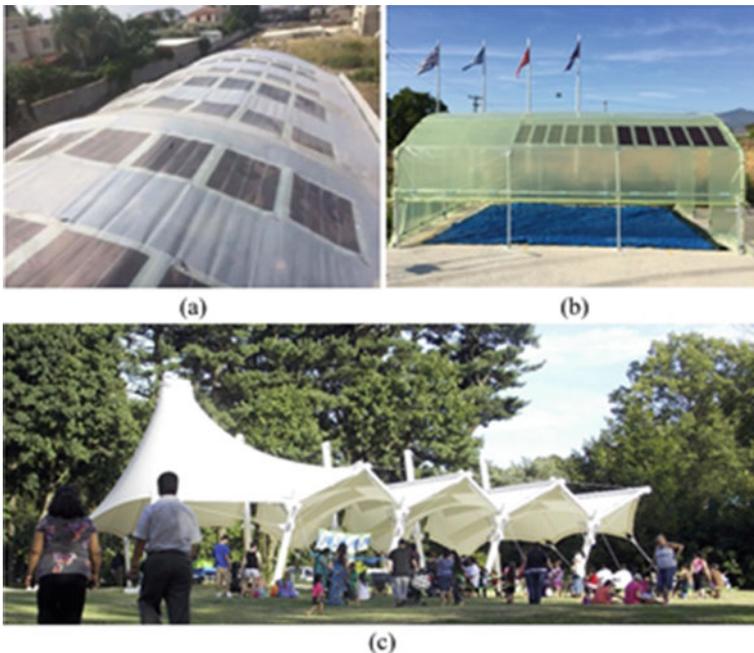
### 3.3.3 Greenhouse

The integration of FPV panels on the roof of the membrane-covered greenhouse facilitates the development of the crop production system “PV greenhouse,” which is appropriate for energy generation and cultivation at the same time (Source: Yano and Cossu 2019). Some membrane materials allow for the passing of UVs that are responsible for promoting photosynthesis, thus facilitating plant growth. In 2010, one of the first projects on membrane-covered greenhouse with FPV was implemented by Shimane University in Japan (Source: Yano et al. 2010). The study investigated the spatial distribution of sunlight energy in the greenhouse equipped with a PV array (12.9% of the roof area) inside the roof. The results demonstrated that the arrangement

of PV on the roof has impacts on Welsh onion growth (Source: Kadowaki et al. 2012). Moreover, the checkerboard configuration provides a more uniform spatial distribution of solar energy in the greenhouse (Source: Yano et al. 2010).

In a Mediterranean area, Zisis et al. (Source: Zisis et al. 2019) used semitransparent OPV modules based on P3HT:PCBM photoactive layer as the greenhouse roof in Greece, as shown in Fig. 29b. The OPV modules are integrated onto low-density polyethylene by double-sided adhesive tape. The research presented that the plants cultivated under shading of the OPV roof had better performance, due to the absorption of UV radiation by OPV integrated into the devices. Interaction of UV with the epidermis or inner plant tissues leads to temperature increase and thermal stress, causing tissue burns and damage. Additionally, higher efficient water exploitation is also expected because of lower surface temperature and lower transpiration rate. However, the research in Morocco showed different results that the PV panels do not have a significant effect on the overall yield of tomatoes. At the same time, there is also another project integrating OPV onto membrane greenhouse roof in Israel, as shown in Fig. 29a (Source: Magadley et al. 2020).

Considering the mentioned advantages, combining PV electricity production and commercial agriculture on the same area of land will be further developed to increase overall land productivity in the future.



**Fig. 29** a Membrane greenhouse with OPV, Israel *Source* Yano et al. 2010), b Membrane greenhouse with OPV, Greece *Source* Zisis et al. 2019), c Sunshade at the Staten Island Children's Center, America (*Source* Carpenter and Gellin 2013)

### 3.3.4 Sunshade

In America, another installation with silicon PV cells attached to the fabric surface was at the Staten Island Children's Center and finished in 2012, as shown in Fig. 29c. A ridge-and-valley structure was designed by Weidlinger Associates company to meet the requirements of aesthetic and maximize southern exposure for the solar radiance receiving. The PV cells were integrated after erecting and prestressing the PTFE membrane, since PV cells do not have sufficient strain capacity to achieve the pretension length of the membrane. Furthermore, the individual PV cell can be removed without disassembling the roof fabric. However, because of the low PV efficiency performance at that period, the energy generation of the application was limited.

### 3.3.5 Residential Building

The projects containing FPV directly integrated into the fabric membrane have also begun to make inroads into European residential buildings (Mather and Wilson 2006).

Completed in June 2013 in German, the SOFT HOUSE with wooden structure (Fig. 30) possesses an energy harvesting envelope that textile-based FPVs components are integrated onto flexible fiber composite boards on the roof, providing shape self-adaptation for daily sunlight tracking by the first 2-axis solar tracking system (Source: Davis 2012). A series of adaptive shading and sunlight effects are created from the simple textile architectural elevation, allowing generous views. These shields are created to exploit the possibilities offered by OPV nanotechnology film mounted on a row of mobile, flexible and semitransparent tracks, remotely controlled. The power generated by the photovoltaic system is stored in a battery and used to operate the same curtains, which can thus be used both to create light or shadow in the rooms and to have areas at different temperatures. The entire apparatus is controlled by a low voltage wireless direct current system that distributes electricity for domestic use, for the water pumps that supply the radiant floor panels and LED lighting.

Compared with glass PVs, OPVs perform better and decrease carbon emissions in manufacturing by 40% due to the R2R production process. As for the building operation, predicted Energy Use Intensity is 95 kWh/m<sup>2</sup> per year, including on-site solar energy 28 kWh/m<sup>2</sup> per year. Owners have the option to sell stored electricity to the grid at peak hours. Furthermore, the building constructed with a locally made solid wood structure can be completely recycled at the end of its life.

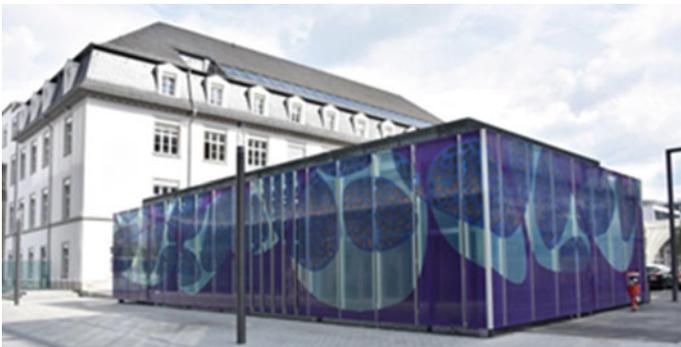
### 3.3.6 Building Retrofit

In 2018, transparent curtain wall façades in modular design method, which constitute the combination of OPV and ETFE film, were built up in the rebuilding project of Merck KGaA company in Darmstadt, German, as shown Fig. 31 (Source: Moritz

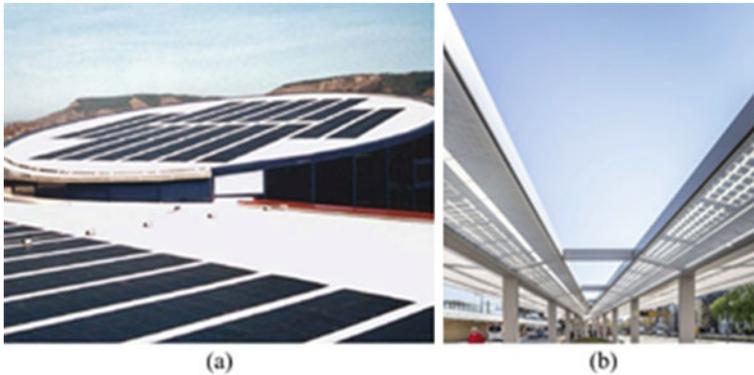


**Fig. 30** SOFT HOUSE, German. *Source* Mather and Wilson (2006)

2019). OPV elements in three different shapes were glued onto the digitally printed backside of the mechanically pre-tensioned ETFE film. Based on a combination of printing, laser and coating technologies, the pattern and color of the façade can meet the requirements of investors in terms of culture, art, and publicity. Due to the small area of OPV integrated into the ETFE foil, the curtain wall can only generate power at a low level. As a result, the façade is only a demonstration project to show the possibilities of the proposed BIPV integrated ETFE foil technology, which is appealing in terms of both architectural aesthetics and multi-functionality (Source: Issa 2018). The façade provides a new concept for the energy efficiency building design, construction, and retrofit.



**Fig. 31** Energy-efficient ETFE façade installed printed OPV. *Source* Moritz (2019)



**Fig. 32** **a** Building-integrated PV installation with waterproofing membrane. *Source* Issa (2018). **b** Bus station with TE-FPV system, Netherland. *Source* Chang (2018)

### 3.3.7 Industry Building

In 1999, a flat roof that consists of the first building-integrated PV installation with waterproofing membrane was built up in the city of Jena by the combination of EVALON® Solar and Alwitra company, as shown in Fig. 32a (Source: Issa 2018). The roof is capable for both electrical energy generation and waterproofing. Furthermore, the technology is also an economical solution for the structure construction due to its lightweight property.

### 3.3.8 Office Building

Pneumatic ETFE roof construction integrated FPV was also applied in the Hightex Office in Rimsting, Germany, in 2007 (Source: Cremers and Felix 2009). The structure is a two-layer ETFE cushion with PV modules integrated on the outer top layer, as shown in Fig. 33. Coverage of PV-area is  $9.3 \text{ m}^2$ , 37.4% of the whole roof area. Installed power is approximately 440 Wp; the integration will be more efficient.

### 3.3.9 Bus Station

In the recent case of the bus station (Fig. 34) in Tilburg, Netherlands, firm Cepezed architects made an integrated design for the ETFE foil awning that is capable of generating sufficient power for functionalities by  $250 \text{ m}^2$  PV panels lying on its top (Source: Chang 2018). The lighting system of the awning, the staff canteen, the digital information signs, and the public transport service point are all included in the energy-supplying list. Furthermore, the panels also cast shadow patterns on the transparent ETFE material to make a comfortable waiting environment for travelers



**Fig. 33** Hightex Office in Rimsting, Germany. *Source* Cremers and Felix (2009)



**Fig. 34** Bus station in Tilburg, The Netherlands. *Source* Chang (2018)

in the daytime. There is also a lighting system fixed on the ETFE foil in order to increase the sense of security for all travelers in the evening.

### 3.3.10 Bridge

In 2016 in Tallahassee, America, the first solar-powered pedestrian bridge provides a passageway for people who commute between the Cascades Park and the Capital



**Fig. 35** First solar-powered pedestrian bridge, America. *Source* Mather and Wilson (2006)

Cascades Trail, as shown in Fig. 35 (Source: Pvilion company 2021). An eco-friendly design has been incorporated into the bridge with organic shape. The PV panels on the fabric capture the solar energy and power the dramatic, color-changing LED lights that will reflect off the canopies at night.

### **3.4 Challenges Facing Flexibles PV**

The expanding future market of architectural membrane products requires more research and design thoughts for flexibles PV, as nowadays far too little flexible PV has seen wide applications. On their way to seize more shares among the PV application market, there are still a great many challenges that need to be overcome.

#### **(a) Puzzle with Conventional PV Application**

Conventional integration of photovoltaic as building components normally fell into a common dilemma in-between the unsatisfactory available PV product and the precious demand of the integration design. The result is either the abandonment of PV application or a curt imposing of immature product. This specific phenomenon exhibits a key barrier in-between the overcapacity of the PV industry and the scarce BIPV application around the world. K. Farkas and M. Horvat have investigated in their IEA SHC report [100] the current situation of solar energy technology and their architectural integration. Design has been regarded as an important parameter that hinders a smooth transfer of PV technology to architectural components. Here more aspects are discussed to facilitate this endeavor. According to the application occasion, the key defects of the flexible PV integration could be specified as follows:

#### **1. For public/private building integration**

Lack of design; architects have not developed a satisfactory language to combine PV and membranes (Fig. 36).

#### **2. For industrial building integration**



**Fig. 36** Typical application of flexibles PV in public/private building (edited by the authors)

Lack of standardization but in the most successful market up to now; the exterior appearance is less important (Fig. 37).

3. For artistic experiments

A very demanding job, as it requires architects to involve in the whole design process or more mature products (Fig. 38).

4. For non-building integration

Inspiring, but the product hosting industry requirements were not fully exerted, the research significance is limited as the market has not yet been mature (Fig. 39).



**Fig. 37** Typical application of flexibles PV in Industrial integration (edited by the authors)



**Fig. 38** Typical application of flexibles PV in artistic experiments (edited by the authors)



**Fig. 39** Typical application of flexible PV in non-building integration (edited by the authors)

### (b) *Requirements of Market Segmentation*

Corresponding to four main applications scenarios of various building types, it should be noticed that, for both important historic buildings, ordinary existing buildings and new buildings, requirements of product with higher standard could be implied due to follows:

For existing buildings:

1. Important existing buildings (listed buildings) to apply membrane would not adapt unsatisfactory flexible PV during conservation and upgrading process; otherwise, their historical value will lose;
2. Ordinary existing buildings to apply membranes also prefer visually pleasing pv products during refurbishment for aesthetic reasons;

For new buildings:

1. For new projects, the purity of architecture usually favors membrane “as it was” (maintain its original form rather than imposed with strong PV sign) during flexible PV integration;
2. In the process of architectural design, a satisfactory (integration) language has not been well-developed for flexible PV; (pattern, color, light control, etc.)

## 4 Conclusions

Considering the increasing popularity of the flexible PVs, this chapter systematically studied the technological and manufacturing pathways, key typology pros and cons, life cycle impacts as well as market entry essentials of this novel product form.

Firstly, all current available PV technologies especially the flexible ones have been comparatively introduced and described, while the significant advantages and corresponding key roles of both OPV and perovskites have been statistically validated.

In addition, the manufacturing processes of three PV generations have been thoroughly reviewed, among which all direct printing fabrication means for key representatives of the third PV generation, the OPV and Perovskite, have been carefully surveyed and summarized regarding their performance features. Both R2R printing methods have been esteemed as the most promising solution for future flexibles PV.

Moreover, the life cycle impacts, in particular the environmental profiles of mainstream architectural integration substrates, as well as the subsequent finishing modules, have been examined in detail with a newly proposed framework. ETFE, with its encapsulated OPV modules, both have their final embodied energy found to be more eco-efficient than most other confrontations.

Finally, the market segments and developing status, with the architectural application as the focus, have been summarized for flexible PVs. Various key obstacles including the lack of design and industrial standardization have been concluded, while the conservation of historical, aesthetic value, and the proposal of satisfactory architectural language of this novel BIPV product exhibit as the sure challenges and requirements of its future market success.

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# Case Study: The SOFT-PV Skin



Alessandra Zanelli, Carol Monticelli, and Zhengyu Fan

**Abstract** This chapter is focused on the fabrication of a new kind of fluoropolymeric foil (ETFE, THV, EFEP) fully integrated with a smart, organic, flexible, and translucent photovoltaic cell (named SOFT-PV). Several investigations have been developed concerning flexibility and translucency of both the PV polymeric cells and ETFE cushions. Furthermore, the application of organic photovoltaic cells as a printable texture onto one of various ETFE transparent layers of an air-supported building component was achieved; however, this technology has not been integrated yet at a fully building scale. Therefore, the goals of this research are the creation of a demonstrator prototype of a SOFT-photovoltaic cell; and, its integration in a building component prototype, to predict its optical, thermal, and structural performance and to assess its environmental profile. Several tests have been conducted through a coupled mechanical and electrical characterization method to monitor the correlation of OPV electrode resistance and cell performance upon tensile strain and to verify the deterioration effect and reason for the tension strain on the OPV performance response. This methodology resulted optimal, and it can contribute to subsequent building of product development toward OPV integration onto ETFE membrane.

**Keywords** Fabrication · ETFE cushions · Organic PV · Mechanical and electrical characterization

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## 1 The First Prototype of SOFT-PV

This research deals with a flexible *building integrated photovoltaic* (BIPV) technology. The scientific and industrial communities are working on the theme PV but the promise of low-cost photovoltaic power has not yet been realized. The integration of photovoltaic (PV) systems into building envelopes to replace conventional building materials must also be greatly improved.

The ultimate goal of the research program was the fabrication of a new kind of fluoropolymeric foil (ETFE, THV, EFEP foil) fully integrated with a smart, organic, flexible, and translucent photovoltaic cell (named SOFT-PV).

The flexibility and translucency both of the PV polymeric cells and ETFE cushions represented the pivotal evaluation aspect from which the research hypothesis began. The application of organic photovoltaic cells as a printable texture onto one of various ETFE transparent layers of an air-supported building component was achieved, but not at a fully building scale. Two relevant results of the research project were:

- (1) the creation of a new OPV cell integrated on ETFE substrate;
- (2) the creation of a prototype of a sun-shading, insulated ETFE cushion.

### 1.1 The Plan and the Objectives

The biennial research program—based on the cross-disciplinary collaboration between architecture and building technology, material chemistry, and physics—proposes the following feasible objectives:

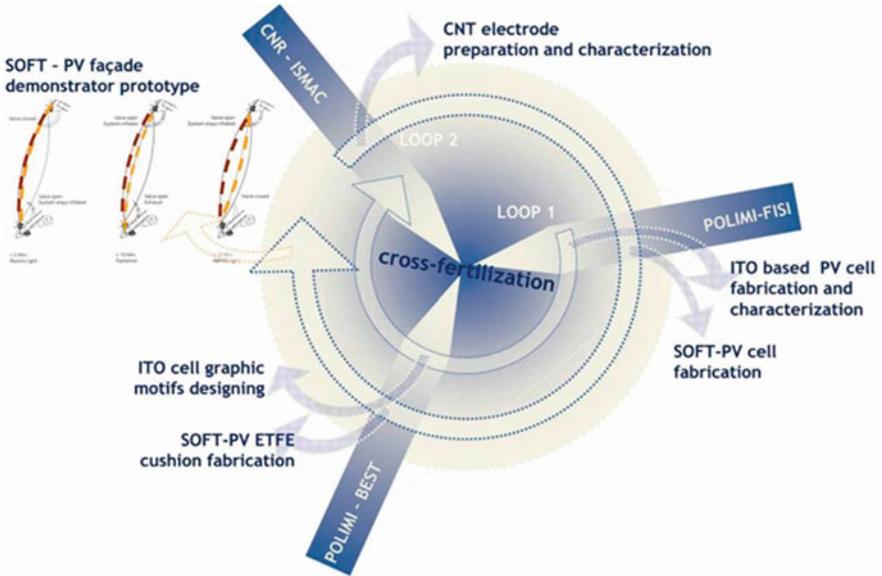
1. the modification of a translucent fluoropolymeric substrate by embedding or depositing carbon tubes;
2. the creation of a demonstrator prototype of a SOFT-photovoltaic cell;
3. the creation of a SOFT-PV cell integrated building component prototype, to predict its optical, thermal, and structural performance and to assess its environmental profile.

The experimental plan foresees two main “cross-fertilization” loops between the different fields of knowledge involved, with the aim of achieving a working prototype of the SOFT cell. The loops are shown in the following scheme (Fig. 1).

### 1.2 Bottleneck and Solutions

During the research, the following problems were faced by SOFT-PV project and some overcoming solutions were deepened:

1. Being a fluorinated material, ETFE is an outstanding barrier for water. Unfortunately, this useful property presents drawbacks, which are difficult to overcome.



**Fig. 1** Experimental plan of SOF-PV research. Elaborated by authors

The hydrophobicity of ETFE does not allow metals and organic layers to properly adhere to the substrate. As a consequence photovoltaic devices on flexible ETFE substrate (named SOFT cell) didn't show reasonable performances, even if different methodologies of preparation have been exploited. Different anodes (a layer of SWCNT and thin layer of Ag) have been used; different cell architectures conventional or inverted (using AZO as a cathode in an inverse cell top or down illuminated) have been tested. The poor results in the fabrication of new SOFT cells can be due to the hydrophobic character of ETFE substrate, which could not be modified by using simple plasma etching apparatus available in ISMAC-Mi and Politecnico Laboratories. Pre-treatment of the substrate through plasma treatment improved the adhesion of metal layers, but not enough to preserve the mechanical integrity of the layer to the bending of the ETFE substrate.

2. To overcome the problems of point 1, different plasma treatments with air or O<sub>2</sub> gas at atmospheric pressure or in vacuum should be applied. As shown in Chap. 4, both corona treatment and plasma brush treatment with air at Fraunhofer Institute showed a modification of the contact angle value and experiments carried out at ISMAC-Bi, in Biella, [20 SCCM (standard cubic centimeter per minute) of O<sub>2</sub>, P = 2 × 10<sup>-1</sup> mbar, discharge power 50 W using 1 min of exposure] allowed a complete adhesion of polar PET to ETFE foils by lamination carried out at Enecom Company in Turin.
3. The surface-bound peroxides formed are not stable enough to allow for a homogeneous and smooth deposition of SWCNT which has polar groups on their surface despite the purification procedures performed. Hence, a subsequent grafting of

polar polymer able to preserve the hydrophilic surface and interact with the carboxyl functionalities still present on SWCNT could be a strategy to solve the morphological problem at ETFE substrate/SWCNT interface which originates the poor coverage of the fluorinated substrate.

4. Anywhere, the poor adhesion of the SWCNT to ETFE substrate, allowed for the fabrication of an OLED having the architecture: ETFE/SWCNT/PEDOT:PSS/F8BT/Al-Ba and showing very low efficiency (low EQE = external quantum efficiency) and light only at very high voltage. Also in this case, the data is important because, once overcome the morphological problems, ETFE substrate with SWCNT could constitute an electrode for electroluminescent devices allowing a further application of fluorinated polymer for architectural purposes. Though this result is reasonable because of the intrinsic ease of fabrication of OLED compared to photovoltaic devices, we note that this result was not expected from the project, and it might be of interest in the context of architecture employing ETFE.
5. Direct printing of photovoltaic cells on ETFE through inkjet printing allows efficient texturing of ETFE cushions, together with current generation; however, lab-scale inkjet printing only allows small prototypes (10 cm × 10cm) which are not suitable for large area application (at least 1 m × 1 m). The problem of upscaling also concerns the deposition of CNT over large areas. This solution is way too expensive for the moment. ETFE cushions have their major strength in ease of use and low cost; hence, it needs to employ cheap technologies. CNT complies with this requirement for the moment. Moreover, while printing techniques of organic solar cells are rapidly evolving toward large-scale application and cheap fabrication, the deposition technique for semi-transparent conductive CNT layers is currently too expensive.
6. Any study of the problems related to the integration of electronic devices in the ETFE substrate and their impact on device lifetime was deepened in the project. We believe this feature is of major importance, and it would require further appropriate investigation time and resources.

### ***1.3 Conclusion and Future Work***

Going through the different phases of the SOFT-PV activity, some problems and constraints were investigated by the researchers. Parts of them are related to the technical properties of used laboratories' technologies. First of all, the spin-coating device: Since the device technique is based on spinning the substrate while pouring the active layer, there are some restrictions regarding the maximum area to be covered as the more the substrate area the less homogeneous the deposited layer is. On the other hand, the poor results in the fabrication of new SOFT cells can be due to the hydrophobic character of ETFE substrate, which could not be modified by using a simplified plasma etching apparatus available in ISMAC-Milan and Polytechnic of Milan Laboratories.

Even if the researchers overcome these difficulties, to get the foreseen goals, the research in this field still needs more studies.

At the scale of OPV/ETFE substrate integration:

- Future steps in identifying the reason for failure of ETFE-based devices should include the study of surface energy of ETFE substrate and its surface topography for the identification of rough spikes that impede a homogenous deposition of the electrode layer.
- It is very likely that the passivation of the ETFE layers with the use of self-assembly monolayers (SAMs) would be an interesting route for achieving a successful deposition of electrodes on the ETFE substrate.

At the scale of OPV/ETFE building component integration:

- looking for other architectural solutions to use the organic solar modules as separate façade components using a light tensile cable net;
- studying the possibilities to realize the solar modules in facades in repetitive grid trying to explore the power connections and wiring problems;
- testing other innovative technical solutions besides lamination to integrate the solar modules in ETFE foils and test manufacturing feasibility.

Also, more environmental and optical research should be directed to study the two integrated elements (ETFE + OPV) on a building scale.

## 2 Environmental Impact Assessment of a Novel Concept of SOFT-PV Skin

During the SOFT research project, the environmental impacts assessment of the new OPV cell was investigated: This activity started in parallel with the first phases of the research, and followed all the other phases, in order to comprehend and deepen the entire SOFT cell fabrication process, step by step, understanding the production processes, the involved materials, their quantities, and the energy consumption during the production.

Why the environmental impact assessment within the SOFT research? The high cost of photovoltaic compared to other energy sources limited their use. However, emerging technologies, such as organic photovoltaic (OPV), which takes advantage of man-made materials and solution processing, hold the promise for inexpensive devices. Although solar cells could be an alternative to energy produced from fossil fuels, it is necessary to ensure avoiding the problem shifts, and specifically not generating different environmental impacts. For this reason, life cycle assessments (LCAs) can be undertaken on emerging organic technologies to evaluate *a priori* the environmental impact of large-scale production and identify pathways toward sustainable energy production (Garcia-Valverde et al. 2010).

The definition of the Life Cycle Inventory (LCI) of SOFT cell materials had complexities, considering that the research aim was the creation of a new technology of PV cells, and it has been difficult to know and quantify the involved materials, because the technologies and the approaches changed more times during the research development.

Referring to the investigation of the literature references of the last years focused on the LCA approach related to the ETFE technology and to the PV/OPV technology, and to the definition of the LCA method to be applied to OPV the approach of the research has been as follows:

- a. the application of the LCA methodology to a smart inflated ETFE cushion with integrated OPV module, built in the Textiles Hub laboratory at Polytechnic of Milan;
- b. the description of the flow chart of materials involved in the production of the new fully integrated OPV module on ETFE.

Actually, the energy payback time for the new module was not deepened.

The LCA was applied at two different levels: a. firstly focusing on the building component—a façade panel—as system boundary, because of the architectural application of the ETFE technology; b. later on exploiting the interest on the environmental impact assessment of the materials involved at the scale of the innovative SOFT-PV cell. As in this case, the shift of the LCA objective means changing the functional unit, the system analysis boundaries, and also the approach.

## ***2.1 Life Cycle Assessment of a Smart Inflated ETFE Cushion with Integrated OPV Module***

One output of the research has been the prototype cushion with an integrated flexible OPV cell, a relatively new approach of the building photovoltaic integration at the scale of the component and of the PV module. A detailed environmental impact analysis of the prototype was part of the research and is here presented.

Considering the focus of the SOFT research on the ETFE technology, it has to be anyway pointed out that the actual ETFE technology development allows the incorporation of “accessories,” such as servicing technologies, to improve the self-sufficient performances. The research proceeds with the evaluation of new solutions for ETFE building application to increase the energy efficiency of this material during its use, as a component of facades and roofs, balancing the huge energy requirement for its manufacturing.

In the SOFT prototype, the lamination of a new generation OPV flexible module power plastic, patented by Konarka, on the ETFE foil was tested, reaching an higher level of integration OPV-ETFE than other previous experimentations, such as a. the integration of second-generation PV cells into a pocket of transparent ETFE foil (as an existing thin-film technology in Amorphous-Si into ETFE PV product, experimented by the Vector Foiltec Texlon PV) and b. the integration of third-generation PV cells

**Table 1** Embodied energy values of the SOFT prototype components

Materials	EE (MJe <sub>q.</sub> )	GWP (kgCO <sub>2</sub> eq.)	References
ETFE (unit/kg)	210	89	Monticelli et al. (2009)
OPV module (unit/m <sup>2</sup> )	300–500	14–23	Lenzmann et al (2011)

The EE and GWP values for the other involved materials are extracted from database Ecoinvent

Elaborated by the author

(Konarka flex OPV panels) lying down on the lower film of the ETFE pneumatic cushion-like in the “Parking module” patented by Canobbio Engineering in 2010.

The LCA framework was selected to analyze the environmental aspects of the SOFT cushion prototype. Typically, the LCA structure consists of three stages after the scope determination: the inventory, the impact, and the improvement analysis.

The inventory analysis identifies and quantifies resource and energy inputs as well as the product, waste, and emission outputs of the system with regard to the unit of the components or process.

*Data sources:* Regarding the environmental impact profile of the production of 1 kg of ETFE, we systematized information by the LCA tool SimaPro and we used the values that came out in the study conducted by Monticelli et al. (2009).

Regarding the environmental profile of the OPV flexible module, with a 4% module efficiency, we considered the embodied energy value reported in Lenzmann et al. (2011). All the other process voices related with the building materials involved in the SOFT prototype (aluminum profiles, screws) were extracted from the Swiss database EcoInvent and processed with the SimaPro software (Table 1).

*Method:* in general in the LCA framework the impact analysis, thanks to assessment methods, characterizes the data from the inventory to define the environmental effects associated with a product’s life cycle. The following LCA (corresponding with the impact analysis in the LCA process) was assessed by the method EPD 2007, in accordance with the environmental indicators provided for in the ISO 21930:2017.

*Indicators:* The two computed environmental indicators are the embodied energy EE (MJ) and the global warming potential GWP (kgCO<sub>2</sub> eq.).

*System limits:* The limits of the analysis are from the raw material extraction to the production of the component and the assembly of the prototype (Tables 2 and 3).

The results of EE and GWP are a range of values, because of the original range of values referred to the solar module.

The results are a rough estimation of the environmental impacts, considering that the presented SOFT technology is under development and is a laboratory result. Further works should consider the comparison with the actual integration ETFE-OPV systems, in order to understand the real ranking of this product hypothesis.

**Table 2** Computation of the materials' quantities for the fabrication of the SOFT BIPV cushion

Elements	Material	Dimensions (mm)	Section surface (mm <sup>2</sup> )	Length (mm)	Volume (m <sup>3</sup> )	Density (kg/m <sup>3</sup> )	Weight (kg)	n	Total Weight (kg)
1. External film	ETFE	(0.2 * 1800 * 1200)			0.000432	1750	0.76	1	0.76
2. Internal Film	ETFE	(0.2 * 1800 * 1200)			0.000432	1750	0.76	1	0.76
3. Intermediate film	ETFE	(0.2 * 2066500)			0.000432	1750	0.76	1	0.72
4. OPV module	Device with highly conductive PEDOT:PSS in combination with current collecting grids	(346 * 254)	93,500					1	
5. Profile 120 cm	Aluminum (EN AW-7022)		541	1200	0.000649	2780	1.80	4	7.22
6. Profile 180 cm	Aluminum (EN AW-7022)		541	1800	0.000974	2780	2.71	2	5.41
7. PE tube	Polyethylene PE-Ld	2	6	200	0.000001	920	0.0012	1	0.0012
8. Keder	Polyethylene HDPUA	10	31	6000	0.000188	1230	0.2317	1	0.23
							6.98		15.10

Elaborated by the author

**Table 3** Results of the environmental impact assessment of the production of the SOFT BIPV cushion

Elements	Material	Data source	Quantity	EE (MJe <sub>q</sub> )	GWP (kgCo <sub>2</sub> e <sub>q</sub> )
1. External film	ETFE foil	Monticelli et al. (2009)	0.76	174.96	201.33
2. Internal film	ETFE foil	Monticelli et al. (2009)	0.76	174.96	190.73
3. Intermediate film	ETFE foil	Monticelli et al. (2009)	0.72	165.75	201.33
4. Opv module	Device with highly conductive PEDOT:PSS in combination with current collecting grids	Lenzmann et al. (2011)		27.9–46.5	1.3–2.14
5. Profile 120 cm	Aluminum (EN AW-7022)	ELCD (2010)	7.22	267.14	17.47
6. Profile 180 cm	Aluminum (EN AW-7022)	ELCO (2010)	5.41	200.17	13.09
7. PE tube	Polyethylene PE-LD	Eco invent	0.0012	0.12	0.00
8. KEDER in PU	Polyurethane HDPUA	Eco invent	0.2317	51.29	3.48
Total				1062.31–1080.91	628.74–629.58

Elaborated by the author

## 2.2 Description of the Materials' Flowchart for the SOFT Cell Production

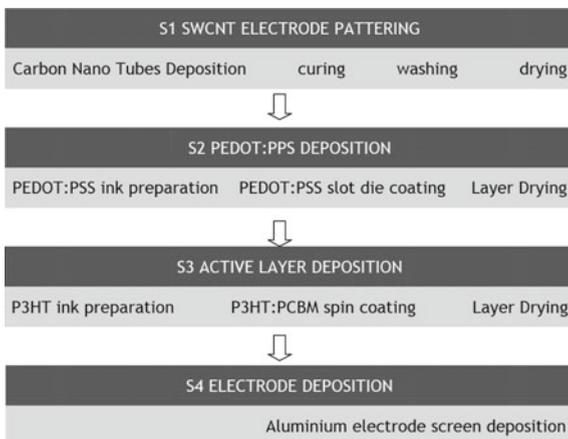
The second level of the LCA application focused at the scale of the innovative SOFT-PV cell. The Life Cycle Inventory of the involved substances was computed, following the steps of the OPV cell fabrication process, featured by three different phases:

- *phase 1*: the deposition of the carbon nanotubes and the PEDOT:PSS;
- *phase 2*: the deposition of the organic active layer PCBm/P3HT;
- *phase 3*: the deposition of the aluminum electrode.

The assumed device architecture was like the type glass/ITO/(PEDOT:PSS)/P3HT + PCBm/Al, but with the aim to produce the Etf/SWCNT/(PEDOT:PSS)/P3HT + PCBm/Al (Fig. 2).

*Phase 1*—The deposition of the CNT & PEDOT:PSS

**Fig. 2** Scheme for laboratory processing of SOFT organic solar cell. Elaborated by the author



Continuous single wall nanotubes SWCNT network was deposited on a film of ETFE, in order to create a new class of transparent conducting materials, in particular the deposition by electrospinning of a 2D network of fibers onto fluoropolymeric substrates; CNT resulted to be embedded into the electrons pinned polymer.

- After this layer, a coating with Poly(3,4 ethylenedioxythiophene- poly (stryrenesulfonate) (PEDOT:PSS) was applied for covering the substrate, using spin coating as the deposition technique. The formed layer was annealed for 30 min at 140 °C to remove H<sub>2</sub>O.

Involved quantities:

- on the ETFE foil after the deposition SWCNT: 44 microgr. /cm<sup>2</sup>
- PEDOT:PSS:  $\leq 1$  ml/cm<sup>2</sup>

#### *Phase 2*—Deposition of the active layer (PCBM/P3HT)

The realization of the flexible PV cell using P3HT and PCBM, respectively, as donor and acceptor materials, followed standard procedures: deposition of the active layer was based on the bulk heterojunction concept where the donor material (typically a polymer) is mixed with an acceptor (a soluble fullerene) in an organic solvent and then deposited in a spin coating device. The solution of (P3HT + PCBM) was in chlorobenzene.

*Quantities:*

P3HT+PCBM: 50 microliters ml/cm<sup>2</sup> of the (P3HT+PCBM) solution for depositing the photoactive layer.

The mixing ratio of P3HT:PCBM was kept fixed at 1:0.8 analogy and the polymer concentration of P3HT was 13 mg/ml of solvent.

*Phase 3—Deposition of the Aluminum Electrode*

As the last step, the aluminum electrode was deposited by a metal perforated template, thermally evaporating it on the (P3HT + PCBM) layer, by using ~10 cm long Al wire of 0.5 mm diameter with the purity of 99.999%.

*Quantities:*

Al: ~10 cm long Al wire of 0.5 mm diameter.

At least, the fabricated device was thermally annealed by leaving it for 15 min on a hotplate at a temperature of 140 °C.

The collection of substances and quantities is the basis for the LCI in the methodology of the environmental impact assessment. Therefore, the research focuses more on the limits and potentials of the technology than the LCA of the cell itself.

### ***2.3 Limits and Potentials of the SOFT Cell and Its Environmental Performance: New Electrode Material Versus Nanotechnology Versus LCA?***

The innovation of the SOFT cell in the field of the organic photovoltaic was based on the hypothesis of a new substrate or encapsulation material and a new electrode:

- a. the fluoropolymeric film instead of PET can ensure a lower permeability to humidity and environmental agents, in fact in Aernouts (2006); it is stated that the conductivity of the ITO layer decreases on plastic substrates, and it has been shown that bending the device processed on a plastic substrate could damage the brittle inorganic oxide layers, thereby reducing their electrical properties;
- b. the SWCNT as electrode substituting the ITO: the high energy content for the production, the price of ITO, and the requirement of expensive post-patterning demonstrated the necessity to look for alternatives as an electrode; different types of transparent electrodes, which are mainly based on carbon nanotubes (CNT) or different types of high conductive PEDOT:PSS, were deepened, although

they do not provide high efficiency with large-scale devices due to the limited conductivity (Galagan et al. 2012). The other side of the medal was the environmental profile and the health and environment risks of the SWCNT, that constituted a relevant aspect to be investigated: the health risks associated with carbon nanotubes, in particular their potential to cause mesothelioma and disease similar to that caused by asbestos, are likely to be most acute for workers exposed during manufacturing; Titanium dioxide nanotubes have a similar shape to carbon nanotubes. The test tube study of Illuminato and Matthes (2010) on lung epithelial cells found that they had a strong dose-dependent effect on cell proliferation and cell death. Carbon nanotube-reinforced polymer composites are also more energy-intensive than conventional materials such as aluminum or steel that they may be designed to replace. A cradle-to-gate analysis found that for equal stiffness design, carbon nanofiber-reinforced polymer composites were 1.6 to twelve times more energy-intensive than steel.

Although the high impacts in the pre-use phase, the product-use phase therefore governs whether or not any net energy savings can be realized for a given nanoproduct; the use-phase must be extremely efficient to justify the disproportionately large energy investment of manufacturing nanomaterials. Carbon nanocomposites may be extremely strong and light, but in applications such as civil infrastructure this advantage is not so strongly evident in use-phase energy savings (Illuminato and Matthes L 2010). Where no energy savings can be anticipated via the use-phase of a nanoproduct, it is highly likely that the nanoproduct's life cycle energy demands will be more intensive compared to its conventional counterpart.

Not all nanoproducts that are specifically designed to save energy may offer net energy savings over their life cycle compared to conventional materials. Healy et al. (2008) observe that there are examples of energy savings nanoproducts associated with the use of single-walled carbon nanotubes (SWCNT) in microelectronics: a single SWCNT can form a switch that would require no power to maintain in the on or off position, yet would deliver significant energy savings through the use-phase of electronic devices.

Surely the OPV and nanosector were plagued with problems scaling up laboratory achievements to commercial products. This aspect involves specifically the durability of the solar panels: that one of dye-sensitized Nanosolar panels and of fullerene-based organic panels is less than ten years: It means fifteen to twenty years less than the durability of conventional silicon panels, reducing the life cycle energy efficiency of these nanopanels.

Focusing on the post-use phase, end-of-life recovery of nanomaterials and recycling is considered uneconomic, requiring government intervention to prevent irresponsible disposal of panels and to recover rare metals and rare earths. The scarcity of metals such as indium and gallium may be a near-term constraint to the widespread development of some thin nanosolar.

Another aspect we underline to be highly considered in the further works toward the hypothesis of flexible SOFT cells is the evaluation of the high mechanical flexibility, an important requirement for all the layers in flexible photovoltaic devices;

i.e., it was demonstrated that, under numerous bending cycles, the brittle ITO layer can be easily cracked, leading to a decrease in conductivity and, as a result, in the degradation of the device performance (Galagan et al. 2012).

Finally, it has to be stated that a step forward would be the use of “roll-to-roll” printing of nano-PV components onto foil or plastic substrates: It offers greater flexibility than the manufacture of silicon solar cells. It is also believed that thin film is cheaper to produce, although many companies do not disclose the cost per watt, and recent price reductions have been achieved with silicon panels. The disadvantage is that roll-to-roll printing introduces a greater level of defects into panels (Illuminato and Matthes 2010).

### 3 SOFT-PV Behavioral Test

As the architectural integrated PV products, the flexible substrate-based OPV needs to ensure its electrical behavior under the action of common stress and strain in buildings. Preliminary behavioral tests have been therefore undertaken to obtain necessary insights over this.

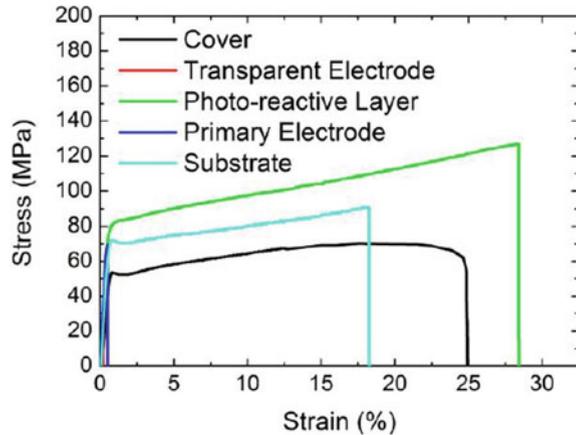
#### 3.1 *Existing Knowledge of PV Flexible Performance Under Loading (1-2p)*

Currently, there are limited researches investigating the performance of OPV directly printed on architectural membranes. Existing OPV products or prototypes are normally fabricated employing commercial polymer substrates like PET and PEN. Most researches regarding OPV are still mainly focusing on device architectures, cell performances, and fabrication technologies, rather than their mechanical responses.

However, quite a number of studies have been carried out with amorphous silicon (a-Si)-based transistors and solar cells fabricated on flexible substrates, most of which are common polymers. Gleskova et al. (2000, 2002, 2006) have reported different performances of amorphous silicon thin-film transistors (TFTs) on Kapton and polyamide foils. Antartis and Chasiotis (2014) have determined the residual stresses among different layers of a-Si photovoltaic thin films based on Kapton layer and aluminum substrate. Meanwhile, relevant research has also been conducted with organic TFTs and organic light-emitting devices (OLED). Sekine et al. (2014) have validated the adhesiveness importance of printed Ag electrodes on flexible plastic substrates for the mechanical durability and real performance of organic TFT. Yu et al. (2011) have developed and examined a highly stretchable electrode based on carbon nanotube-polymer composite for their polymer light-emitting devices.

Relevant research on OPV that can withstand reasonable tensile strains, the so-called stretchable OPV, is rarely seen in academia.

**Fig. 3** Engineering stress–strain curves of each layer of Konarka OPV (curves of electrode layers can hardly be identified in this figure) (Brand et al. 2012)



Lipomi et al. (2011a, b, 2012a, b) evaluated several different conjugated polymers with an effort to achieve a mechanically robust and intrinsically stretchable OPV. Leppanen et al. (2013) have studied the flexibility limit of ITO through bending tests to examine the critical bending curvature and the correlation between the material conductivity and cracks. Similar work has also been done by Cairns et al. (2000) to point out the trade-off between using thick layers of ITO to reduce resistivity and using thin layers of ITO to withstand greater strain.

Brand et al. (2012) have quantified the film stresses developed in polymer films and metal electrodes of P3HT and PCBM-based bulk heterojunction organic solar cells. Chen et al. (2012) have investigated the mechanical behavior of a commercially available OPV product from Konarka Technologies, Inc. through tensile test. They obtained the fracture sequence of each layer through the test and showed that the two electrodes present in the stack are the short slab of the cell performance (Fig. 3).

### 3.2 OPV Performance Under Tensile Loading (0.5p)

Here, we report the research outcome through a coupled electrical–mechanical test methodology to verify the effect of tension strain on the performance response of OPV. The test method enables real time and simultaneous characterization of both mechanical and electrical properties of a tested flexible electronic composite. The experimental method can also monitor the correlation of OPV electrode resistance and cell performance upon tensile strain. An uniaxial tensile test has been utilized rather than a bending test because it is closer to the operational state of membrane-integrated OPV products.

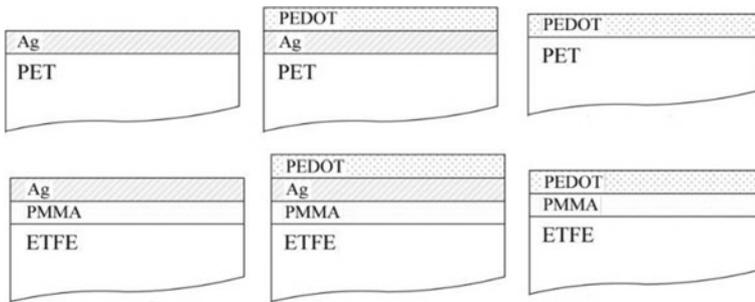
We employed this test methodology on both a commercial OPV module and its conductive layers printed on an architectural membrane. The test on the commercial OPV module can help elucidate the effectiveness of the first two integration strategies.

The test on printed OPV layers on ETFE is even more appealing because the direct printing strategy is found to be the most promising production method of OPV. In the absence of knowledge on membrane printed full OPV devices, preliminary research on the performance of printed OPV layers can already provide useful insights.

### 3.2.1 Experimental

The tested specimens were cut into dumbbell-shaped specimens. Detailed specimen dimensions can be checked in the section of supporting information. For the characterization of commercial OPV modules, the specimens were fabricated from a commercial OPV product. For the characterization of membrane printed OPV, the experiments have been performed on two types of electrode layers normally employed in OPV structure: Ag and Ag/PEDOT, printed on both PET and ETFE. The layering structures of different specimens are shown in Fig. 4. The thicknesses of different specimen layers and substrates are listed in Table 4.

The details of the coupled mechanical and electrical characterization, including the mechanical tensile test setup as well as the electrical characterization experimental configuration, will be further explained in the supporting information section.



**Fig. 4** Specimen layering structure. Elaborated by the author

**Table 4** Thicknesses of tested specimens

Specimen layers/substrates	Thickness
PEDOT	~100 nm
Ag	~200 nm
PMMA	~500 nm
PET	~75 μm
ETFE	~100 μm

Elaborated by the author

### 3.2.2 Characterization of Commercial OPV Modules

#### (a) Stability Test Results

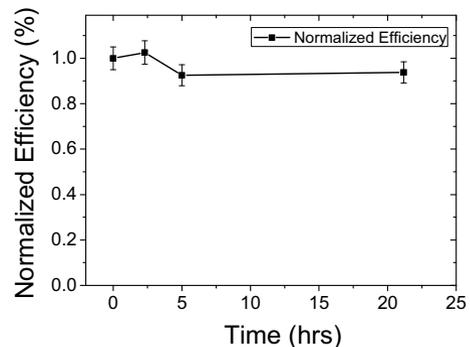
The stability test results for an individual cell cut from the whole module are reported in Fig. 5. It can clearly be seen that after the cells are stored for 22 h in the ambient environment, the efficiency does not show a significant decrease. The cell maintained more than 90% of its initial efficiency after being stored for 22 h in an ambient environment. This fact proves that it is safe and reliable to perform the tensile test with electrical characterization for several hours in an ambient environment.

#### (b) Mechanical Test Results

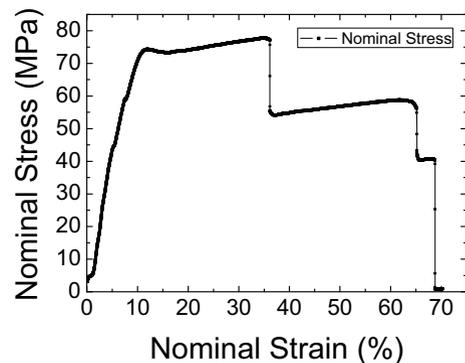
Figure 6 shows the nominal stress–strain curve of the tested OPV cell sample. Compared with the result reported by X. Chen, this curve shows a similar shape but not the identical damage sequence.

The cell structure tested can be described in Fig. 7. Through the rupture process of the cell package, it is clearly visible that at least four polymer-based encapsulation layers have been adopted for fabricating this Konarka OPV module. According to the stress–strain curve, we obtained (Fig. 6), the first fall with approximately 35% strain

**Fig. 5** Single-cell efficiency through stability test. Elaborated by the author



**Fig. 6** Nominal stress–strain curve of full cell packaging. Elaborated by the author



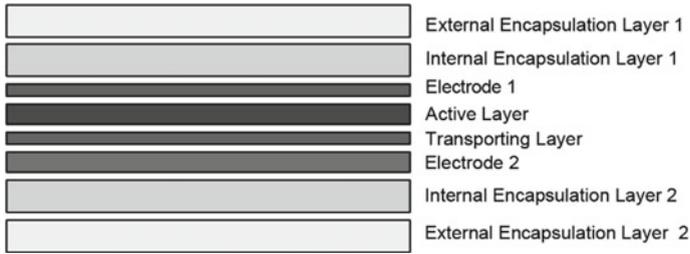


Fig. 7 Solar cell sample’s layering structure. Elaborated by the author

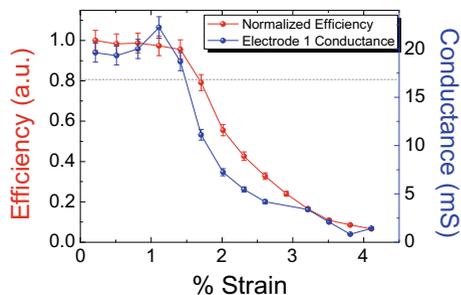
is due to the rupture of internal encapsulation layer 2 (the layer in direct contact with electrode 2), together with the bottom encapsulation layer (external encapsulation layer 2 in Fig. 7). In most of the samples we tested, these two layers burst at the same time, which is likely due to the strong adhesion between them. We also once observed a separate rupture of the two layers, which proves that the cell adopts two different layers. Afterward, near the strain of 65%, the cell shows the rupture of the top encapsulation layer (external encapsulation layer 1 in Fig. 7). At the very end of the curve, near the strain of 68%, the cell shows the largest fall, corresponding to the rupture of internal encapsulation layer 1. The close distance of these two falls may imply that these two layers adopt very similar materials. Later in this work, the electrical data prove that the two electrodes are damaged much earlier than the encapsulation layers’ failure.

(c) Electrical Characterization

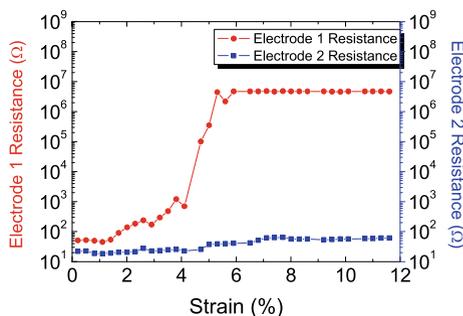
Figure 8 illustrates how the cell efficiency and the conductance of electrode 1 (the transparent electrode) deteriorate with the increasing strain of the whole cell package. It can be seen that after the cell reaches approximately 2% strain, it loses 50% of its initial efficiency. At strain of 3%, the cell has only 20% of its initial efficiency. The cell generates almost no power after the strain reaches 4% strain. From the figure, we can also see that the conductance of electrode 1 follows almost the same decreasing trend through the test. This implies that a highly likely reason for the cell efficiency degradation is the loss of electrode 1 conductance, which is later verified with the I–V curve. Considering the above two facts, if we assume that the critical point of the OPV stack refers to the moment when it loses 20% of its initial efficiency (Krebs 2012, Grossiord et al. 2012), which has been commonly used for defining the lifetime of photovoltaic devices, we can place the critical strain level of the cell at 1.8% and the corresponding critical stress at approximately 20 MPa. The fast degradation of the organic solar cells with strain critically underlines the importance of their mechanical properties for practical application as flexible PVs.

To investigate in detail which electrode is the main reason for the cell deterioration, we monitored the conductance of both electrodes through the tensile test. In Fig. 9, we can see that electrode 1 is much more sensitive to strain than electrode 2. With the strain at approximately 4 ~ 5%, where electrode 1 experiences a significant increase

**Fig. 8** Sample cell normalized efficiency and electrode 1 conductance through tensile test. Elaborated by the author



**Fig. 9** Sample cell electrode's conductance through tensile test. Elaborated by the author



in resistance, the conductance of electrode 2 maintains its starting level. Actually, the resistance of electrode 2 starts to increase rapidly after the strain reaches 20%. With these results, we can conclude that the transparent electrode (electrode 1) used here is not mechanically robust upon large strain, whereas the metal electrode (electrode 2) is less sensitive to strain and could be a good choice with high stability for application in flexible BIPVs.

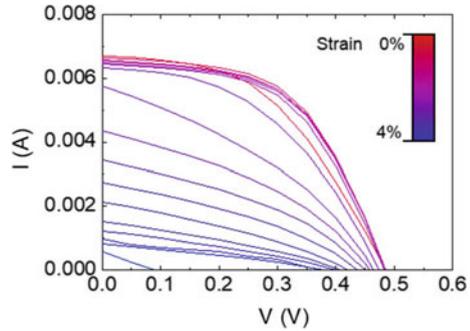
The influence of the increase in electrode resistance with increasing strain on the cell power conversion efficiency was also verified by the I–V curves as illustrated in Fig. 10. We can see that through the degradation of the cell, the decrease in ISC (short-circuit current) plays a more important role than the decrease in VOC (open-circuit voltage). Because the decrease in the short-circuit current is closely related to the increase in series resistance, we have a further confirmation of the main role played by electrode 1 in the degradation of the solar cell efficiency (Krebs 2012).

### 3.2.3 Characterization of Architectural Membrane-Printed OPV

#### (a) Electrical Characterization

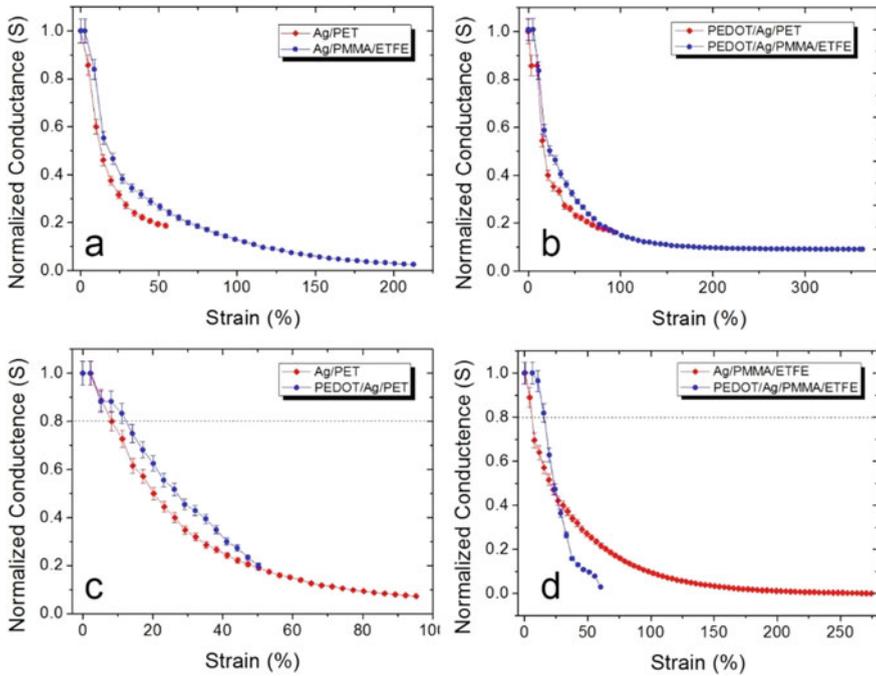
Figure 11a shows the recorded normalized conductance of Ag layers coated on PET and ETFE substrates through the uniaxial tensile tests. Both PET- and ETFE-printed specimens saw a rapid decrease in conductance during the initial phase, which implies

**Fig. 10** I–V curve of tested cell sample from the strain of 0% to 4%. Elaborated by the author



that both of them are highly sensitive to tensile strains. However, the ETFE-based Ag layer experiences a slightly slower decrease in layer conductance at the same strain level compared with the PET-based one, especially within the 20 ~ 50% strain region, where the conductance–strain curve of ETFE-printed specimen exhibits a lower line slope than PET-printed one. This phenomenon reveals that the ETFE-printed Ag layer conductance is still slightly less sensitive than the PET-printed one with large strains, which is highly favored for the utilization of ETFE as an OPV substrate. Meanwhile, it can also be found that the ETFE-printed specimen saw a much higher strain at the rupture point, whereas the PET-based sample commonly met a brittle-like failure at a relatively smaller strain level. Moreover, at a higher strain level where the PET-printed specimen cannot reach, the ETFE-printed specimen’s layer conductivity maintains its lower sensitivity to strains, decreasing gradually with stable speed until the final rupture.

The same phenomenon has also been observed with PEDOT/Ag layers coated on PET and ETFE substrates (Fig. 11b). It can be seen that the conductance–strain curves of PEDOT/Ag layers adopt quite similar shapes compared with those in Fig. 11a. To further investigate the role of PEDOT in PEDOT/Ag layers, another set of tests has been performed with the same specimen form and experimental configuration. Figure 11c shows a clear difference between Ag/PET and PEDOT/Ag/PET configurations. At the same strain level, the PEDOT/Ag/PET configuration generally maintains higher conductance than the Ag/PET configuration. To reach 80% of the initial normalized conductance, the configuration with PEDOT as the top layer can withstand almost double strain compared with the Ag/PET-based one. This demonstrates that PEDOT helps increase the conductance of the Ag layer through the tensile stretching, especially after the specimen has reached the 10% strain level. This phenomenon could be explained by the “bridging effect,” as depicted in Fig. 12. Through the imposed tensile forces, the Ag layer will experience increasing strains all over the layer. Some high-strain locations will develop into cracks over the Ag layer, where the charge carrier mobility will be greatly reduced when applied in OPVs. However, the additional PEDOT layer above can partially ameliorate this phenomenon. Although the PEDOT layer will also develop cracks upon strains, the double-layer structure still maintains a certain probability of inter-crossing between

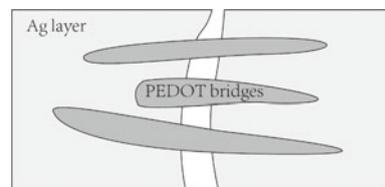


**Fig. 11** Conductance through tensile test of specimen **a** Ag/PET & Ag/PMMA/ETFE, **b** PEDOT/Ag/PET & PEDOT/Ag/PMMA/ETFE, **c** Ag/PET & PEDOT/Ag/PET, **d** Ag/PMMA/ETFE & PEDOT/Ag/PMMA/ETFE. Elaborated by the author

the two layers. When this occurs over the cracks of the Ag layer, the PEDOT can act as a bridge to increase the mobility of charge carriers through those cracks. Eventually, this will help ease the effect of the strain on the Ag layer conductance.

Through the results comparison of Ag/PMMA/ETFE and PEDOT/Ag/PMMA/ETFE configurations, as shown in Fig. 11d, we can find similar behavior with a strain of less than 25%. The configuration with the PEDOT top layer maintains almost the same conductance level with double the strain of the Ag/PMMA/ETFE configuration. This could be explained similarly with the “bridge effect” from the PEDOT layer. However, with a strain higher than 25%, we observe a quite different phenomenon. In Fig. 9d, we can clearly observe crossing at the

**Fig. 12** “Bridging effect” of PEDOT layer over Ag layer through tensile test. Elaborated by the author



25% strain of the Ag/PMMA/ETFE and PEDOT/Ag/PMMA/ETFE configuration curves. After 25% strain, the PEDOT/Ag/PMMA/ETFE specimen saw a more rapid decrease in conductance than the Ag/PMMA/ETFE specimen.

### ***Morphology characterization***

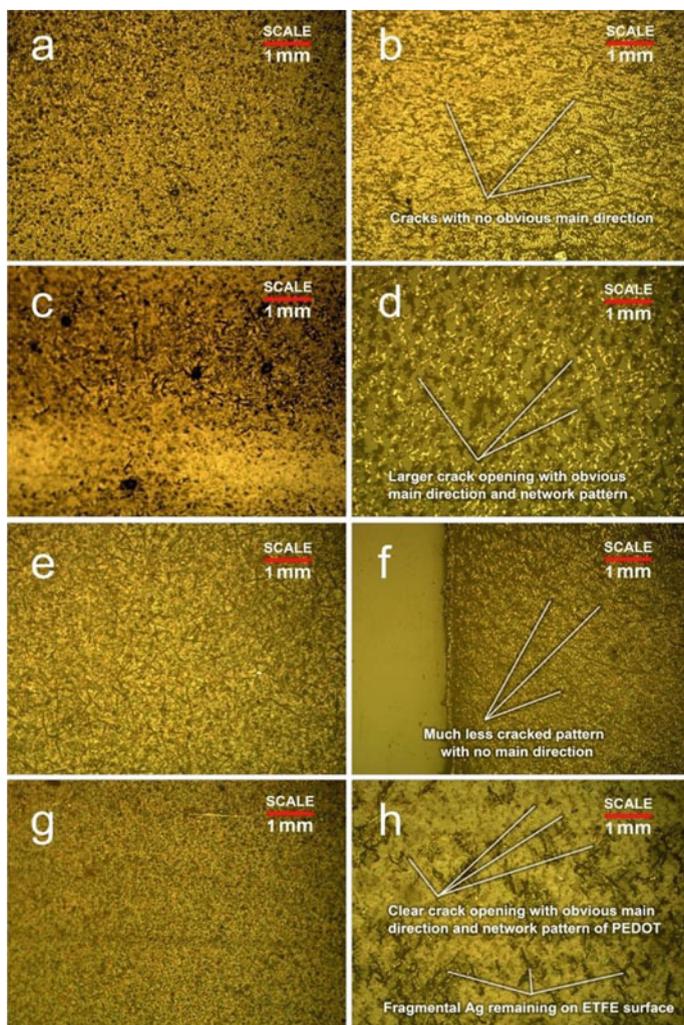
The stretched samples with different configurations were then observed under the microscope as shown in Figs. 13 and 14.

Figure 13a, b shows the texture of the Ag/PET layer before and after the tensile test. Small cracks with no obvious main direction were scattered over the PET substrate. Compared with Fig. 13c, d of Ag/ETFE specimens, where the rupture occurs with a much larger strain and the printed Ag layer sees larger crack openings, the PET substrate acts as the bottleneck of the printed electrode layer. The crack pattern on ETFE also sees a more obvious main direction perpendicular to the stretching direction, which is probably the reason for the lower sensitivity of the ETFE-printed Ag layer to strain because the resulting network pattern of the Ag layer can be more beneficial to the layer conductance than the orderless crack pattern on PET. A similar situation has been observed with PEDOT/Ag/PET and PEDOT/Ag/PMMA/ETFE configurations (Figs. 13e–h). The PET-based specimen sees a much less cracked pattern compared with the ETFE-based specimen. However, in contrast to the PET-based configuration, the PEDOT/Ag/PMMA/ETFE specimen sees much less Ag remaining on the ETFE surface after the tensile test compared with the Ag/PMMA/ETFE configuration. This can explain why in Fig. 13g and h, with strain larger than 25%, the PEDOT/Ag/PMMA/ETFE specimen met a more rapid conductance decrease. In Fig. 13h, we can also observe the smaller cracks of the PEDOT layer compared with the fragmental Ag shards below it. This also proves our “bridging effect” assumption of the PEDOT layer.

In Fig. 14, we also reported the texture of the PEDOT/PET and PEDOT/PMMA/ETFE layer after the tensile test. Because the PET layer ruptures at a relatively lower strain, the PET-printed PEDOT layer remains almost plain, whereas the ETFE-printed PEDOT layer shows an obvious crack pattern. The crack pattern shows a scattered distribution over the whole layer and also a more obvious main direction perpendicular to the stretching direction, quite similar to that seen with the Ag layer in the stretched Ag/PMMA/ETFE specimen. However, the crack openings are still not comparable with those of the Ag layer in the PEDOT/Ag/PMMA/ETFE configuration. This further confirms the PEDOT layer’s bridging effect.

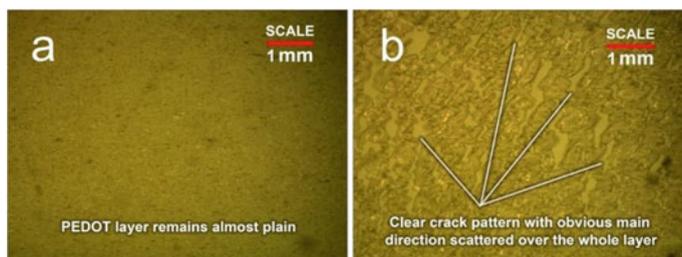
## **4 Conclusions**

This work proposed a coupled mechanical and electrical characterization method to monitor the correlation of OPV electrode resistance and cell performance upon tensile strain and to verify the deterioration effect and reason for the tension strain on the OPV performance response. The employment of the test method with a commercial OPV module implies the following. Firstly, the strength of the encapsulation layers,



**Fig. 13** Specimen observed under  $10\times$  microscopes of **a** Ag/PET layer before tensile test, **b** stretched Ag/PET layer, **c** Ag/PMMA/ETFE layer before tensile test, **d** stretched Ag/PMMA/ETFE layer, **e** PEDOT/Ag/PET layer before tensile test, **f** stretched PEDOT/Ag/PET layer, **g** PEDOT/Ag/PMMA/ETFE layer before tensile test, **h** stretched PEDOT/Ag/PMMA/ETFE layer. Elaborated by the author

rather than the functional layer, is the decisive factor in the cell package ultimate strength. Secondly, the transparent electrode in the test commercial OPV module is more sensitive to strain than the metal electrode, and the decrease in the transparent electrode conductance has been determined to be responsible for the cell degradation upon tensile strain. The transparent electrode in the tested OPV is therefore not mechanically robust upon large strain, whereas the metal electrode characterized



**Fig. 14** Specimen observed under  $10\times$  microscopes of **a** PEDOT/PET layer after tensile test **b** PEDOT/PMMA/ETFE layer after tensile test. Elaborated by the author

by high-strain stability is a better choice for PV flexible product integration. The threshold of tensile strain for the tested OPV module to lose function has been recorded at 1.8%, with the corresponding critical stress at approximately 20 MPa.

The key weakness of the electrode in OPV upon tensile strain inspired the following employment of the coupled test with ETFE- and PET-printed OPV layers. The experimental results indicate the following. The electrode conductance of both the ETFE-printed Ag and Ag/PEDOT is less sensitive than the PET-printed one at small strains (<50%), where the PET-printed configuration commonly shows a brittle-like failure, but ETFE shows a plastic-like stretching. At higher strain levels (>50%) where the PET-printed specimen cannot reach, the ETFE-printed electrode conductivity maintains lower sensitivity to strains. Further data analysis together with microscopic characterization confirms the following. The network pattern of ETFE-printed electrodes contributes to the lower sensitivity of ETFE-printed electrodes upon tensile strain. The adoption of Ag/PEDOT layering can improve the tensile strain threshold to approximately double for maintaining 80% of the initial normalized layer conductance. The favor of PEDOT in increasing the Ag layer conductance is due to the “bridging effect.” It loses its effectiveness only at strain levels higher than 25%, with a PEDOT/Ag/PMMA/ETFE configuration, where less Ag remains on the substrates after tension.

Our coupled test methodology and test results provide valuable information on the effect of tensile strain on the electrical performance of the OPV layer and module. It can contribute to subsequent building of product development toward OPV integration onto ETFE membrane. More efforts are needed to find stretchable alternatives for OPV integration in flexible PV products. Further, investigation is also required to explore the properties of direct-printed full OPV on ETFE or other architectural membrane materials.

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# Case Study: TIFAIN Facade



Nebojsa Jakica , Carol Monticelli , and Alessandra Zanelli 

**Abstract** This chapter presents the Italian national research project TIFAIN that explored the possibilities of designing complex and multifunctional, semi-transparent, and colored Building-Integrated Photovoltaic glazed facades. Moreover, the project analyzed integrating Dye-Sensitized Solar Cells (DSSC) into a Complex Fenestration System (CFS) with the light management technology that controls reflection, refraction, and light trapping for energy conversion. Developed integrative performance-based design methodology considers multiple criteria such as the high building energy efficiency, the energy generation by PV, and the user comfort, to achieve a symbiosis of both design and high performance in a unique facade system. This methodology is demonstrated on two different TIFAIN facades and their design, material, and performance criteria. Finally, the chapter describes the project consortium, the whole design process and roles, the upscaling process including prototyping and testing, and various studies including Life-Cycle Assessment (LCA), solar radiation, layout, and structural system.

**Keywords** Building-integrated photovoltaics · Facade · Dye-sensitized solar cells · Complex fenestration system · Life-cycle assessment · Solar design · Light

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# 1 Introduction

High performance and complex facades get more attention nowadays with the community awareness of sustainability issues (UNFCCC 2015) and the importance of energy savings and energy generation from renewables, especially in the building sector. The way buildings were designed in the past, when energy and environmental issues were not so prevalent, and have had enormous influences on today's energy consumption. For example, the modern architecture of the twentieth century, usually characterized by highly transparent curtain glass walls of the International style, has very poor or no insulation. Many decades have passed since the early glass curtain walls' poor thermal characteristics and resulting user discomfort were improved through technological advancements of glass coatings and Insulating Glazing Units (IGU). Buildings contribute to almost half of the total energy consumption in Europe (Recast EP 2010), and this trend is similar across the globe (Cao et al. 2016). Moreover, building facades can save up to 60% of buildings' energy consumption (Bragança and European Cooperation in the Field of Scientific and Technical Research (Organization). COST Action C16 2007).

Nowadays, after decades of technological developments, advanced facade systems such as complex fenestration systems, electrochromic windows, low-e glazing, micro-structured shading, and dynamic shading systems, are in focus more than ever before. Many solutions with multilayered facades, such as double-skin facades, external shading, and recently closed-cavity facades, have been explored and built, producing various alternatives for energy performance and building comfort improvements. Furthermore, energy-activated building skins in Building-Integrated Photovoltaics (BIPV) represent a desirable solution to address energy needs and compensate for building energy consumption to a large extent and even reach zero Plus-Energy targets. These trends had been recognized by green building energy standards such as BREAM (Aubree 2009) and LEED (US Green Building Council 2014) that gave credits to daylighting, low energy consumption, renewable on-site energy generation, and integrative and performance-driven building design.

This chapter presents a BIPV facade system capable of reducing building energy needs and providing on-site energy generation through Photovoltaics to address these issues.

## 1.1 TIFAIN Research Project

TIFAIN was an Italian national project financed by the Lombardy Region and the Italian Ministry of Education, Universities and Research (MIUR) under Grant number 30221157—Fig. 1. Acronym TIFAIN stands for photovoltaic integrated glass tiles for innovative architectural application (Tessere Integrate di vetro Fotovoltaico per applicazioni Architettoniche INnovative—ita.). The main objective



Fig. 1 TIFAIN project and consortium

of this research was to explore the possibilities of designing complex and multi-functional BIPV facades with daylight redirection capabilities made of Complex Fenestration System (CFS) glass and Dye-Sensitized Solar Cells (DSSC).

CFS glass component in this concept has a double function. Firstly, it serves as a Daylight Redirection Component (DRC) to control light deflection and improve indoor daylighting. Secondly, it functions as a light-trapping device that controls the light passing through and collected by PV cells. It is made of a pressed glass process that allows manufacturing such complex profiles and geometry. DSSCs are designed to be placed on this CFS glass substrate and laminated by an encapsulant to the supporting glass. Moreover, they provide different color options and transparency levels that can be used as a design and performance feature. Advanced light management and light redirection potential on both facade sides offer a unique feature that aims to balance urban light pollution, increase absorption in PV cells, and bring more light indoors—Fig. 2.

Three different facade modules were designed:

- TIFAIN 1 is a middle-scale tile of 10 × 10 cm with a double-sided saw-tooth geometry and various options for DSSC. The double-sided periodic macro-structured saw-tooth surface is designed to control reflectance, transmittance, and absorption of the CFS. These three criteria represent key parameters in PBD as they directly influence all other performances on the building scale. Reflection is set

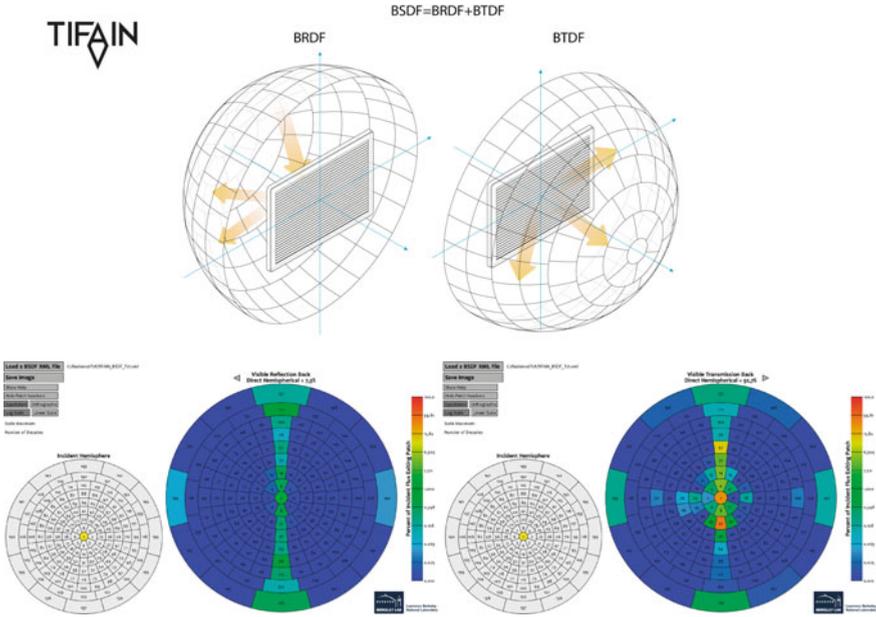
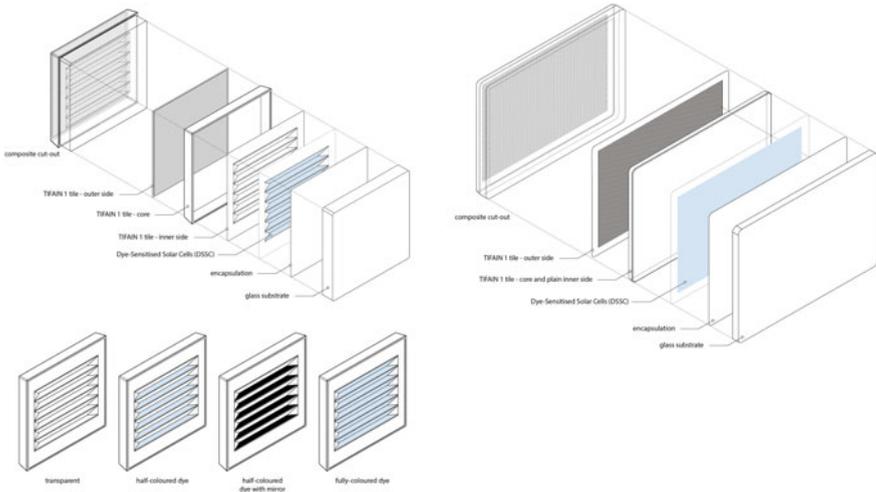


Fig. 2 TIFAIN CFS properties

to be minimized to decrease the amount of light that bounces from the vertical surface, especially in the case of a high incident sun angle. Absorption on the PV cell is set to be maximized to increase irradiation levels on the PV cell surface and thus the efficiency of the PV system—Fig. 3 left.

- TIFAIN 2 tile was designed as a full-scale module with a size of 25 cm × 35 cm. This tile has grooves on only one side for more straightforward PV disposition and testing efficiency for big PV areas, but it has a lower ability for light control. Moreover, it predicted only two types for integration, with and without PV—Fig. 3 right and Fig. 4.
- TIFAIN Diamond facade that used the same principles of light management and saw-tooth profile, but at a larger scale and smoother design shape. At the larger size, the wavy shape becomes a design identity and performance concept simultaneously. The concept was developed during the latter stage of the project TIFAIN, as an improved version of the first two prism concepts. The idea has initiated after analyzing potential in prism design and its limitations in terms of production, maintenance, and architectural design—Fig. 7.

The idea was formed as a response to market research showing that most BIPV solutions originated from the PV sector, focusing mainly on PV performance and energy output, generally have lower design qualities. Only recently, BIPV systems



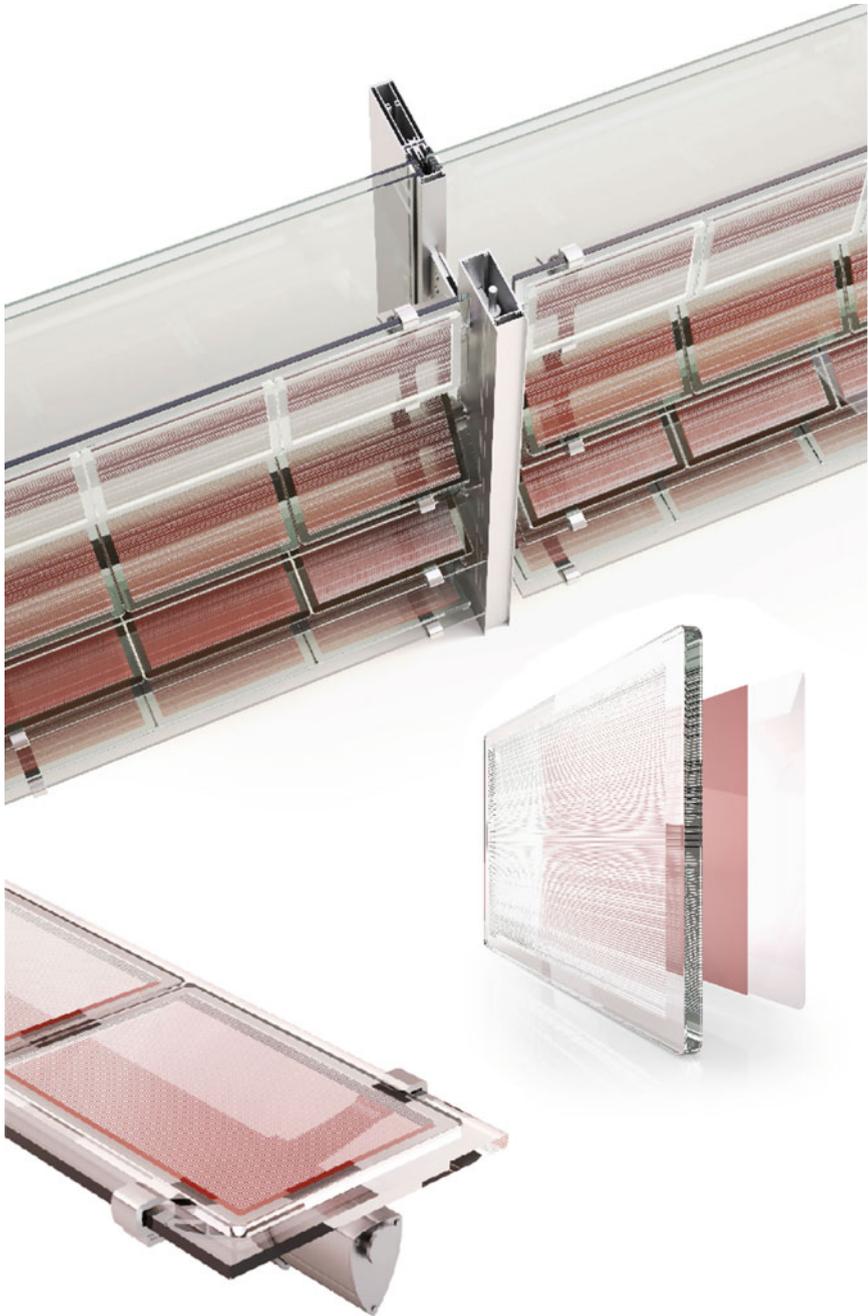
**Fig. 3** TIFAIN tiles 1 (left) and 2 (right)

have started exploring a multitude of architectural design pallets that communicate better to the architects’ needs and visions, especially in terms of PV integration, aesthetics, and customization. Here, we have seen many opportunities for improvement: Firstly, propose a design concept that can respond to the increasingly demanding current and future sustainable trends and redefine the existing market and, secondly, to rethink the way BIPV is integrated to improve PV performance through design.

### ***1.2 The TIFAIN Consortium and the Prototyping of First OPV Transparent Tiles***

In the first phase of the project, the role of POLIMI-DABC was to outline and present to other partners the specific requirements of the innovative TIFAIN photovoltaic facade, valid for the management of industrial research at different levels. For the design of the photovoltaic tile and the integrated facade, was proposed the adoption of the most innovative principles and methods of architectural design and execution, based on the performance-based design (PBD) integrated with tools for parametric modeling and optimization of the design process, which allowed then, in the following phases of the TIFAIN project, to interface the additional requirements arising from the industrial research activities of the other partners of the project.

In the industrial research phase, the role of POLIMI-DABC was to support the objectives of UNIMIB (specifications useful for the choice of dye cells) and those of INDI, IIT, and RCR (specifications related to the sizing of the glass substrate of cells) and RCR (Life-Cycle Inventory of the photovoltaic tile Tifain 2).



**Fig. 4** TIFAIN 2 tiles and facade

After the investigation of different application scenarios of the new photovoltaic tile (redevelopment of existing facades; new facades of complex shape; continuous or suspended facades; large membrane photovoltaic roofs), we focused on the simulation of a new complex facade system including both the energy efficiency strategies of active type (electricity generation via photovoltaic) and those of passive-type (daylighting, shading, natural ventilation, radiative effect, and heat conduction through the facade; direct radiation and influence of the buildings around). The aim has been to prefigure that the new facade can meet the objectives of nZEB (Nearly Zero Energy Buildings). The cost optimum for this category is expected in terms of the durability of ease of maintenance over time, limiting impacts over the entire life cycle.

In the experimental research phase, POLIMI-DABC has supported EG in realizing the TIFAIN facade demonstrator on a 1:1 scale and testing the mechanical strength and durability of the new photovoltaic tiles. To such a purpose, the partner POLIMI-DABC has been planning the mock-up of the new TIFAIN photovoltaic facade and comparing the simulations on the daylighting performance of the new facade and the validation of data through the experimental tests conducted in the open field on the mock-up.

POLIMI-DABC has finally taken care of the realization of a video documentary with the dual objective of documenting TIFAIN prototypes and demonstrators and allowing all partners to share the different phases related to the specific industrial research experimental development processes for both didactic and informative purposes. The Pert chart of the project is presented in Fig. 5.

### ***1.3 The Architectural PV Integration Requirements***

The role of POLIMI-DABC has been to collaborate on the coordination of the first phase of the project, defining specific requirements of the TIFAIN project regarding the functionalities of the photovoltaic system to the various levels. In particular, POLIMI-DABC has investigated and determined functional specifications related to the architectural application of new photovoltaic components.

In fact, prior to the design of the glass support and the photovoltaic part of the new tiles, it was essential to share with the other partners of the project:

1. The understanding of optical specifications (transmission, absorption, the reflectance of sunlight), thermal requirements, structural and mechanical related to DSSC cells, and printed glass substrate to translate these specifications into requirements and expected performance in the new integrated photovoltaic facade system;
2. The investigation of projects, references, ideas, design concepts, emerging technologies, which could make all partners grasp the concept of a new BIPV facade, its qualities, and its innovation from the architectural point of view;

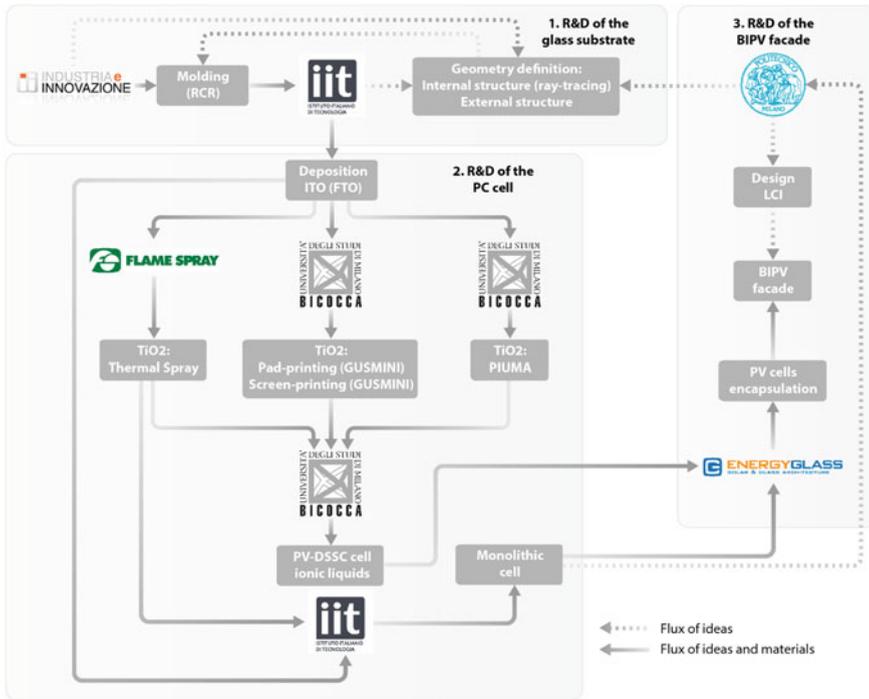


Fig. 5 TIFAIN project Pert chart

3. The presentation of the most innovative principles and methods of performance-based architectural design or integrated with tools for parametric modeling and optimization of the design process allowed, in the subsequent phases of the TIFAIN project, to incorporate other design processes, as well as additional requirements of other project partners;
4. The classification, organization, and presentation of all performance requirements and relevant concepts of sustainable architectural design, based on a careful methodological approach to understanding in an integrated way the different aspects of the comfort of the end-user, minimization of energy needs at the level of the building, aesthetic integration, and integration with the urban and territorial context;
5. The focus of the need to introduce requirements of architectural and constructive value, able to include in the best way both the strategies of active energy efficiency (electricity generation via photovoltaic) and those passive (daylighting, shading, natural ventilation, radiative effect, and heat conduction through the facade; direct radiation and influence of the buildings around); this to design an innovative photovoltaic facade system that can aim at the objectives of the nZEB (Nearly Zero Energy Buildings) and the cost-optimum that for this category is expected

in terms of the durability of ease of maintenance over time, limiting impacts over the entire life cycle;

6. The verification of the consistency and compatibility of the architectural, functional specifications of the future TIFAIN facade with the indicators necessary to obtain voluntary type certifications such as LEED and BREEM.

## ***1.4 Design Processes and Materials***

### **Design and Simulations at the Level of the Architectural Component**

At this stage, the POLIMI-DABC working group dealt with:

- the detailed design and simulation of components, in close cooperation with the INDI and IIT partners;
- the development of specific software of “ray tracing” for the design of the complex geometry of TIFAIN cards, in close cooperation with partner IIT;
- the support to the work of the partner UNIMIB in the choice in the optimal dye is for the efficiency of the cards is for the optimization of the performance of the integrated photovoltaic facade.

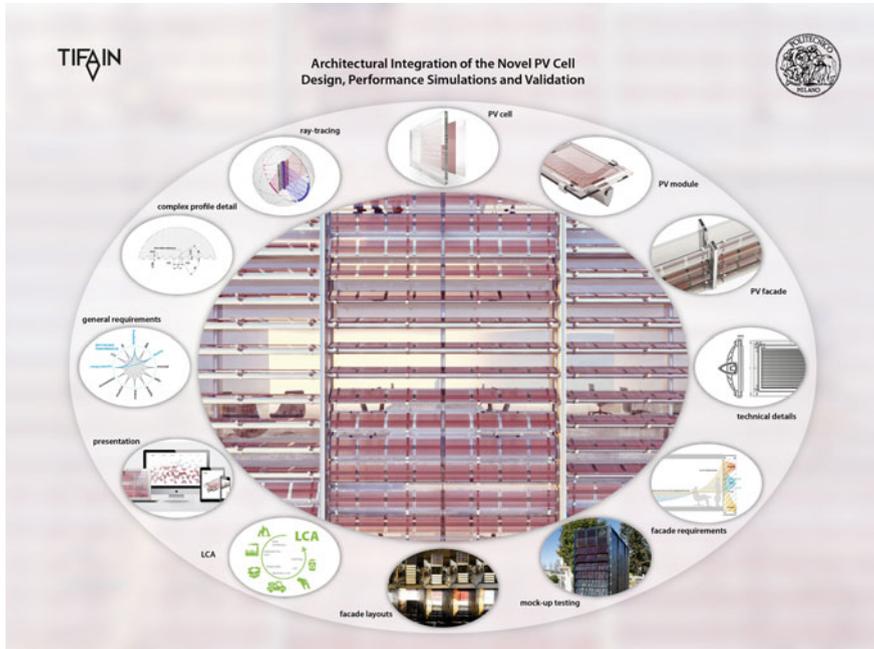
### **Design of Architectural Integration of photovoltaic Facade Components**

At this stage, the POLIMI-DABC working group dealt with:

- the design of new building components for facade systems, based on the use of new photovoltaic cards, using the tools and methodologies of performance design;
- the identification of strategies for the development of the new facade and its sub-components at different scales; at level MICRO (cell); at level MESO (facade module); at level MACRO (the facade system);
- the creation of a 3D meta-model of TIFAIN 1 and TIFAIN 2; useful both for the industrial manufacture of printed glass supports and for the simulation of the positioning of photovoltaic cells; for this phase POLIMI-DABC has interfaced with the INDI partners, IIT, UNIMIB;
- the proposal of an additional type of integrated photovoltaic facade based on TIFAIN technology, called “TIFAIN DIAMOND” aims to optimize the efficiency and aesthetic performances for designing the complex shape;
- this proposal has been submitted to the Technology Transfer Office of the Politecnico di Milano and patents were granted for industrial innovation (Patent No. 102015000061983, 2015) and design (Patent No. 002824847–0001, 2015).

At the executive design level, POLIMI-DABC then dealt with:

- The development of a supporting substructure system for new photovoltaic tiles, taking as a reference a technology already available on the market and assessing the differences and the best to introduce.

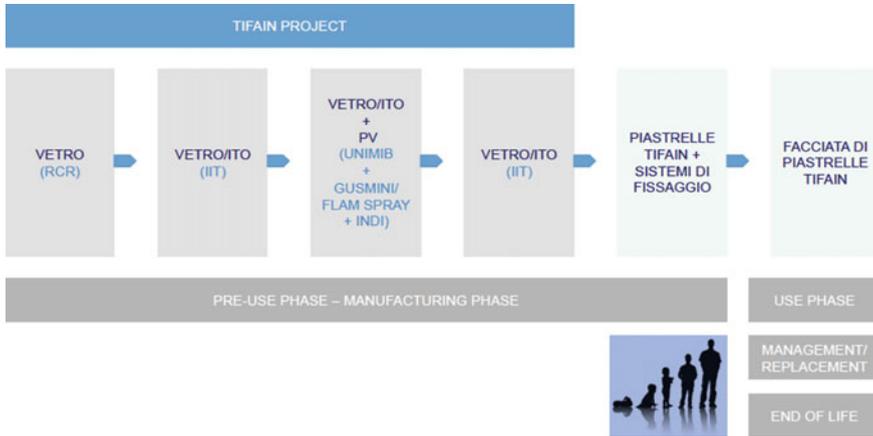


**Fig. 6** Architectural integration design process

- The development of a tensile support system for the application of the Tifain Diamond tile in systems of suspended facades and/or large roofing with complex membrane development and shape.
- Finally, a software tool PBD has been created that can support designers in the use of the new photovoltaic cards TIFAIN from the early stages of design, to fully exploit the aesthetic qualities and functional and performance attitudes resulting from the energy efficiency strategies, both active and passive, that this innovative facade system TIFAIN promises. The design process is shown in Fig. 6.

### ***1.5 Life-Cycle Inventory of the Photovoltaic Tile TIFAIN 2***

POLIMI-DABC performed the first phase of the environmental impact analysis LCA (Life-Cycle Assessment) of the printed glass tile integrated with organic photovoltaic (DSSC cells) developed in the project. This part of the work began after the initial phases of the research, where the shape of the tile was realized. After the formal optimization linked to the technical and physical requirements, the other phases to collect the information followed. The purpose of this part is to understand the entire manufacturing process of TIFAIN tiles and photovoltaic integration, calculating the materials involved, their respective quantities, and the energy consumption during



**Fig. 7** Diagram of the photovoltaic tile TIFAIN 2 fabrication sequence (10 cm × 10 cm)

production. This appears to be the preliminary stage for the assessment of the environmental impacts of the TIFAIN system. Specifically, this contribution POLIMI-DABC consisted of the following:

- Investigation through data in the literature on studies conducted so far concerning the environmental profile of organic photovoltaic technologies, which shows that some important steps in recent years have been taken in the following years and that research prospects are promising in this respect;
- Investigation through data in the literature concerning studies carried out so far concerning the environmental profile of printed glass technology and investigation of similar technologies present on the building market;
- Definition of the Life-Cycle Inventory of a photovoltaic tile TIFAIN 2 (10 × 10 cm);
- Description of the flow diagram for the production of the photovoltaic glass tile TIFAIN 2 (10 × 10 cm), from the glass molding (with a visit to the INDI production site and collection of the necessary information) to the deposition of the conductive layer in ITO (with information from partner IIT), active layer deposition for solar energy collection (with collection and collation of data from the partner involved in this UNIMIB Solar process and with support and observation of deposition operations);
- Establishment of the functional diagram of the glass printed tiles production process;
- System setting with a graphic return of the sequence of the process of integration of DSSC photovoltaic cells on the tiles;
- Systematization of the quantities of materials involved in the different processing phases (Fig. 7).

## 1.6 Testing of Processes and Materials

### Tests on the Printed Glass Backing: Structural and Durability Tests

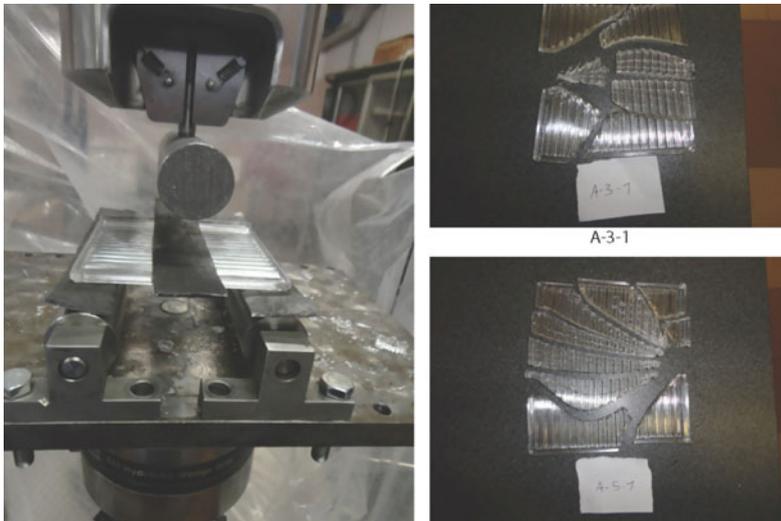
The POLIMI-DABC working group investigated the mechanical performance of the printed glass support of the photovoltaic card TIFAIN, assuming two main scenarios of use:

- A scenario of the application of the photovoltaic card in systems of a continuous facade;
- A scenario of applying the photovoltaic tile in membrane-developed tensile-structural systems for coverage of large light and/or hanging facades.

TIFAIN 1 ( $10 \times 10$ ) rupture tests were carried out, which showed that the mechanical strength of the printed glass tile is greater where the mechanical action is perpendicular to the roughness direction of the tile. These tests served as preliminary checks to the industrial research phases of the partner INDI, RCR, and Energy Glass, for the choice of the correct inclinations of the rough surfaces of the printed glass support (Fig. 8).

A system for connecting TIFAIN tiles to a tensile substructure in a cable network has been verified using biaxial traction tests. The mechanical characterization tests of a facade component are made with a series of tiles TIFAIN laminated with tempered glass (size  $40 \times 120$  cm) in compliance with the standard, CEI EN 61215-61730. These verifications were concluded together with the partner Energy Glass.

Together with the Energy Glass partner, POLIMI set the durability tests of TIFAIN 2 tiles ( $20 \times 30$ ) deposited with dye and assembled with a structural glass using four



**Fig. 8** Rupture testing of the photovoltaic tile TIFAIN 1

different types of stratification material (EVA, PVB, TPU, and SGP) in accordance with IEC 61215-61646:

- Visual inspection
- 30% of the Humidity-freeze
- 30% Dump-Heat
- 30% Thermal cycling.

### ***1.7 Realization and Characterization of Components***

In this phase, the contribution of the Polytechnic Group was only to check the coherence between the shades of color assumed by small devices developed by other industrial research groups and the expectations of photovoltaic facade modules expected in the next up-phase-scaling to the architectural dimension.

In particular, TIFAIN 1 and 2 tiles were produced in both colored form with DSSC PV on the back side, as well as in form of a daylighting device without the PV. In this way, it was possible to distinguish between manufacturing defects of the glass substrate and the color homogeneity separately. Considering glass itself, the main defects were visible in the lack of surface flatness and grooves precision, especially in the front of TIFAIN 2. Consequently, glass grooves looked distorted as only small deviations could cause optical clarity in both grooved and flat parts—Fig. 9. Main reasons for such distortion came from the heat shock when glass was poured in the molds. For reducing this effect, more time would be needed to calibrate glass and molds temperature. However, as a redirecting daylighting device with the purpose of scattering light mainly upwards and without the requirement of precision, TIFAIN 1 and 2 quality of production was sufficient to provide these functions as a first functional prototype.

Considering tiles with PV on the back side, TIFAIN 1 had a limitation in manufacturing precise PV areas mainly due to the slightly wavy surfaces, but also due to the manual placement of PV in form of painting on the glass grooves. Therefore, on the close-up views showed inconsistencies and imperfections that could have resulted in efficiency drops. TIFAIN 2, on the other hand, had more uniform color and PV surface edges due to the flat back side. Overall, both tiles provided pleasant interplay of the effects of light scattering, reflections, dispersion, transparency, and translucency. Moreover, manufacturing defects were not visible from the distances of one meter and beyond (Fig. 10).

### ***1.8 Upscale and Prototype Testing***

#### **Assembly and Testing of the Photovoltaic Facade Panel**

This task was coordinated by the partner Energy Glass, while the partner POLIMI-DABC was responsible for the design of the mock-up of the new TIFAIN photovoltaic



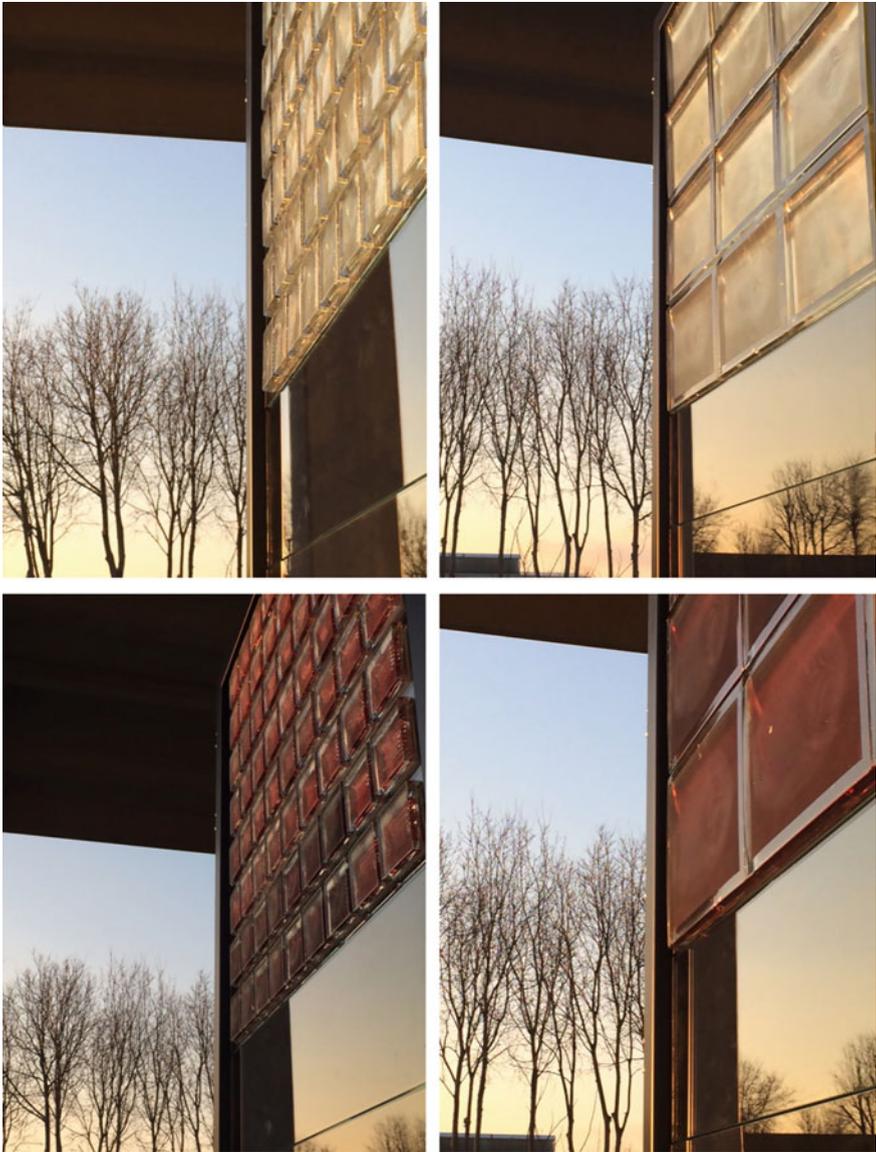
**Fig. 9** TIFAIN 1 and 2 component prototypes

facade and the comparison between the simulations on the daylighting performance of the new facade and the validation of data through the experimental tests conducted in the open field on the mock-up.

The mock-up is a facade module connected to a black box; it was designed by POLIMI-DABC and made by Energy Glass. The two partners under the supervision of INDI worked on the development of the testing methodology, while for the validation methodology of the simulations carried out during the parametric design phase through the data obtained experimentally, the partner POLIMI-DABC has availed itself of the scientific contribution of the colleagues of the SUPSI (Fig. 11).

## 2 LCA of a Novel Concept of TIFAIN Skin

This part focuses on a particular type of organic photovoltaic cell, designed and experimentally integrated into patterned glass tiles. The aim was the investigation of its environmental profile through LCA comparative assessment. The work has been developed for research of industrial development rather than for the optimization of the production. As a result of the experimental research project TIFAIN, the LCA was carried out for the specific product to support the investigation of first tiles facade prototypes and lead toward the optimization of processes. Knowing the quantities involved and their impacts was the crucial aspect that has oriented the general choices

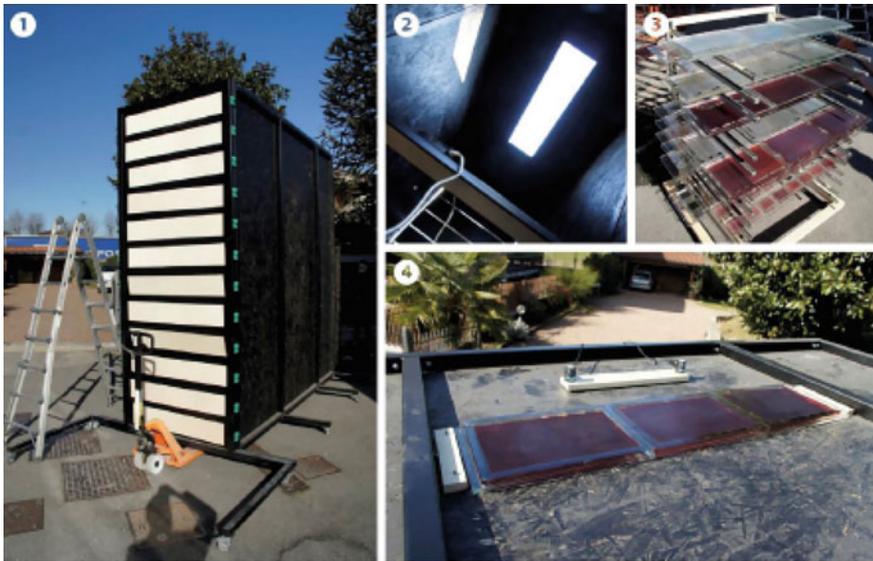


**Fig. 10** TIFAIN 1 and 2 facades mock-up

of research. The investigated PV technology was based on the Grätzel cell, a dye-sensitized solar cell technology developed by the same scientist in 1991.<sup>1</sup> This system

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<sup>1</sup> The classic Grätzel cell has a “sandwich-like” structure made out of by two flat glass conductors that act as photo anode and cathode, in between which is a porous layer of titanium dioxide



**Fig. 11** Images of the mock-up designed by Polimi and realized by EG

sets itself out as an alternative to conventional photovoltaic systems that generate electricity from solar radiation by combining this function with a high degree of transparency and, therefore, a broad spectrum of possibilities for integration into the facade system.

## ***2.1 Comparative LCA of New Photovoltaic Glass Tile Facade Systems***

The study's objective was the application of the LCA environmental evaluation methodology to the building industry, specifically to the integrated photovoltaic facade system and its basic component (the single photovoltaic tile). The study consisted of two consecutive evaluation processes: First, the LCA method was applied to the experimental tile, and then, the data that emerges, as a result, was used in the subsequent evaluation of the entire facade system; the LCA aimed to compare three different facade typologies to validate their eco-efficiency. The function of this system included both the generation of renewable electricity from third-generation photovoltaic technology (in particular the Dye-Sensitized Solar Cells, belonging to the general technological category of Organic PhotoVoltaic) and the integration of cells into the building envelope.

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nanoparticles ( $\text{TiO}_2$ ) impregnated with dye. This layer (called "active layer") is immersed in an electrolytic solution.

The boundaries of the system have been extended to all phases of life of the materials that make up the system, from production (including raw material extraction, transportation, and transformation, assembly) to end-of-life (tile dump, where appropriate, recycling as the end-of-life treatment) and throughout the use phase (the advantage of the photovoltaic system was evaluated by quantifying the production of avoided primary electricity). The production facilities needed for the various processing phases were considered. Concerning the processes of realization of the photovoltaic glass tile, quantities of substances and data from production processes at the laboratory scale of experimental research have been considered.

## ***2.2 Functional Unit and Data Quality***

A single experimental glass tile of 10 cm × 10 cm dimension was assumed as a functional unit for the LCA at the scale of the component; for the LCA at the scale of the entire facade system, 5 × 3 m<sup>2</sup> of facade was assumed as a functional unit. These functional units, these quantities otherwise said, were evaluated over the system's lifetime spanning thirty years. The data regarding the emissions during use and end of life have been estimated. The Eco invent 3.1 database in the Alloc Def U version is considered to represent processes (including sub-processes); in the absence of existing processes, some have been created ad hoc. The used computing code has been SimaPro 8.04. Damage assessment was performed by applying IMPACT 2002+, modified by the research group.<sup>2</sup> The constants were assumed in all of the data: suction system, different filters according to the type of emission, laboratory equipment (including its washing), PPE, transport, and disposal (quantities in excess).

## ***2.3 LCI—Inventory Phase at the Scale of the Component***

To define the inventory of the production phase, all processes necessary for the production of one photovoltaic glass tile (U.F. 100 cm<sup>2</sup>) have been assessed. The processes taken into account included the materials and energy required for the treatments, thermal and not, for the different stages of processing, the suction system with electro-ventilator and filters during the realization of the photovoltaic onto the glass substrate, the electricity required for the operation of this system, laboratory

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<sup>2</sup> This study was conducted in collaboration with the Research group of the UNIMORE University of Modena led by prof. Annamaria Ferrari and eng. Paolo Neri. The modifications regarded the introduction to the Carcinogens category, starting with EcoIndicator99, of the impact of Heavy Metals, unspecified for the definition of Indium and Lead emissions in the air, of the impact of Metals, unspecified for the emissions of TO<sub>2</sub> Tetrachloride in the air, in the category of the Carcinogens Inhaled of the impact of Particulates < 100 nm indoor for the definition of Nano-titanium emissions, in the category of Respiratory inorganics of the impact of Particulates < 2.5 μm for the emissions of NH<sub>4</sub>F in the air and of the impact of ethanol with the emissions in the air.



**Fig. 12** Morphological–typological comparison of the proposed facade solutions: from left Type A, Type B, and Type C

equipment used including its washing, the personal protective equipment PPE, atmospheric and indoor emissions, transports (for each stage of the production process), and various disposal processes. Regarding the quantities of input substances prone to emissions in the production cycle, in the mass balance, the weight of these input substances has been augmented to offset for the emissions: In this way, the part of processing waste with relative emissions, which did not take part in the final product, was taken into account. During the management phase, with the assumption of thirty years of useful life, scheduled maintenance was scheduled every ten years to restore the sealing on the edges and holes of the glass tile. This period is commensurate with the capacity of the nanoparticle solution sprinkled on the tile to stay fixed. During the management phase, the production of electricity during the lifetime of the photovoltaic tile with an efficiency of 10%<sup>3</sup> was calculated as an avoided product. The starting point has been the existing entry in Switzerland's *Ecoinvent* database on electricity produced by conventional photovoltaic technology. The process has been adapted to this efficiency and a type of sun radiation. At the end-of-life phase, the tile was supposed to be disposed of on a landfill for particular waste due to the presence of nanoparticles that may detach themselves during the eventual disassembly. The difficulty of separating the materials and components of the cell to recycle as much as possible renders this scenario very uncertain.

#### **2.4 LCI—Inventory Phase at the Scale of the Glass Tile Facade**

For evaluation at the scale of the subsystem, three different facade solutions are proposed below, distinguished by their structure and the type of tile and structural and safety requirements. For all three cases, a 5 m × 3 m portion of the facade was considered the U.F (Fig. 12).

##### **Type a: Structural Facade with Vertical Uprights and Slats**

This facade solution is structured as a classic steel vertical upright structure (three tubular steel posts) supporting thirty horizontal slats; these are made up of eight

<sup>3</sup> Gratzel's first cells had an efficiency of 7% in the 1990s; with slight changes and improvements, an average value of 10% has been achieved, with a maximum peak of 11%.

photovoltaic modules, each consisting of six 10 cm × 10 cm photovoltaic glass tiles lodged on a 13.6 mm thick layered glass plate. The adhesion of the glass modules is accomplished with a 25 mm thick layer of sealing film, while the presence of laminated glass gives the facade the safety requirement for shock and wind resistance. The overall weight of the system is 997 kg. This configuration includes 1440 tiles on laminated glass slats, with an active photovoltaic area of 8.06 m<sup>2</sup>, equal to 53% of the total area.

### **Type B: Structural Diagonal Facade with Rhomboidal Elements**

A predominantly rhomboid geometry characterizes this solution due to the lozenge shape of the base tiles. The tiles formed in this way have a prismatic lozenge section suitable to optimize the capture of solar radiation to increase the system's efficiency. Complex geometry is possible thanks to the glass molding technique. This shape makes it possible to optimize the support structure for the facade, formed out of a grid of steel cables with the reduced section, mounted diagonally concerning the internal plan of the building: Its weight is less than the structure of type A with the same mechanical performance. Photovoltaic tiles have been designed to be lodged on laminated glass plates of the same geometry to guarantee structural glass facades' mechanical and safety requirements. The three hundred and fifty tiles are anchored between these glass plates and the structure through the grid of thirty steel cables. The overall weight of the system is 712 kg. The active photovoltaic surface of 13.97 m<sup>2</sup> makes up 93% of the total area.

### **Type C: Diagonal Facade with Rhomboidal Elements**

This facade system is the same as type B but without the application of the laminated glass tiles. This solution significantly reduces the overall weight of the facade system. Still, it does not guarantee the structural and safety performance of the glass (in case of breakage) (Italian glass facade regulations do not permit this solution.). The overall weight of the system is 246.5 kg. The active photovoltaic surface of 13.97 m<sup>2</sup> makes up 93% of the total area.

The difference in the active photovoltaic surface between the facade system if type A and the other two systems depend on the shape of the tile and the design of the support structure: In the case of the type A facade system, the contour of the tile is very "non-active," and the supporting structural elements occupy greater surface.

## ***2.5 Results of the LCA Evaluation on the Scale of the Component***

From the life cycle analysis results performed by applying IMPACT 2002+, the production process presented the greatest impact, with damage of 8.99 mPt, due to 163.52% of the production process, 0.11 at the end of life, with an advantage that can be accumulated during the use phase of -63.63%, due to the consideration of the electricity produced by solar capture as an avoided product of the Italian energy

mix (expansion of the system to the use of the co-product of the photovoltaic tile production process).

From the analysis of the LCA results for the production of the photovoltaic tile (Figs. 13 and 14), it is noted that the total damage is 14,696 mPt and is generated 0.59% from “Molded Glass,” 0.83% from “Indium tin oxide (ITO),” 4.77% from “Deployment of ITO,” 7.32% from “Washing + bathing + washing of the tile,” 0.70% from “Application of nanoTiO<sub>2</sub> (1% aqueous solution with TIP without no loop),” 7.42% from “Fixing,” 76.34% from “Bath for the colouring of the tile,” 0.14% from “Counter electrode,” 1.59% from “Cell Closure,” 0.09% from “Electrolyte Injection,” 0.01% from “Sealing of the holes,” and 0.21% from “Coating.”

Furthermore, the damage is conferred: 27.77% to Human Health, 11.14% to Ecosystem Quality, 37.29% to Climate Change, 23.80% to Resources, 9.08E−6% to Human Health Indoor, and 1.04E−8% to Carcinogens Inhaled.

In the production process, the “Coloring Bath” (Fig. 14) is the most impacting with total environmental damage of 11.22 mPt. This can be attributed 76.34% to the tile coloring process, mainly due to the electrical energy required for the use of the suction system (34.22%), the same (9.27%), for the active carbon filter, of the equipment (pellets, extraction pliers) with the washes (29.50%) (Fig. 15). In this

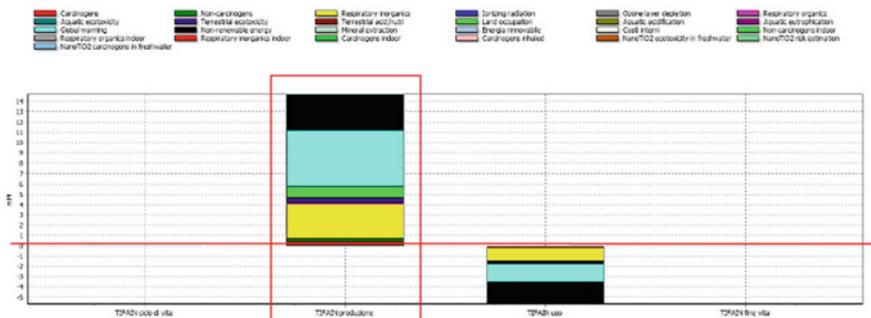


Fig. 13 Life-cycle analysis of a PV tile: single score evaluation diagram

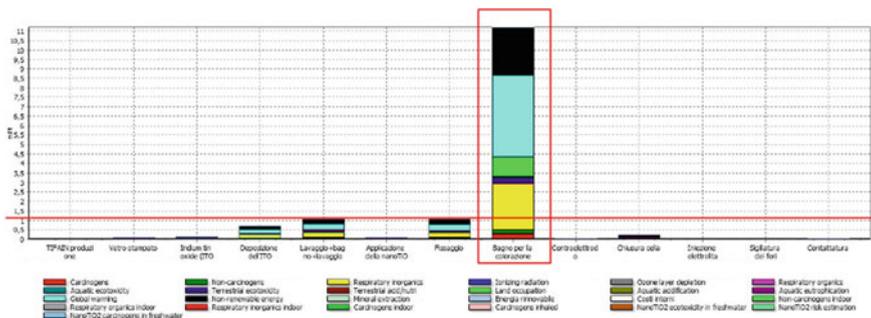


Fig. 14 Pre-use phase LCA analysis of the PV tile production: single score evaluation diagram



responsible for a considerable part of the overall impact. The damage attributed to glass tiles includes the benefit of the electrical energy avoided from the grid because it is self-produced by that PV system. The most affected category of damage, in this case, is also *Climate Change*, followed by *Human Health* and *Resources*. Given the significant difference between the impacts generated by facade system Types B and C compared to those of A, a precise evaluation of the latter is carried out to highlight the critical issues (Fig. 17).

The total damage is 13.12 mPt, for 98.70% attributable to the photovoltaic tile production. Out of this consideration, the difference between the typologies emerges: The present one presents many photovoltaic tiles four times greater than the tiles used in the other solutions, with consequent environmental impacts.

The other components have significant environmental impacts and are not comparable to the emerging ones.

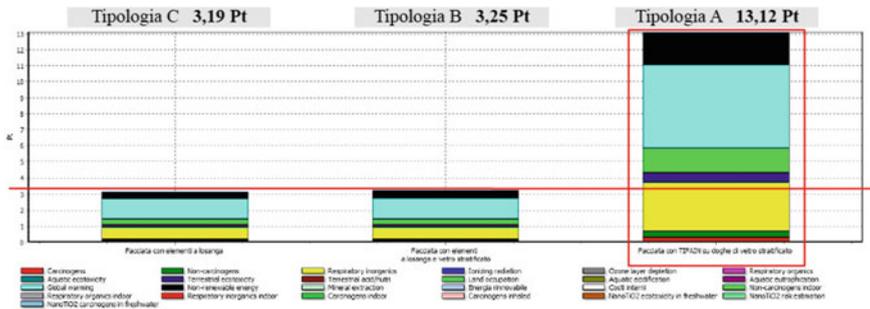


Fig. 16 The pre-use phase, LCA analysis for the production of the PV tile: single score evaluation diagram

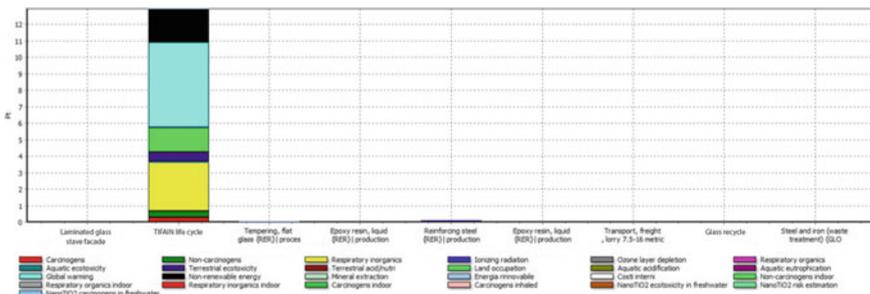


Fig. 17 Single Score Evaluation diagram for Type A facade system

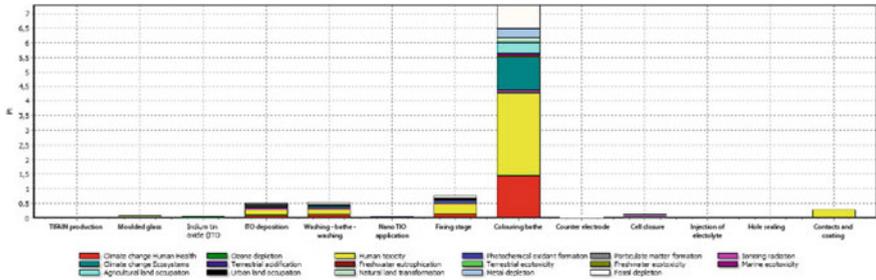


Fig. 18 Single score evaluation diagram of the Type with the ReCiPe method

### 2.7 Analysis and Verification of the Results

Sensitivity analysis, through verification by different methods, aims to demonstrate the consistency of the LCA analysis results. To this end, an evaluation of the process for the “production of PV glass in glass” was carried out, which is more interesting in terms of technological improvement prospects. The process was studied for 100 cm<sup>2</sup> with the ReCiPe Endpoint (E) V1.11/Europe ReCiPe E/A Method (Fig. 18).

This assessment gives rise to the following considerations:

1. The category in with the maximum damage produced is *Human health*, with 61.38%;
2. The process that produces the maximum damage is “Coloration Bath” for the tile;
3. In this process, the suction system generates the impact for the materials and the energy consumed (due to the duration of 20 h for the Coloration bath phase).

### 2.8 Conclusions

The LCA analysis of the photovoltaic glazed facade system allowed us to understand its critical issues and points of strength. At the level of the product, the evidence has shown that the production and processing phases are responsible for the overall impacts to a greater degree than the materials used. This opens up tremendous possibilities for improvement without the need to study any alternative solutions that would affect the material properties of the cell. At the level of the facade system, there are significant prospects for improvement when it comes to facade glass technology. On the one hand, the technique of molding the glass that holds the photovoltaic allows the cell to have a custom geometry optimized for solar capture.

On the other hand, the design of the facade system concerning the characteristics of the tiles is not only an innovation in the continuous glass facade technology, but also allows for a coherent and eco-efficient support structure when it comes to the amount of metal material used, ultimately being able to achieve an aesthetic and

compositional result of excellent transparency. Indoor emissions at the operational stage, to which much attention has been paid (especially to nanoparticles), have minimal damage. The application of alternative methods to IMPACT to evaluate the process has brought about similar results, which confirm the origin of the maximum damage. The reconstruction of the production processes, during the product's use and end of life, from the primary data has constituted a fundamental moment in the investigation regarding the modalities themselves. As an image of the impact that producing photovoltaic glazing tiles had, the obtained results should be commensurate with the laboratory and experimental scale in which tiles have been designed and produced. At that moment, a non-laboratory production dimension of this process did not exist. However, technology is conducive to improvements in processing time. It appears to be of great potential for architecture, compared to traditional ones, because of the high level of possibilities for integration, customizable geometry, and variable dimensions. This allows for greater capacity for solar capture, transparency, coloration, and lower production costs. Considering the current evolution of this technology, disposal and end-of-life treatment processes are not yet distinguished.

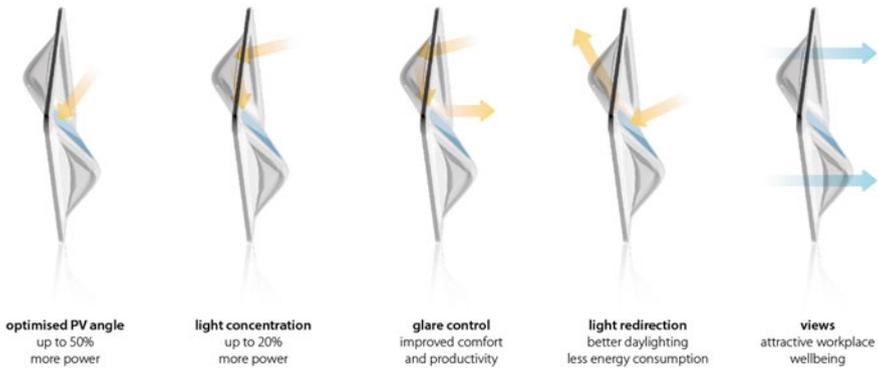
### **3 Pilot Project TIFAIN DIAMOND**

#### ***3.1 Methodology***

This chapter proposes the integrative performance-based design methodology, which considers multiple criteria such as the high building energy efficiency, the energy generation by PV, and the user comfort, to achieve a symbiosis of both design and high performance in a unique facade system. Furthermore, the concept can be applied to arbitrary climates and fitted to any context while maintaining architectural and performance integrity. Such a methodology can be later used to create new facade concepts that facilitate the ideation of highly customizable and performative facade systems that satisfy initial architectural ideas.

Providing an end-user or architects a facade system to customize, rather than having only two binary style solutions, opaque and transparent, brings much more possibilities in design. Smoother gradual transitions of the facade surface, achieved through functionally grading properties, provide a broader range of solutions to fine-tune facade modules according to the localized facade requirements. Authors believe only a holistic and systemic approach can adequately address the increasing range of complex requirements in unique flexible solutions.

TIFAIN Diamond facade is a hybrid concept that has both passive and active properties. Firstly, passive properties such as daylighting, glare control, view control, shading devices, and daylight redirection aim to balance solar heat gains by balancing light reflection according to the solar angles—Fig. 19. These properties strive to maintain homogenous daylighting levels indoors and prolong daylight autonomy, consequently reducing the energy consumption of artificial lighting. Furthermore,

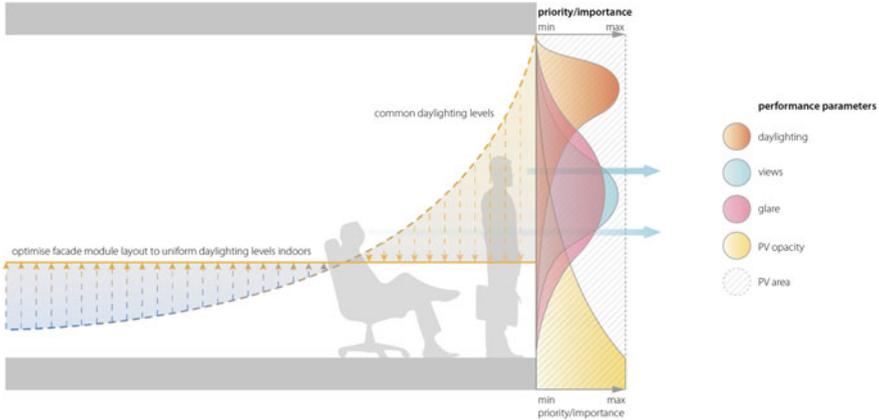


**Fig. 19** TIFAIN diamond facade active and passive properties

in climate zones with requirements for low solar heat gain coefficients, such as ASHRAE zones 1-3 (ASHRAE, 2019), this concept provides better transparency, glare control, and views than a comparable facade system with a classical shading or low  $g$ -value. Secondly, the concept has active properties through PV that can cover a high percentage of energy needs and even reach zero-energy targets in some climates. Furthermore, the customization of versatile angle setting property allows fine-tuning and simultaneous optimizing of performances. Therefore, the facade system can find an optimal balance of multiple criteria according to the project and climate needs to achieve high overall building efficiency, architectural design goals, and user comfort.

The concept opposes the classical repetitive placement of float glass that maintains the same properties all over the facade in combination with external or internal shading elements. Instead, this concept proposes a variety of curved glass tiles that enable mass customization and greater control of different performances than classical curtain walls. Therefore, the main idea of this facade concept is to merge high performance with bespoke design and aesthetics in a performance-based design process, where the performance requirements and the physical properties of light directly influence the geometry and shape of every single tile or facade element. This procedure uses a design feature to improve performance rather than decrease it, as it may happen in design-driven processes.

The concept assumes that different performances have different requirements and efficiency along with the facade height—Fig. 20. Daylighting, for example, is more efficient close to the ceiling. On the other hand, glare and clear views should be prioritized at the center of the floor-to-floor height. Regarding energy production, the PV area should be maximized equally over the entire height. Yet, the opacity of the PV may be maximized at the lower parts while gradually decreasing with the height to allow better daylighting.

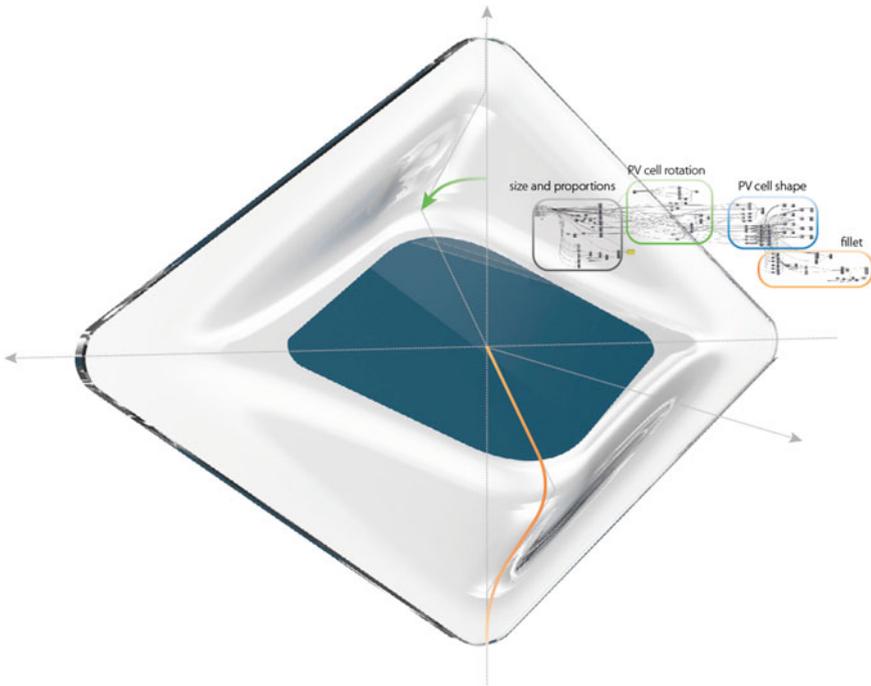


**Fig. 20** TIFAIN facade performance parameters and priorities

### 3.2 Design

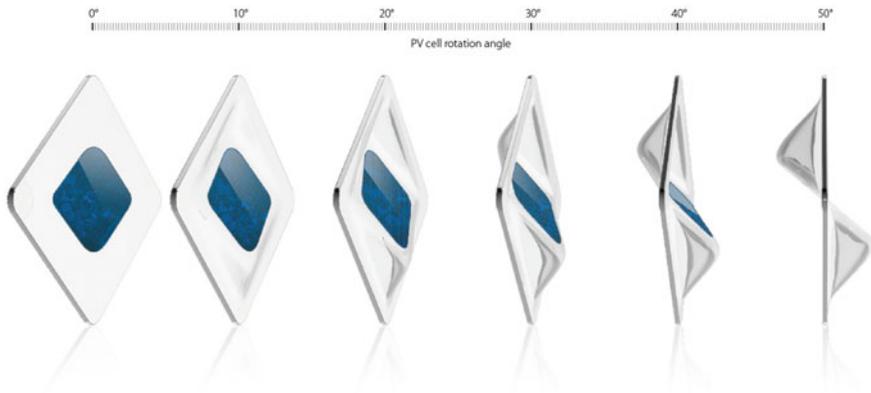
The design concept is based on a system of typological facade modules with distinct features and variable parameters. Specifically, the facade modules have a rhomboid-shaped glass, sometimes called diamond-shaped tiling, with an inner core, where a PV cell is placed. The inner core is defined as an offset from boundary rhomboid shape—Fig. 21. The core has a design feature of the PV rotation that creates a curved glass surface that emphasizes smooth reflections and creates a facade identity. This property also increases the PV energy generation, owing to the solar concentration on PV and better PV angle setting, as well as controlling the light deflection for improved daylighting and glare. The curved part seamlessly blends to the frame surface that is planar close to the edges. In this way, any module can be combined and placed next to any of the modules with different core rotations, or planar ones, while maintaining continuity of the surface. In the case of a transparent central area, the module functions only as a daylight redirecting device. At the same time, with the PV, it also becomes an active facade module that produces energy. This central area can be rotated at several predefined angles that characterize specific properties of each module, manifested in variable sun control in terms of reflection, transmission, and absorption of the PV cells.

Based on the different requirements, module layout can accommodate other modules to create functionally graded surfaces. Furthermore, the rotational design feature also allows aesthetic effects such as colors, transparency, surface curvature, and caustics. Due to the non-linear Fresnel reflectance, Sun incidence angle, and various module rotations, the facade surface can produce a highly dynamic caustic interior, similar to the underwater caustic effects. Therefore, the dynamic behavior of daylighting will make the interior an attractive artistic place to observe light phenomena of caustics, colors, and dispersion. Moreover, since modules can accommodate different PV cell technologies, facade surface integrity remains intact even

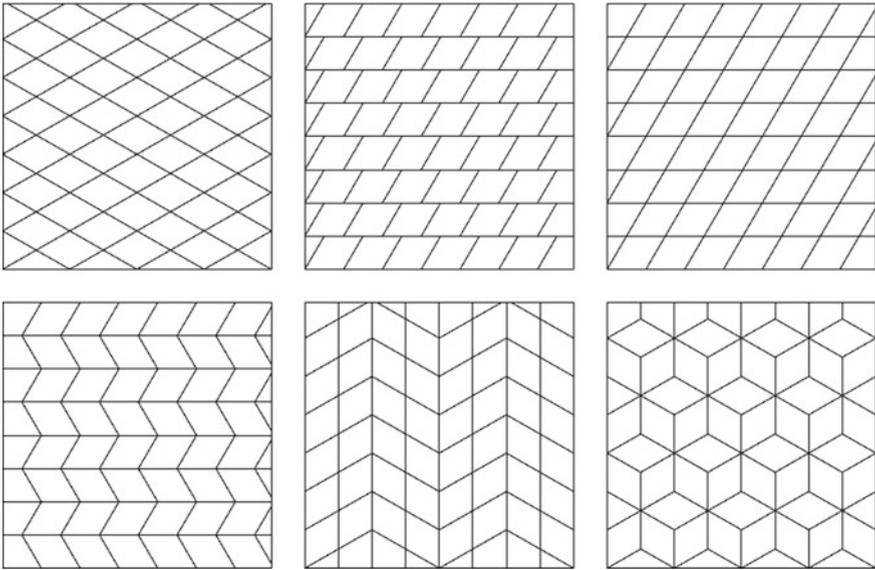


**Fig. 21** TIFAIN Diamond facade module

with a combination of PV cells on facades with different orientations to better suit particular irradiation potentials and efficiencies—Fig. 22.



**Fig. 22** Typology of facade modules



**Fig. 23** Tessellation strategies

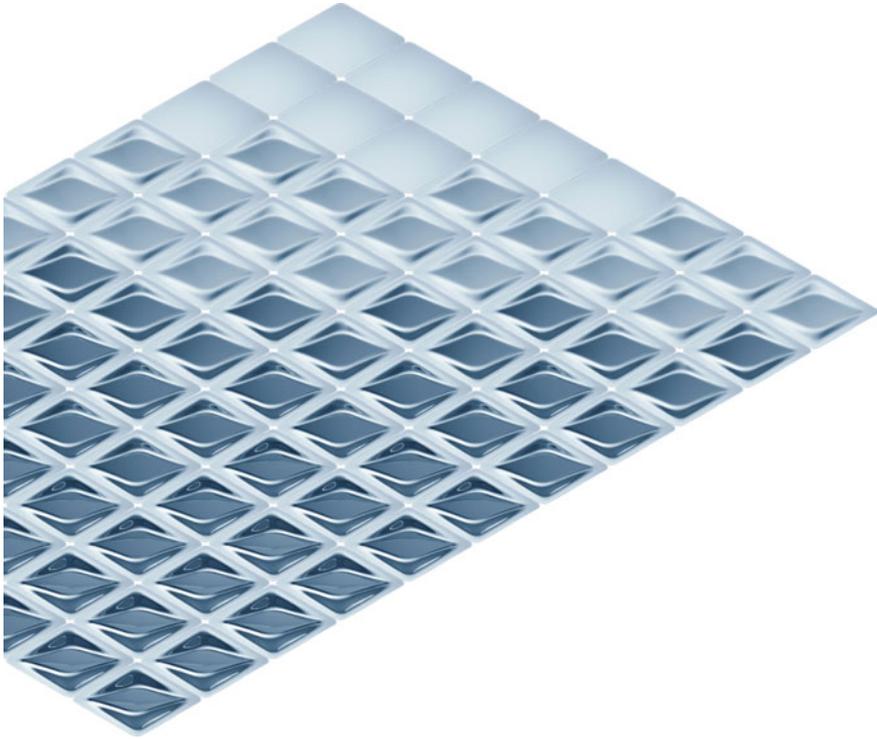
### 3.2.1 Layout

Modules come in standard rhomboid size, with 30 and 60 degrees. These angles allow various tessellation strategies: diamond, hexagonal, diagonal, etc.—Fig. 23. Since modules are planar around the edges, they can be fitted in standard glass frames. Therefore, every tessellation may be completed with common frames and joints. Diamond tessellation is chosen and used through the presentation to demonstrate layout variation potential for one tessellation strategy.

The standard size of the whole module series makes substitution and customization of layouts during design and operation possible. By combining only several modules with different PV technologies and rotation angles, it would be possible to create numerous layouts providing custom solutions for a specific urban context and climate, building owner requirements, as well as a particular end-user demand. Figure 24 shows a diamond tessellation with functionally graded modules ranging from planar at the top and 50 degrees rotation at the bottom. In this image, only reflections are shown to understand the curvatures of modules better and focus on gradient transition and local customization potential.

The layout assumes an equator facing a facade where the rotational axis of the core is placed horizontally. However, since there are many layout possibilities, the axis of module core rotation may be placed in other directions, for example, vertically on east or west facades, to allow effective solar control at the low Sun angles Fig. 25.

The layout placement of modules may be performed in multiple ways. Architects/designers may choose a layout based on an image where pixel properties drive



**Fig. 24** Diamond tessellation

the module placement. This is a purely artistic approach, and it may decrease overall performance due to the non-optimal settings. However, architects/designers may also implement machine learning strategies to define and choose optimal layouts based on previously set priorities. The third option is to manually coordinate placements by customizing previous approaches or selecting an arbitrary artistic strategy. In any way, layout strategy will always be in line with methodology and provide an integrative process where design and performance may constantly shift priorities and allow a flexible design process.

### ***3.3 Structure***

The cable net curtain wall is imagined as a facade layer that addresses multiple performances at various scales, from global to local. Furthermore, it is imagined as versatile, practical, and useful for the range of applications and project requirements. It can be used as the first layer of a ventilated or non-ventilated double-skin facades, suitable for new buildings or for adding a new layer in the case of refurbishing.



**Fig. 25** Layout rotation

The glass tiles can also be combined to form an Insulated Glazing Unit (IGU) or glass prisms, thus making it suitable for a single-layer curtain wall with a closed or ventilated cavity.

One of the possible structural systems is shown in Fig. 26. This concept uses a standard two-way cable system with crossing angles of  $60^\circ$  and  $30^\circ$ , following the rhomboid directions of the module shape. This supporting system defines a “diamond” tessellation pattern. The cables are designed to be pre-tensioned to withstand tensile forces greater than 1 MPa in both pressure and suction modes. Gravitational loads from the glass tiles are carried through the fittings in the nodes. Due to the custom crossing angle, fittings are custom-made as 4-part stainless steel casting to fix the intersecting cables of the net and support glass tiles in two opposite corners. At the same time, the other two are just held on for disabling rotation but allow in-service deflection—Fig. 26.

The cable net structures found their application firstly in materializing free-form shapes to decrease material weight and significantly reduce custom-cut elements and,



**Fig. 26** Cable net facade cut-out detail

therefore, the price. As long as tension principles are respected, the cable nets can be applied to any surface no matter of complexity, whether single or double curved (Zanelli and Campioli 2009). The cable net structure takes advantage of cable net minimal volume, thus avoiding dense grid aesthetics, typically caused by a glass-supporting aluminum or steel frame structure. Remarkably, the cable net minimizes the visible structure from the inside and outside and allows more light to enter the interior. Each cable is composed of cold-drawn wires twisted together in a wire strand. The strand consists of individual wires twisted about a central core wire. The wire rope is made by twisting the strand cables about a central core strand. The glass tiles are fastened to fittings through the patch plates and the silicon adhesive bonding, and additionally, they are supported from all four lateral sides—Fig. 27. This way of support creates a smooth and seamless-looking facade from the exterior side, emphasizing the curvature and reflections and making the transparency of glass the standout feature.



**Fig. 27** Structural fitting node detail

### 3.4 Glass

One of the most distinctive features of this concept is curved glass. Contrary to the standard float glass process that produces flat glass panels, the glass tiles here used are designed for the pressed glass production process (also called the hollow glass process). In this process, melted glass is injected into rotational molds and pressed to form a curved shape. Due to the imperfections caused by heat shock, the glass surface is always slightly wavy. This was one of the main issues in previous TIFAIN concepts, as tiny grooves had tension to distort and caused manufacturing imperfections. In this concept, this manufacturing property is used as a design feature as whole glass geometry is composed of curves, so imperfections work together with the shape to express fluidity and distorted reflections.

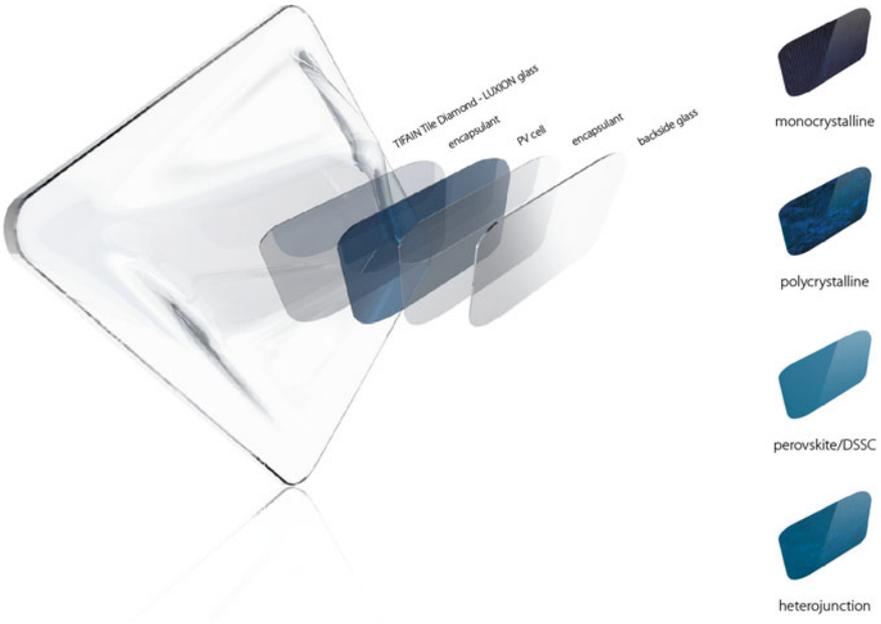
Moreover, a curved glass profile increases the strength against winds so that the glass thickness can be reduced compared to the standard float glass. This implies significantly less weight for the same mechanical strength. The glass is additionally heat-strengthened by the heat shock that causes pre-tension inside the glass. Considering the price, two glass processes could be comparable, meaning curve glass aesthetics comes at no additional cost. This is particularly attractive, knowing that bending and shaping flat glass drastically increase the price due to the excessive energy needed for heating the glass, even by order of magnitude. Therefore, the pressed glass process allows significant energy savings in production since there is no re-heating to get a curved shape. This leads to a much more environment-friendly solution, material reduction, and carbon reduction than the hot bend glass process. Furthermore, this innovative BIPV curved glass facade concept was specifically designed for LUXION® glass that is completely colorless and has the highest transparency on the market that exceeds 96%. This enables perfect reflections and transparency to maximize sun concentration on PV cells and deflection of the light for daylighting—Fig. 28.

### 3.5 PV

The central core of the glass tile is designed as a flat element, as the standard c-Si cells are rigid and do not support bending. However, the flat core also ideally allows the placing of other types of cells, for example, the second and third-generation ones, such as thin-film and Dye-sensitized solar cells. The uniform size of the PV area also enables mass production and customization, as one tile can be substituted with another. A variety of choices enables the versatility of this design concept to adjust the PV types according to the specific project and the budget requirements while keeping the design consistency. In other words, the PV integration is here imagined as a benefit for the concept and choice of the cells, and the amount of power that could be produced can significantly vary. The curved glass still works for the design and daylighting requirements without PV—Fig. 29.



**Fig. 28** Curved glass tiles



**Fig. 29** PV cell types

The rotational feature that creates the glass curvature was specifically designed to produce a semi-concentration effect and increase the amount of solar irradiation on the PV cell surface. Mainly used PV cell type c-Si is very sensitive to the angle setting. The rotation angle should generally correspond to the latitude of the project location and the orientation of the facade. Due to Lambert's cosine law and Fresnel effect (Jakica and Zanelli 2014), and the highly optimized PV cell structure that captures light best at perpendicular incidence angle, rotation of PV cell to optimize sun incident angle means that only slight adjustments to the angle would produce much better performance, increasing PV energy potential and generation (Jakica and Zanelli 2015a, 2015b). Therefore, the rotational design feature provides flexibility for the vertical facade to use favorable angle settings for particular latitudes.

A study was conducted for the Milan climate to assess PV potential for different facade orientations and module core rotations throughout the year. Results have shown that there is a significant increase in PV potential, particularly for 50 degrees rotation. Cumulative irradiation for the south-facing facade showed the highest PV potential increase of 50% compared to the flat vertical module—Fig. 30. Consequently, this solution can produce the same energy as the standard flat glass BIPV vertical facade with less PV surface and significant cost savings. Moreover, as the ratio of opaque vs. transparent parts is much higher in favor of transparency, this concept directly improves daylighting and clear views.

### 3.6 Conclusions

The TIFAIN Diamond concept aims to innovate within an interdisciplinary context and propose a unique hybrid type of lightweight BIPV facade. It demonstrates a method of transferring multi-criteria requirements from design and performance realms into digital working data that could be handled with the parametric and computational approach. This data-driven methodology effectively manages various criteria, thus reaching the main objective—a high-performing and high-aesthetic facade solution that actively contributes to the Building Energy Balance.

Despite significant improvements in design and performance, this concept is still in the prototype phase. It requires prototyping and testing to improve operational and maintenance performance. Furthermore, it requires innovative solutions, particularly in electrical wiring, nano-inverters, and batteries, to improve energy conversion, transfer, and storage or grid connection. On the other hand, prototyping and testing would uncover possible installing and operational issues, specifically placing new and replacing individual malfunctioning modules, cleaning and maintaining airtightness, wind resistance, and dynamical behavior under wind loads.

Due to the specific requirements from the project partners concerning production, this concept explores only pressed glass modules with limits in the dimension of around 50 cm. Overcoming this limitation in either blending modules in post-production, increasing mold size, or considering custom molding during the float glass process would additionally improve aesthetics and performance. It will

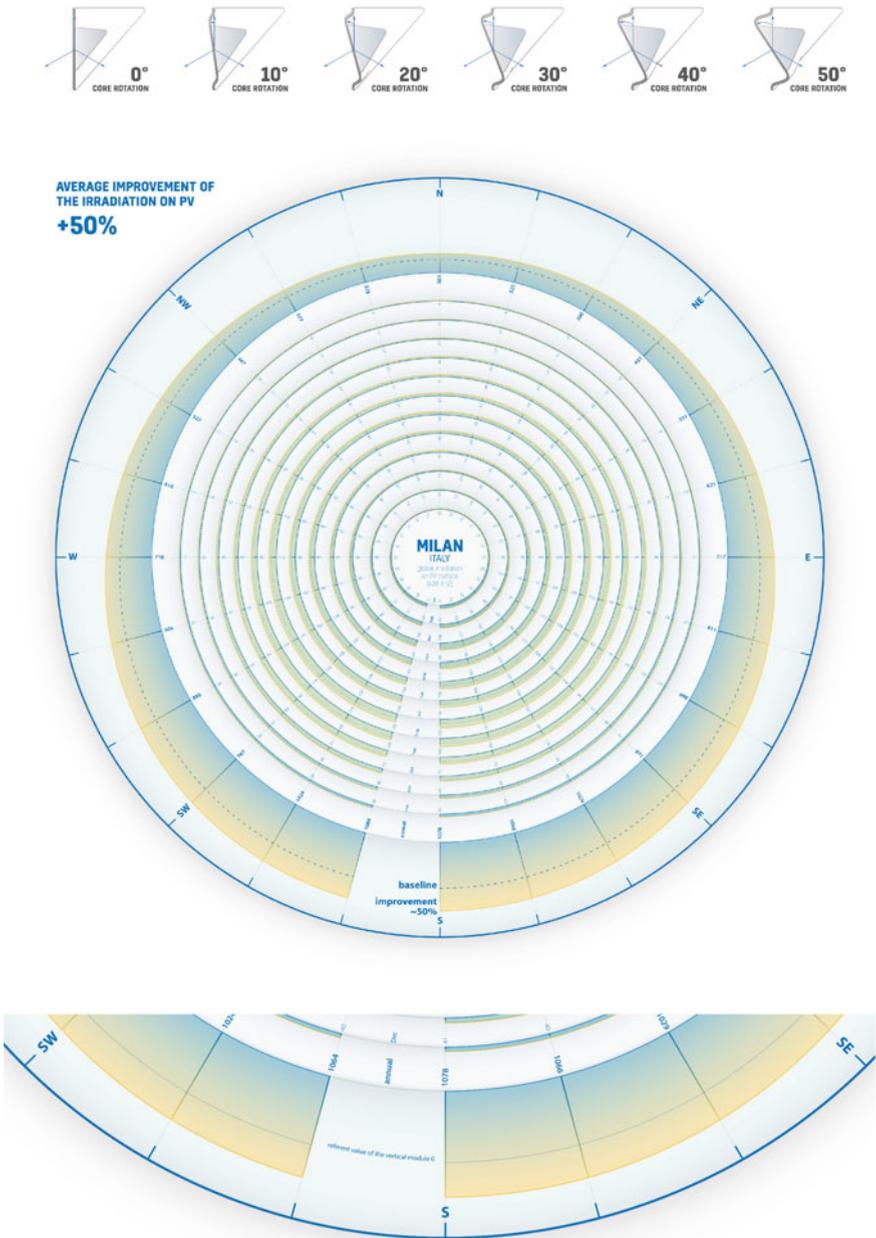


Fig. 30 Performance assessment for the Milan climate



**Fig. 31** TIFAIN diamond facade exterior view

also allow creating multiple single or multi-layer solutions for cavity closed, air-ventilated, and insulating glazing facades. Authors believe that only such a hybrid concept together with numerous design customization options for a relatively small price tag that matches one of the standard cable nets can boost the application of BIPV, addressing the high-energy demands—Fig. 31.

## 4 Conclusions

The project TIFAIN addressed a broad range of performances, paving the way toward an integrated design methodology for BIPV facades. The progress was made from the original Tile 1 design toward TIFAIN Diamond that improved both design and performance. Multiple experimental tests were carried out on small and 1:1 scales to validate simulations and demonstrate manufacturing feasibility.

However, limited timeframe, budget, and production capacity have imposed barriers to the large-scale implementation and extensive testing of all three prototypes. With the demonstrated potential, the TIFAIN BIPV facade showcases the complexity and beauty of high-tech facades and buildings. The authors believe that there will be more projects and developments based on this methodology to secure a successful transition toward renewable energy sources for a sustainable future in the near future.

**Acknowledgements** This work was supported by the Lombardy Region and the Italian Ministry of Education, Universities and Research (MIUR) under grant number 30221157 (TIFAIN project, 2014–2016).

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# Case Study: Fog and Dew Net



Di Bitonto Maria Giovanna

**Abstract** The chapter aims to analyze fog and dew harvesting's system as a possible solution to deal with the water issue in different territories. This phenomenon appears to be a powerful and efficient alternative water resource. The aim is to present a comparison between two areas that are characterized by the fog phenomenon, Chile and Italy. Chile is the leading country experimenting with fog harvesting projects; therefore, to apply this technology in other locations, it is relevant to study the climatic and geographical characteristics that permit fog formation and the factors that determine fog collector device efficiency. From this analysis emerged that the fog phenomenon results in very different characteristics in the two analyzed locations. Therefore, its collection process may vary. While in Chile, the system deals properly with fog collection in Chile, it should work with dew collection in Italy. Consequently, thanks to some meteorological calculations, a theoretical investigation about dew collection in Milan has been developed, as a means to understand if dew collection in Milan could be as efficient as fog collection in Chañaral, evaluating the potentialities of two different climatic regions, affected by two other fog phenomena. Moreover, the structural system has been studied to develop an experimental project related to a master thesis dealing with the dew collection in Milan. Furthermore, on-site and in the lab, the investigation is still ongoing, thanks to the European project Cost Action (CA17107).

**Keywords** Water issue · Fog and dew phenomena · Meteorological analysis and calculations of Po's Valley fog

## 1 Fog and Dew Harvesting

In a scenario of unpredictable water provision, water vapor collection represents an alternative solution to face the hydric crisis. This system can collect water from the air. To preserve global water supplies and relieve the stress upon conventional

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and over-exploited freshwater sources, fog and dew harvesting devices stand as a promising yet relatively unexplored solution.

Some areas of the world are characterized by an intense fog phenomenon called *oasis de niebla*. Some of them are located in the most critical hydric conditions areas. In contrast, other territories will face this hydric struggle in the following years due to climatic changes and anthropic demand. Since ancient times, we can observe several techniques to exploit the phenomenon and produce water in these oases. These fog collectors are called *atrapaniebla*. They are a tensile-textile structure made of mesh and supporting poles and cables.

Over time, various fog collectors, also called *atrapanieblas*, have been tested to maximize fog water capture. Generally, the model most applied worldwide is the Chilean type (designed by Fog Quest), a tensile bi-dimensional structure composed of a mesh, two poles, and tensors. Most of the other kinds of fog collectors are still at an experimental level. Dew collectors are very little explored. Commonly, they form a separate and different structure from the fog collectors and are composed of a waterproof membrane on inclined planes.

The challenging requirements for fog and dew collectors concern:

- (a) the study of the phenomena characteristics;
- (b) the structural shape, regarding exposition, wind flows, and resistance;
- (c) the relation between fog and dew collectors should be explored.

Since the tremendous potentiality of fog and dew harvesting, a research question arises:

How can technology be developed to preserve the environment, society, and the economy in the coming years, in which the effects of climate change will be increasingly evident and devastating?

Currently, the *atrapaniebla* is used in desertic areas (in an approximate and primordial way). Instead, it would be interesting to apply it in regions with a more temperate climate, inevitably facing a water crisis in the coming years.

Moreover, nowadays, this system is conveyed to an individual instrument. It is exciting its integration in construction to make a building self-sufficient in terms of water demand. Furthermore, it would be helpful to combine two currently different tools, fog and dew collectors, because phenomena are closely linked.

So, the ultimate aim of this project is to develop a performative textile architecture applicable in various fields of climate contexts, which incorporate the collection of fog and dew.

The research objective is developed through a methodological structure that involves the study of the existing literature. Once the critical points of the current technique are learned, such as mesh and structure efficiency, a new system will be developed, following a path of material-driven design and simulation-driven design, thanks to the use of parametric tools integrated with field test data analysis.

The work plan is developed in three sections. The first is focused on a deep investigation on climatic conditions and data analysis and cross-comparison; the second is dedicated to the literature study, especially concerning mesh and structure design; and finally, the design of a new innovative model.

## 2 Climatic Analysis

In Chile, the research on the fog phenomenon is developed both theoretically and experimentally, although there is a limited number of application projects. Instead, in Italy, the research concerning fog and dew formation is still very modest. It is not possible to rely on data derived from experiments yet. Therefore, a theoretical evaluation of fog presence or absence has been determined. These calculations are based on data provided by the ARPA Lombardia.

Camanchaca (Chilean fog) and Po's Valley fog are different in many aspects, both for their physical characteristics and how the water can be collected.

Fog is the meteorological phenomenon for which a cloud is formed in contact with the earth's surface. It consists of droplets of liquid water or ice crystals suspended in the air. Due to the diffusion of sunlight by the suspended water, the fog manifests itself as a whitish halo that limits the visibility of objects.

When solar radiation comes into play, the temperature rises, exceeding the dew point, and then, the liquid water in the humid air evaporates.

Due to the presence of intense winds, the capture of fog water in Chile is purely mechanical. In condensation conditions (verified by the experiments carried out on-site by *Centro del Desierto de Atacama*), the condensed vapor droplets are deposited on the mesh where the filaments intercept them, flow by gravity toward the collecting channel, and are then stored (Cereceda et al. 2011). Therefore, the efficiency of the collection depends on the presence of the winds, the diameter of the droplets, the diameter of the filaments, and the percentage of shading of the mesh. It has been verified that the optimal conditions occur with a droplet diameter of about 11  $\mu\text{m}$  and a wind speed between 3.5 and 6.5 m/s (Schemenauer 2015). In Milan, however, the rate of the winds is much lower, with an annual average of about 2 m/s, besides the size of the condensate droplets is not documented.

Based on that, for this study, in Milan, the capture depends only on dew formation on the mesh. To appear, the temperature of the mesh must be lower than the dew point. In contrast, in Chile, water particles are already present in the air and are captured because dragged by the wind through the mesh filaments. The study aims to find whether and how dew capture is possible in Milan weather conditions.

### 2.1 Methodology

To verify the possibility to apply the dew harvesting system in Milan, in Piazza d'Armi, a simplified physical model for a dew harvesting vertical mesh was developed. Its design will be better explained in the following section. First, it is essential to understand its efficiency. The metropolitan city of Milan is part of the Pianura Padana, the most extensive valley in Italy, characterized by a humid terrain due to the presence of many rivers such as Po river.

On one side, climatic data were processed to determine dew point temperature during the year. On the other side, an energy balance equation for the mesh was set to evaluate the surface temperature. Condensation on the fabric was considered to occur whenever the mesh temperature was lower than the dew point temperature (Di Bitonto et al. 2020). In this case, the condensation rate was roughly estimated from the wind speed.

Night hours are the ones taken into consideration because solar radiation causes the temperature to rise, and therefore, the dew point is more likely exceeded. At first, the months taken into examination correspond to the winter season (October–March) because the average temperature is lower. Therefore, the temperature can quickly drop below the dew point and so inclined at dew formation. Subsequently, as favorable results were also noted in March and October, the analysis has been extended throughout the year.

The yearly weather data taken into considerations are of two types: The first is a standard meteorological year for Milan, namely composed of months considered “typical” for their characteristics, and derives from an analysis that goes from 1984 to 1996; the second year corresponds to 2018, and data from ARPA station in Milan, Zavattari, have been chosen to analyze also a more recent period to have a comparison.

### Psychrometric Calculations

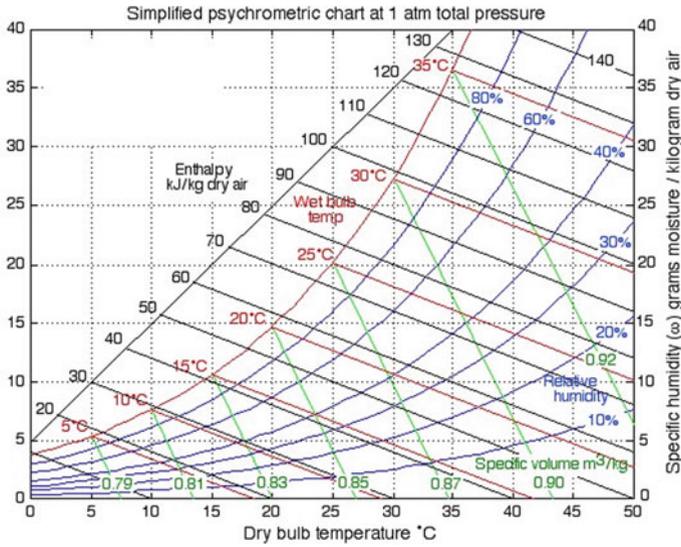
To verify the presence of dew, it is necessary to analyze the status of the humid air. The Carrier Diagram (also called psychrometric chart or Grosvenor diagram) is frequently used to determine the properties of a water–air mixture at constant pressure. Therefore, the diagram can be considered a graphic representation of state equations. The diagram is used to graphically estimate the characteristic of the mixture (dry air + steam) subjected to a thermodynamic transformation with constant pressure. The X-axis corresponds to dry air conditions (TBS), while the Y-axis to specific humidity. In the psychrometric diagram, the line of saturation (that corresponds to 100% relative humidity) separates the “fog zone” (where the system consists of air saturated of water and liquid water dispersed in it, in the form of tiny drops or aerosols) to the area of unsaturated air (where the system consists in a mixture of dry air and water vapor) (Fig. 1).

The graphic procedure indicated by the psychrometric diagram has been translated into formulas to speed up the verification process. The determination of the dew point temperature allows the detection of the temperature ( $T_x$ ) at which the mesh should be in order to have condensation (temperature below dew point).

In this section, the process is described; the calculations have been developed with Microsoft Excel, based on UNI EN 13,786.

Firstly, the saturated vapor pressure  $p_{vs}$  [Pa] is calculated. It is the maximum pressure achievable for vapor at a given temperature; in this situation, the liquid substance is in equilibrium with its vapor independently of the air pressure, because its molecules do not interact with those of the steam.

In addition, the saturated vapor pressure increases in relation to temperature increasing. In fact, as the temperature rises, molecules acquire higher kinetic energy and are more likely to evaporate. The following empirical equations from UNI EN



**Fig. 1** The psychrometric chart (Source Redmond R. Shamshiri, A lecture note on Ideal levels of Vapor Pressure Deficit in Greenhouse Production, 2014)

13,786 relating  $p_{vs}$  with the dry bulb temperature  $T_{DB}$  are used:

$$\text{If } T_{DB} > 0^{\circ}\text{C} : p_{vs}(T_{DB}) = 610.5e^{\frac{17.269 \cdot T_{DB}}{237.3 + T_{DB}}} \quad (1)$$

$$\text{If } T_{DB} < 0^{\circ}\text{C} : p_{vs}(T_{DB}) 610.5e^{\frac{21.875 \cdot T_{DB}}{265.5 + T_{DB}}} \quad (2)$$

From the relative humidity RH [%] and the saturated vapor pressure  $p_{vs}$ , the vapor pressure  $p_v$  [Pa] is calculated as:

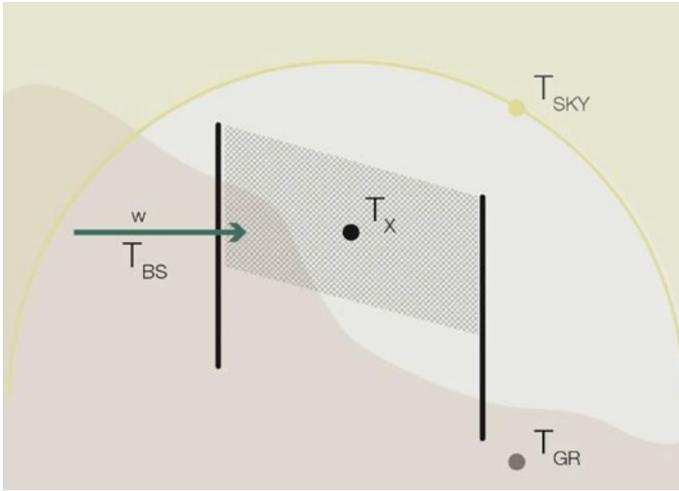
$$p_v = RH * p_{sv}(T_{BS}) \quad (3)$$

Then, the dew point temperature  $T_{DP}$  [°C] is obtained by reversing Eqs. (1) or (2).

$$T_{dp} = \frac{-237.3}{\left(1 - \frac{17.263}{\ln \ln \left(\frac{p_v}{610.5}\right)}\right)} \quad (4)$$

**Energy balance equation for the mesh**

As depicted in Fig. 2, the mesh is modeled as a vertical plane exchanging heat by convection with the air and by radiation with the sky and the ground. We remark that the balance is performed during the night; therefore, there is no solar radiation.



**Fig. 2** Exchanging flows between the mesh and the environment (Edited by the author)

Then, the mesh temperature ( $T_X$ ) is determined as a function of the air temperature ( $T_{DB}$ ), the sky temperature ( $T_{SKY}$ ), and the ground temperature ( $T_{GR}$ ).

The sky temperature [K] is calculated according to the following correlation:

$$T_{SKY} = 0.0552 * (T_{BS} + 273.15)^{\frac{3}{2}} \tag{5}$$

while for the sake of simplicity, the ground temperature is assumed equal to the air temperature.

The energy balance equation at the equilibrium is an algebraic equation of the 4th degree, where the three heat flows are balanced to zero:

$$\sum_K \varphi_K = 0 \tag{6}$$

$$\varphi_{CONV} + \varphi_{RAD,SKY} + \varphi_{RAD,GR} = 0 \tag{7}$$

$$h_{cv}(T_X - T_{BS}) + \varepsilon\sigma F_{X,SKY}(T_X^4 - T_{SKY}^4) + \varepsilon\sigma F_{X,GR}(T_X^4 - T_{GR}^4) = 0 \tag{8}$$

In Eq. (8):

- $h_{cv}$  is the convective coefficient [W/(m<sup>2</sup>.K)], which can be calculated from the wind speed  $w$  [m/s] with the following correlation:

$$h_{cv} = (4 + 4) * w \tag{9}$$

- $\varepsilon$  is the mesh emissivity, equal to 0.9;
- $\sigma$  is the constant of Stefan–Boltzmann equal to  $5.67 \bullet 10^{-8}$  W/(m<sup>2</sup>.K<sup>4</sup>);
- $F_{X,SKY}$  and  $F_{X,GR}$  are the mesh to sky and mesh to ground view factors, respectively; the view factor can vary from 0 to 1; and in this case, due to the vertical orientation of the mesh, the factors are both equal to 0.5.

Equation (8) can be simplified to:

$$AT_x^4 + BT_x + C = 0 \quad (10)$$

where:

$$A = \varepsilon\sigma(F_{X,SKY} + F_{X,GR}) \quad (11)$$

$$B = h_{cv} \quad (12)$$

$$C = -h_{cv}T_{BS} - \varepsilon\sigma[F_{X,SKY} * T_{SKY}^4 + F_{X,GR} * T_{GR}^4] \quad (13)$$

### Condensation rate

Once the presence of condensation has been identified, that is when  $0 < T_X < T_r$ , also setting  $T_X > 0$  °C to exclude frost phenomena that would lead to mesh properties reduction and therefore annul the harvest, the condensed flow per unit mesh surface  $m_c$  [kg/s/m<sup>2</sup>] is calculated assuming that unsaturated air enters the mesh at the wind velocity and leaves it in saturated conditions, namely:

$$\dot{m}_c = \dot{m} * (x_A - x_X) \quad (14)$$

where

- $m$  is the airflow across the unit mesh surface roughly estimated assuming that the wind flows perpendicular to the mesh through the pores

$$\dot{m} = \rho * w \quad (15)$$

- with  $\rho$  the air density, taken equal to 1,2 kg/m<sup>3</sup>;
- $x_A$  and  $x_X$  indicate the air-specific humidity and saturated air-specific humidity calculated as (Fig. 3):

$$x_A = 0.622 * \frac{pv}{(p - pv)} \quad (16)$$

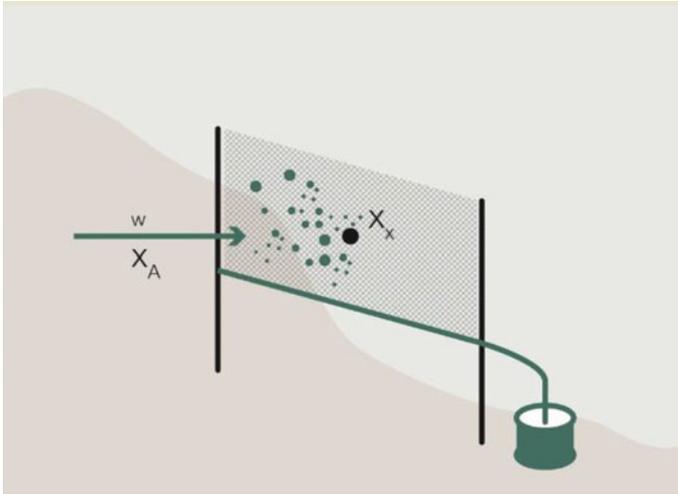


Fig. 3 Condensation process (Edited by the author)

$$x_x = 0.622 * \frac{pvs}{(p - pvs)} \quad (17)$$

with  $p$  indicating the atmospheric pressure corresponding to 101,325 Pa.

## 2.2 Results and Discussion

The results obtained show that by the Eq. (1–13) the primary condition has been verified: The temperature of the mesh cannot be higher than the air temperature, nor less than the sky temperature. Figure 4, where the temperature of the mesh and the dew point is compared, shows that dew collection can be obtained when the temperature of the mesh is lower than the dew point; therefore, winter season is the most favorable for dew harvesting.

In the following figures (Figs. 4 and 5), just the analyses that outcome from the year 2018 are shown, that is due to a doubtful result in the calculations of the “typical year”; in fact, it has demonstrated optimal results also during the summer period, and that is a very unlikely condition. These results in both years perhaps depend on an excessive simplification of the methodology, and for sure, more likely results will be registered with the on-site empirical investigation.

The results obtained in 2018 (Fig. 5b) show an annual water collection capacity of about  $600 \text{ kg/m}^2$ . This result from the equations was compared with the amount of fog water collected in Chile annually, that is  $550 \text{ kg/m}^2$  (Fig. 5a) (Larrain et al., 2001). Although the study areas belong to completely different climatic and social

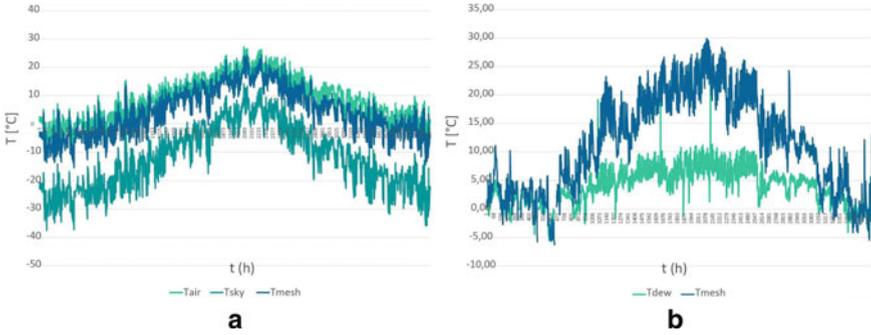


Fig. 4 a Comparison of temperatures (Edited by the author); b dew formation (Edited by the author)

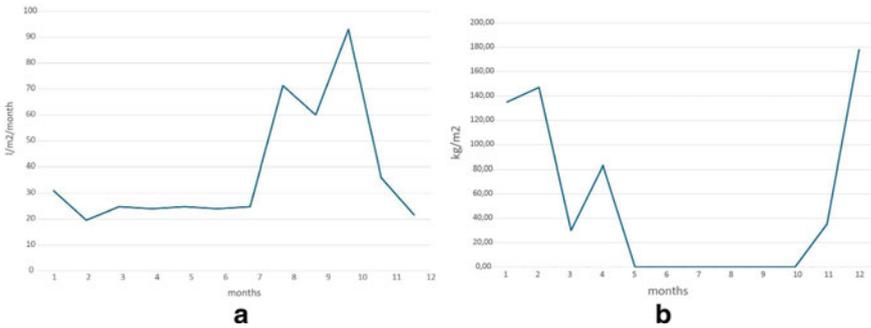


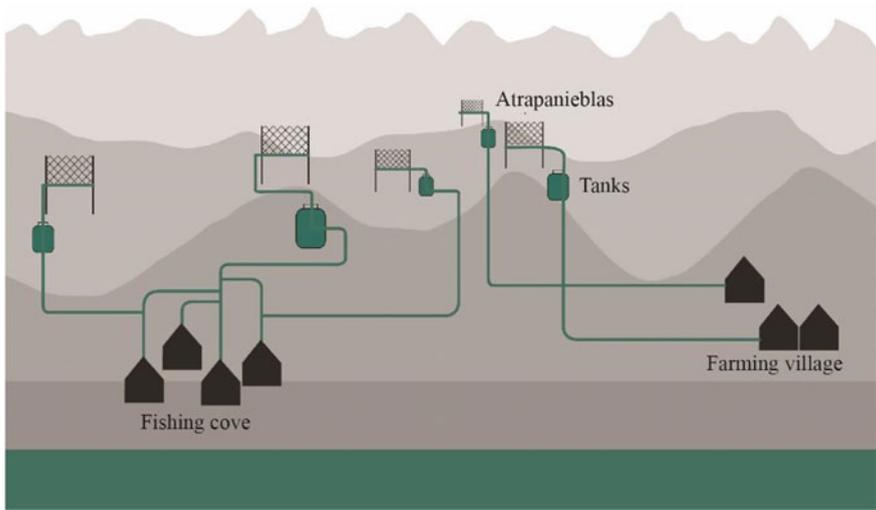
Fig. 5 a Camanchaca formation during the year, Chañaral (Edited by the author); b dew formation during the year, Milan (Edited by the author)

contexts, both have demonstrated the potential for the operation of vapor harvesting systems, for the capture of fog water in the Chilean case and dew water in the case of Milan.

It is also interesting to note that the two formations have different origins. Moreover, one is present throughout the year, with a more or less constant collection (Chañaral), while the other (Milan) presents the phenomenon only during winter and in particular conditions. Therefore, the harvest is limited only to a season of the year, which unfortunately corresponds to that which has less water, thus presenting seasonal peaks of yield much higher than those of Chile.

### 3 Technology and Applications

The so-called *atrapaniebla* captures the tiny drops of water contained in the mist and stores them in liquid form. The atmospheric water vapor contained in the air, through the condensation process, is deposited on the cold surfaces of the *atrapaniebla* mesh,



**Fig. 6** Water distribution system (Edited by the author based on the *Source* Gobierno de Chile, Oasis de niebla Alto Patache)

naturally forming drops of water. However, when encountering “obstacles,” the fog follows its path until evaporation (Cereceda et al. 2014) (Fig. 6).

### 3.1 Components

A Fog Water Reception System is composed of:

- (i) *atrapaniebla*, a hydraulic system (from the *atrapaniebla* to tanks),
- (ii) tanks
- (iii) conduction system (from tanks to the consumption places).

Water storage is necessary because fog is discontinuous, and usually, the formation periods do not coincide with the consumption needs. Storage may be short term to compensate for differences between water reception and consumption in cycles of one week or one month, or long-term, considering the annual cycle.

The *atrapaniebla* consists of a textile mesh, a support structure, and a channel at the bottom of the mesh, toward which the water drips by gravity.

#### Elements

Over the years, various types of *atrapaniebla* have been tested to maximize the capture of fog water. There are two main types of *atrapaniebla*: two-dimensional and three-dimensional. A further subdivision depends on the kind of anchoring of the mesh to the structure: those with a rigid frame structural support or the tensile structures (Cereceda, et al., 2014).

In *atrapanieblas* with rigid frame supports, the surface of “capture” is stretched using a continuous fixing to the structure. Instead of the *atrapanieblas* tensile structure, only the vertical poles are rigid elements. In contrast, all the other parts are hollow and knitted tensioned.

*Two-dimensional Atrapanieblas:*

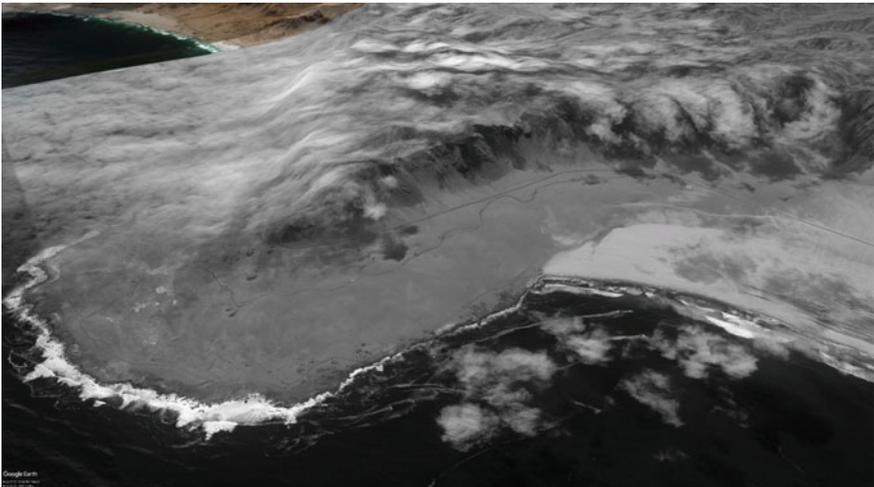
These are the most installed worldwide and are generally applied when there is the main wind direction. The arrangement depends on the physical conditions of the place and the wind. These are characterized by structures consisting of a catching surface (mesh raschel or similar), framed or stretched in two poles so that it lies perpendicular to the direction of the wind. These models vary in size, materiality in mounting ground solutions, and mesh anchoring system.

These solutions are economical and straightforward but present problems, for example, the rupture of the mesh or the structural stability due to strong winds (Fig. 7).

*Three-dimensional Atrapanieblas:*

Three-dimensional *atrapanieblas* are less common, primarily associated with research experiments, which seek solutions to optimize the yield of the harvest and, in some cases, optimize the structural stability compared to the strong winds. Generally, they are applied when there is no main wind direction, so they are looser in positioning. Therefore, they can offer various fronts of fog water capture surfaces; on the other hand, the three-dimensional structure makes them a much more stable system in case of wind gusts, also when there is a principal direction (Fig. 8).

Nowadays, the most used capture system was designed by Fog Quest in 1980. It is the *atrapaniebla* (two-dimensional) collector, efficient and easy to build, and reaches a height of 6 m and a width of 10; its structure consists of two stainless steel



**Fig. 7** Falda Verde project, bi-dimensional fog collectors, Chañaral, Chile (Edited by the author on the source Google Earth)

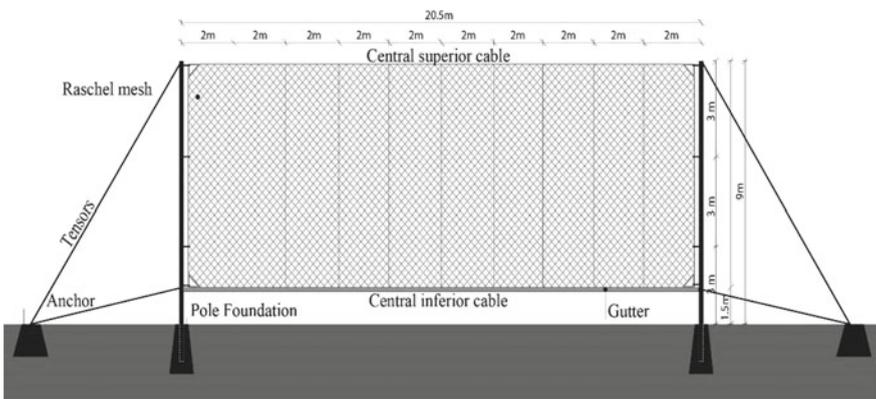


**Fig. 8** Nieblagua project, tridimensional fog collectors, Islas Canarias (Source Nieblagua, <http://www.nieblagua.com/>)

pillars, or pine, which support a mesh raschel with 35% shading and the size of 4 × 10 m; and this is tightened by steel cables connected to the pillars that are fixed with steel tensors to the ground (Cereceda, et al., 2014) (Fig. 9).

**Operation principle and collection efficiency**

Harvesting performance depends on three factors: aerodynamic efficiency, storage efficiency, and drainage efficiency (Rivera, 2011).



**Fig. 9** Fog Quest atrapaniebla standard (Edited by the author on the source Pilar Cereceda et al. 2014)

To understand the aerodynamic efficiency of the collection, it must be taken into account that the mesh is an obstacle to the flow of the fog. Therefore, part of the flow will pass around the mesh. The fraction of fog passing through the mesh depends on its permeability (which is the inverse function of the shading coefficient) and on the characteristics of the mesh fabric; on the other hand, the quantity of water drops deposited on the filaments of the mesh is a direct function of the shading fraction.

Concerning mesh productivity, there is an optimal shadow fraction for each type of mesh. If it consists of a few drops, it will settle on the filaments, while the first droplets will saturate the passage if it is tiny. The deposition efficiency considers that the water drops follow the airflow lines and then pass around the filaments.

Capture mechanisms are more efficient if the diameter of the filament is in the order of the volume of the drops, which are between 1 and 20  $\mu\text{m}$  in diameter. Therefore, the mesh should have the filaments as thin as possible. However, there are two main limitations to the thickness of the filaments. The most obvious is that by decreasing its diameter by the same shading coefficient, the mechanical strength of the mesh decreases. The second limitation is that keeping the coefficient of shading constant and reducing the diameter of the filaments also decrease the volume of the openings between them (Park et al. 2013).

Ultimately, the drainage efficiency is defined as the difference between the water that reaches the storage tank and the one that has settled on the mesh.

The losses are produced due to the action of the wind. When the mesh is convex, the water deposited does not flow to the collection channel but falls to the ground. Finally, these losses can be due to malfunction of the canal, if it is poorly positioned or if it has holes (Park et al. 2013).

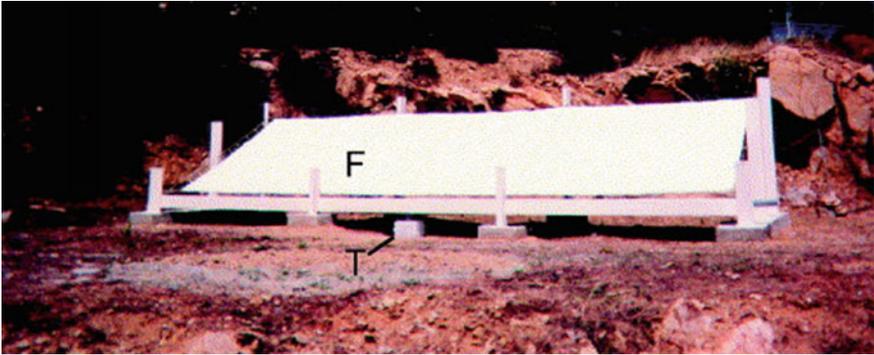
### **3.2 Dew Collectors**

Concerning dew collection, new technologies differ considerably from older ones. Thanks to a significant improvement in the physical behavior of condensation on surfaces, it was possible to develop captors made of lighter and more efficient plastic film (Alton et al., 2003). These achievements have emerged valuable insights on dew harvesting: favorable conditions for condensation, materials, and substrates that give high production levels. Many research and technical experiments have tried to identify the attributes of a good collector and the most efficient way to build it.

These studies indicate that the “ideal condenser” should have similar behavior to the lawn, then be a lightweight film thermally insulated from the massive part of the ground, and be exposed without hindrance to the reception of dew above it (e.g., trees), (Sharan 2006).

In addition, the condenser should stay away from surfaces that can reflect its radiation (such as dark surfaces or water mirrors) to minimize the greenhouse effect, so films should be of a light color.

An important factor is the location of the condenser, and particularly, windy areas and those where the radiation is intense should be avoided. To obtain rapid cooling,



**Fig. 10** Dew collector, Ajaccio, France (Source Marc Muselli et al. Dew water collector for potable water in Ajaccio, Corsica Island, France, 2002)

and thus to prevent evaporation of the collected dew, the surfaces must have a high degree of emissivity with a low thermal mass, then have a small thickness, and be supported by insulation at the bottom to avoid an increase in temperature due to ground emissions. Another aspect is the inclination of the panel. The ideal inclination to slide the collected water toward the eaves was  $30^\circ$  (Beysens et al. 2006, 2007; Clus et al. 2009).

The majority of "dew catchers" are built for research purposes, and they are mainly composed of four parts: panel, frame, drip, and accessories. They are generally formed by a membrane located on a rigid support, almost in a horizontal position (Fig. 10).

### 3.3 Innovations

In the development of new models of *atrapaniebla*, innovative research opens up new frontiers for innovation. The main objective is optimization in functional, productive, economic, and sustainability aspects.

In this context, it has been possible to determine a set of design factors that allow us to understand and develop *atrapanieblas* as a highly efficient integral system. Indeed, increasing the harvesting area would be helpful, but we must consider the contraindications, less resistance of the structure and the mesh.

#### Efficiency in water collection

Materials and design are the main challenges to being able to increase the efficiency of water collection. The design factors should be considered related to the mesh design and therefore to the efficiencies mentioned above: aerodynamic, storage, and drainage, which involve a study of the weaving and the materials that make up the mesh.

In addition, the orientation of the mesh surface concerning the wind direction shall be taken into account.

Moreover, to increase the efficiency of the collection system, it is necessary to consider the design of the channeling and storage systems, making them more resistant to wind forces and radiation, both for the durability of the materials and the quality of water.

### **Efficiency in the structure (in case of strong winds)**

The pressure of the wind on the mesh has a consistent impact, which implies a great challenge for its structural stability. The *atrapanieblas* are exposed to very violent gusts of wind that can suffer severe damage to both the mesh and the structure. The aim in these cases is to make the structure as stable as possible, experimenting with different materials and different types of foundations for the poles and anchoring for the tensors. In addition, it would be helpful to find systems that can decrease the pressure of the wind on the mesh, such as reducing its size or making the mesh with more resistant materials.

This research and the following experimental project aimed to combine the qualities that fog and a dew collector must have, looking for a unique model, which can be applied and function in both conditions. Fog and dew originate from the exact mechanism, and it is difficult to predict if the phenomena will form simultaneously. There can be dew without fog, but never the opposite.

## **4 Project Development**

The experimental project presented in the following pages is the result of a double degree course at Pontificia Universidad Católica de Chile and Politecnico di Milano.

The project developed in Chile, precisely in Chañaral, Falda Verde, results from an investigation related to fog harvesting. First of all, the site's climatic conditions have been studied, which permits the system to work, and then, once defined the characteristics which a fog harvesting device should present, a model has been designed. This acquired knowledge has been related to investigating Italian climatic conditions, Po's Valley fog and dew, and the study of collector characteristics that may lead to new experiments. Therefore, the same project has been adjusted. To make it work in both conditions, the final result in Milan's periphery is presented.

### **Site**

The Municipality 7 is located in the west of Milan and has the largest number of green areas in the whole city of Milan. In fact, its territory includes the Parco delle Cave, the Bosco in Città, Parco di Tenno, Parco di Baggio, Parco di Valsesia, Parco di Annarumma, and Parco del Centenario.

The project area is the Piazza D'armi, a site of historical value that is currently in a state of abandonment. For this reason, in the area, the association "Le Giardinieri" is active in its defense, with President M.Castiglioni and Vice President V. Bacchelli.

The urban space now occupied by Piazza d'Armi, the Santa Barbara Barracks, and the Military Hospital of Milan extends on a surface that borders to the north with Via Novara, including Via delle Forze Armate. These two roads, whose existence has been witnessed for centuries, confirm the area's historical importance.

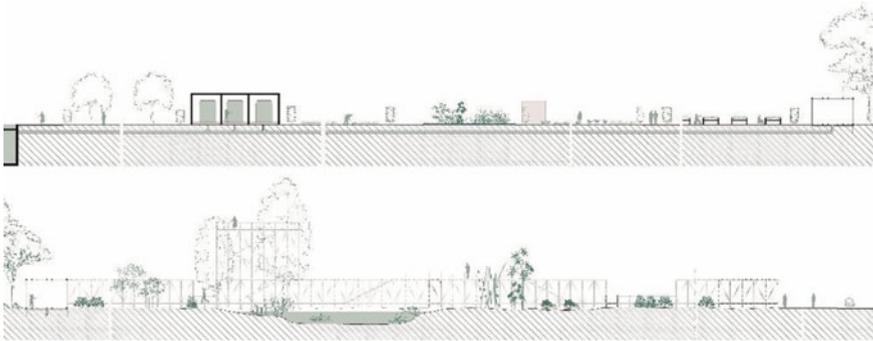
**Masterplan**

The functional program considered in the development of the master plan followed the project proposals in progress, particularly on maintaining and spontaneous urban gardens present (Fig. 11).

The main point has been maintaining the green character of the area. This means that the absorbent and waterproof spaces remain unchanged between the state of fact and project (83% permeable and 17% waterproof). This is of fundamental importance to allow the water present in the soil to evaporate and, therefore, form fog or



**Fig. 11** Piazza D'Armi masterplan (Edited by the author)



**Fig. 12** Piazza D'Armi sections (Edited by the author)

dew, depending on the case. As previously illustrated, fog in this area is formed by radiation.

The square can currently be considered an island that the city cannot reach, so the project provides pedestrian paths that connect this square to a system of parks and functions present in the area. The paths just mentioned will be marked by the fog and dew harvesting device. So fog and dew net systems are two- and three-dimensional structures that form protected walkways (Fig. 12).

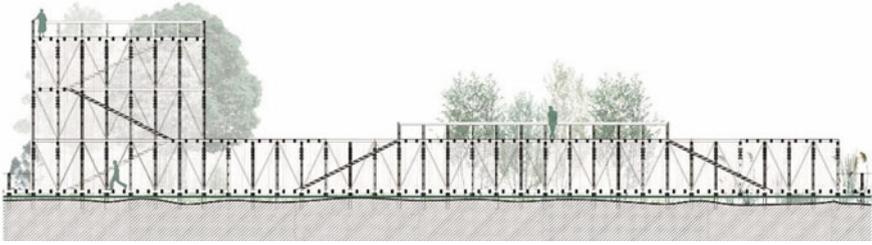
These systems are bi-dimensional because the mesh is arranged for each module in one direction but at the same time three-dimensional, making the structure more resistant, allowing the integration of space and the inhabitant inside it. Still, above all, it provides a double layer of capture. Moreover, it is a modular system of reduced dimensions. This allows it to have more minor lacerations in the mesh because of the winds and the possibility to have a collection on more fronts still depending on how the modules are grouped. Details are explained in the following paragraphs.

### **Fog and dew net**

Fog and dew net comprises standard modules of  $1.5 \times 1.5$  m of base and 3 m height with double mesh surfaces. Instead of the Chilean project, the vertical length was 9 m.

The module's height of the two projects is different. In Chile, the dimension is given by freedom in design due to the desert territory and the level of camanchaca's formation (Chilean fog), which can reach very high elevations, commonly over 9 m. On the other hand, in Milan, the project area is part of an urban context, so a height of 9 m would be out of scale and almost a barrier to the site. Moreover, the Po's Valley fog and dew reach a few meters from the ground. For this reason, 3 m is considered the appropriate size.

The two projects share the same structure because, although the two phenomena have different characteristics, they perform the same function differently. While in Chile, the double layer of mesh collects droplets that can escape from the first layer,



**Fig. 13** Path section, Botanical garden (Edited by the author)

in Milan, it helps to increase the collection surface without doubling the extension. In both cases, a safe walkway is created in the selected park.

In addition, the paths are defined and well delimited to avoid further damaging the nature reserve created (in both case studies, the site corresponds to a protected area), so this “inhabited” wall performs well the function and is a place for the educational activity.

To vary the walkway and make it interact with the context, various “moments” have been designed. There is the classic walkway enclosed by the meshes, the accessible walkway (concerning some wetland, to observe the landscape openly), the elevated roof (walkway on the roofing surface of the module, concerning the height of the surrounding vegetation, as in the walkways of the Arab gardens), and finally the towers-mirador. The latter allows visitors to get at the tops of the trees and glimpse the natural oasis, which public visitors cannot reach, serving as an educational path and birdwatching (Fig. 13).

From the calculations performed on the data, the total annual requirement of an urban vegetable garden in the Milan area is 361 l/m<sup>2</sup>. As already noted, the average yearly collection of dew water is about 600 l, so 0.6 m<sup>2</sup> of mesh can meet the need of 1 m<sup>2</sup> of a vegetable garden.

Considering that the area of the vegetable gardens is about 20'000m<sup>2</sup> (30,000 m<sup>2</sup> of which 1/3 was considered for routes and warehouses), the required mesh area is 12'000m<sup>2</sup> (20,000\*0.6), thus 1333 modules [12000/(1.5\*3\*2)], meaning an extension of 2'000 m of walkways (Fig. 14).

## Conclusions

In conclusion, the same module of *atrapaniebla*, designed for a rural arid context, resulted in an optimal solution in an urban area, thanks to its modular-adaptable system.

Water demand is an essential factor to take into account. Moreover, in Chile, the project area corresponds to a deserts territory, which depends on 100% of external supplements for water and food, in addition to social and ecological problems. In Milan, the situation is quite the opposite. It is a wet territory and historically agricultural (the Agricultural Park Milano Sud is located there). Even if the climate issue is changing in this state, the conditions of the two areas are much different. So we

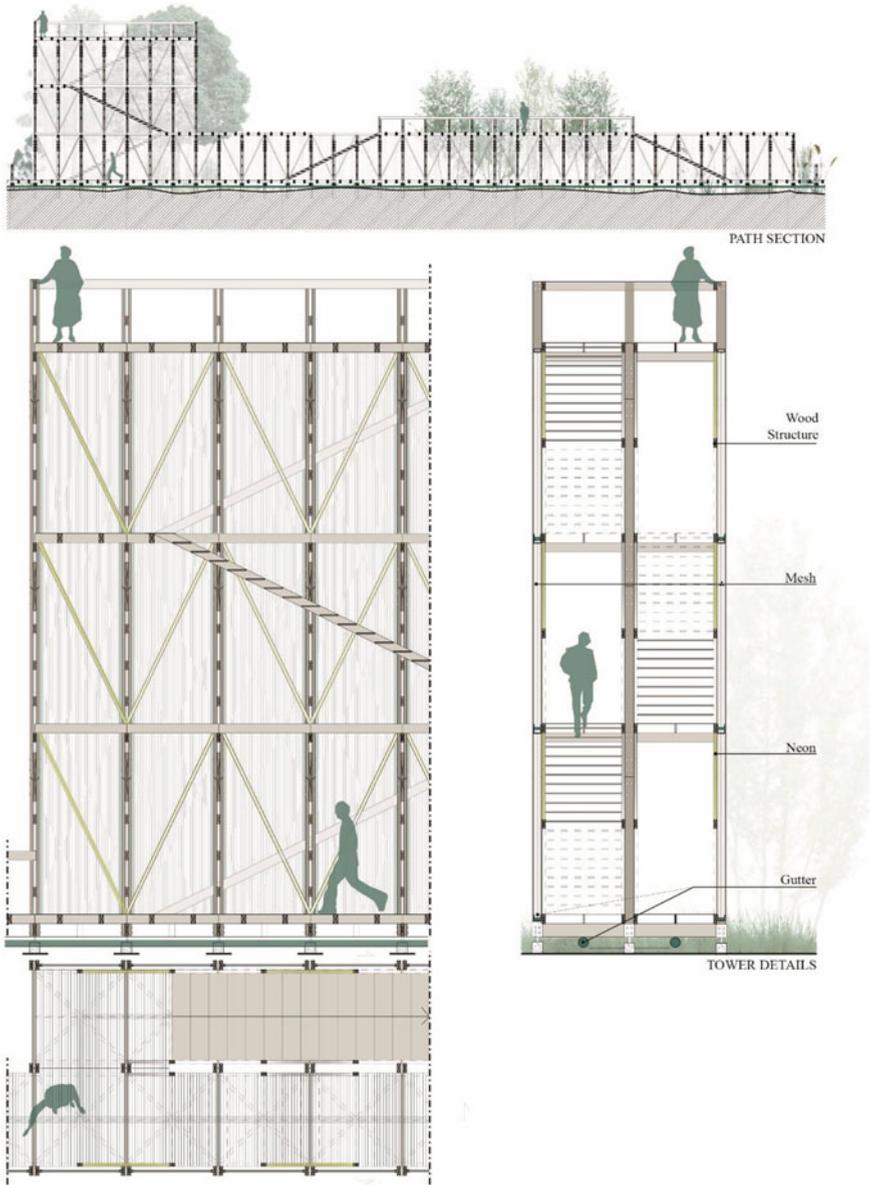


Fig. 14 Fog and dew net details, Tower (Edited by the author)

can deduce that, while nowadays the camanchaca water is a fundamental source in Chile, it is still not so necessary in Milan.

However, a new source of clean water should not be discarded due to the unpredictable water situation. So even if the amount of water collected is minimal, it would be interesting to collect this dew water for urban gardens, irrigation, or domestic use. This system can determine the way water resources are managed in cities and rural areas.

**Acknowledgements** The author of this chapter would like to thank Prof. Adriana Angelotti, from the Energy Department at Politecnico di Milano, for her relevant contribution specially in psychrometric calculations. Moreover, the author wishes to acknowledge Prof. Alessandra Zanelli, from ABC Department at Politecnico di Milano, for her helpful guidance regarding the project development.

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# Case Study: TemporActive



Carlotta Mazzola

**Abstract** The chapter introduces the TemporActive pavilion, an ultra-lightweight hybrid structure built as a pilot project of a doctoral research on membrane-based temporary structures. The research focus presented in this chapter reports on various technological strategies to improve the indoor comfort condition both for warm and cold climate scenarios. Considering the requirements that constrain a temporary structure, alternatives to the technologies commonly used for lightweight flexible envelopes were sought. In particular, a series of shading systems were proposed for the warm season and, in the cold season, it was envisaged to insert recovery materials inside the double-layer envelope to provide translucent thermal insulation. Together with the presentation of the various technological solutions, the results of preliminary research are presented.

**Keywords** Structural membranes · Temporary architecture · Indoor comfort condition · Technological solutions · Shading elements · Transparent thermal insulation

## 1 Project Presentation

TemporActive is an ultra-lightweight hybrid temporary pavilion whose design followed an experimental process aimed at testing a simplified and quick installation method for temporary architecture. Innovative and sustainable strategies have been investigated, on the one hand, to lighten the structural elements and materials and, on the other hand, to apply a time-based and disassembly oriented design approach in order to foresee multiple cycles of use of the temporary pavilion. The project is the practical application of the research work conducted by the Textile Architecture Network (TAN) research group of the Politecnico di Milano on lightweight structures. In particular, TemporActive is the pilot project of a doctoral research conducted by the

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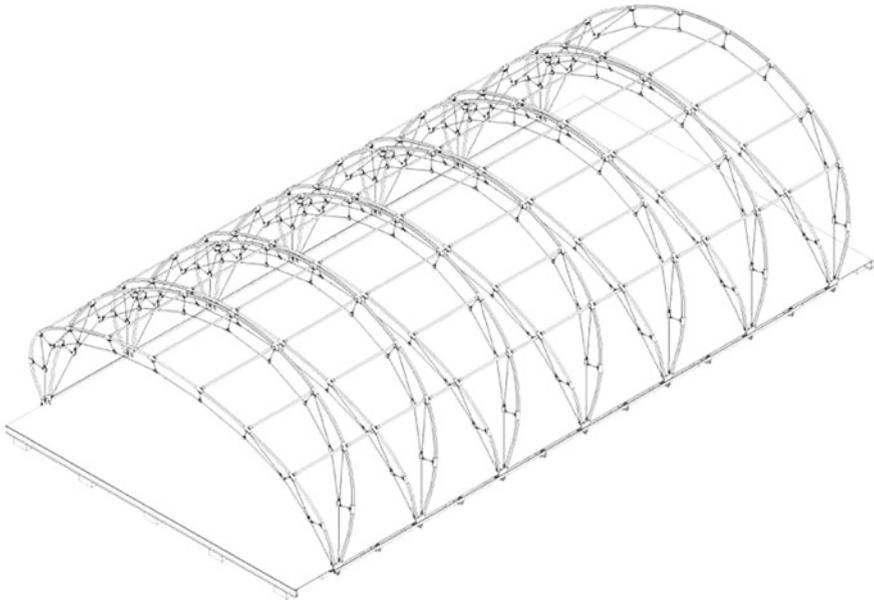
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author at the Department of Architecture, Construction Engineering and Built Environment (DABC), Politecnico di Milano about ultra-lightweight membrane-based temporary architectures.

The design and construction of TemporActive involved a multi-disciplinary team. The pavilion was designed by the Interdepartmental Laboratory on Textiles and Polymeric Materials Research—TextilesHub of the Politecnico di Milano which oversaw the design and technical coordination of the project in collaboration with the engineering office FormTL, responsible for structural design, and the company Canobbio Textile Engineering, responsible for engineering, manufacturing, and installation (Fig. 1).

The pavilion experiments the combination of ultra-lightweight glass fiber-reinforced (GFRP) bending-active arches, a stainless steel cables restraining system, and a transparent membrane envelope. In particular, it consists of  $2.00 \times 7.00$  m self-bearing modules reaching a maximum height of 3.50 m made of double-wing shape restrained arches which are designed to be structurally efficient and extremely lightweight, weighing only 50 kg each. A transparent membrane skin provides protection to the weather and has a bracing function for the extremely lightweight structure.

On the occasion of the 6th TensiNet International Symposium 2019 “Softening the Habitats: Sustainable Innovation in Minimal Mass Structures and Lightweight Technologies,” held at Politecnico di Milano from the 3<sup>rd</sup> to 5th June 2019, seven modules were built in a tunnel-shape configuration, covering a footprint area of



**Fig. 1** Seven modules of the TemporActive pavilion



**Fig. 2** TemporActive pavilion built on occasion of the 6th TensiNet international symposium 2019 “Softening the habitats” in front of the Politecnico di Milano

100 m<sup>2</sup>. During the days of the conference, the temporary pavilion, located in the center of the pedestrian area of Piazza Leonardo da Vinci in front of the Politecnico di Milano, became the Main Entrance Pavilion of the international conference and hosted a lounge space dedicated to sponsors of the event (Fig. 2).

## **2 Research Focus: Improving the Indoor Comfort Condition**

Setting up a pilot project has as its objective the study and in-field experimentation of ongoing theoretical research about lightweight membrane-based structures. Among the variety of topics analyzed, two main interrelated issues guided the research work.

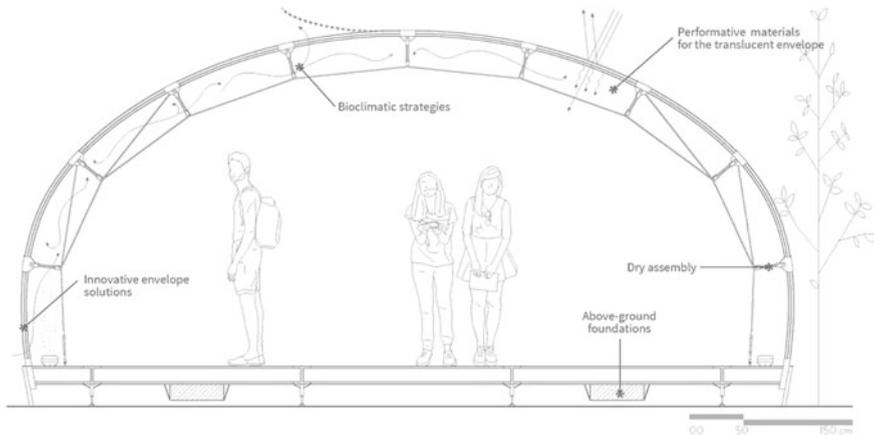
First is the ease of assembly/disassembly and structural efficiency, achieved through a non-conventional combination of lightweight flexible materials. Full-scale

prototypes were built to optimize the design and make the pavilion installation quick and easy (Mazzola et al. 2019a, b; Zanelli et al. 2019).

The second research line is environmental efficiency meant both as sustainability and comfort, which will be the main focus of this chapter. The almost negligible thickness of membranous materials and the prescribed transparency of the envelope particularly challenge the design and require the development of innovative technological solutions to ensure adequate indoor comfort control. Indeed, while in traditional membrane structures, it is possible to insert additional thermal and acoustic insulation layers or reflective films to increase the envelope performance, in transparent and high translucent systems, it is necessary to opt for materials that allow to see through and ensure diffused light permeability. A technological research of non-standard solutions has been carried out to guarantee a high envelope performance level without renouncing to the envelope's transparency.

Creating multi-layer systems is often a good strategy when the internal comfort of a low-mass membrane envelope wants to be improved. The air gap between the two or more membranous layers has a beneficial effect in terms of thermal comfort, i.e., by reducing the heat transfer by convection that is generated between the external surface and the enclosed space. While in the warm season air is functional to dampen the high temperatures affecting the external membrane (thus preventing internal space overheating), in the cold season it provides a natural insulation effect that enhances by increasing the number of functional layers of the envelope. In addition to the benefits on thermal performance, material combinations with different degrees of translucency may also result in interesting effects in terms of surface textures and diffusion and/or filtering of natural light.

In the case of TemporActive, a double-skin system with an air gap of about 30 cm can be easily created by leaning the outer layer on the actively bent GFRP arches and hanging the internal layer on the stainless steel cables restraining system (Fig. 3).



**Fig. 3** Section of the TemporActive pavilion: double-layer envelope system

A methodology for setting priorities has been proposed to deal with the comfort issue of membrane-enclosed spaces. The performance of different envelope systems has been studied and compared according to three aspects:

1. *feasibility*, e.g., degree of complexity and installation time, costs;
2. *environmental performance*, e.g., thermal and optical comfort performance; and
3. *spatial and aesthetic quality*, e.g., adaptability, light permeability, and texture.

The three above-mentioned categories take on different degrees of priority in each project according to characteristics such as the building's expected lifespan, its function, the architectural configuration (i.e., opened, semi-closed, closed), and the context in which it is installed. The project-specific balance to be found between these three aspects leads to the selection of the most suitable envelope technological system.

In particular, the interest of the research focus was to understand how the spatial quality changes and what level of comfort performance must be guaranteed if the lifespan of the structure increases, for instance, from an ephemeral to a long-term temporary scenario. For temporary buildings (CEN 2015), feasibility aspects (e.g., easy assembly, reduced weight and size of the components, transportability, costs, and materials' properties such as to allow multiple assembly/disassembly cycles) are of primary importance. Generally, the shorter the lifespan of the building, the more these aspects predominate.

In the case of the TemporActive temporary pavilion, the technological choices and details have been designed to facilitate the (dis)assembly process and transportability. In particular, the consideration of feasibility requirements has led to the exclusion of the technological systems commonly used to increase the comfort performance of membrane-based envelopes such as pneumatic cushions or active mechanized systems to control solar radiation. These systems, in fact, are appropriate for long-term temporary and permanent solutions but they are unsuitable for short-term temporary applications due to the significant weight and size of the components and complex installation methods. Since the majority of the most widespread technological systems are excluded a priori, alternative solutions have been sought. But, if on the one hand low-tech solutions prevail in the project, on the other hand, high envelope performances want to be reached to provide a high architectural spatial quality level (Fig. 4).

In the present evaluation, to reduce the variability related to different project- and site-specific conditions, the pavilion's configuration and location are assumed as invariants. It was assumed that the configuration of the TemporActive pavilion is open on the two short sides of the tunnel in the warm season (with the possibility of closing the two side walls at night for safety reasons) and closed in the cold season (except for the brief opening moments for entry and ventilation) to ensure a controlled indoor environment. The pavilion is imagined to be built in a temperate climatic area. While the variables related to the context (e.g., location, climate) and use (e.g., activities carried out and time spent by people inside) are kept fixed, the degree of temporariness and the season are considered as variables. Several scenarios considering three expected lifespans (i.e., short-, medium-, and long-term temporariness) are set both

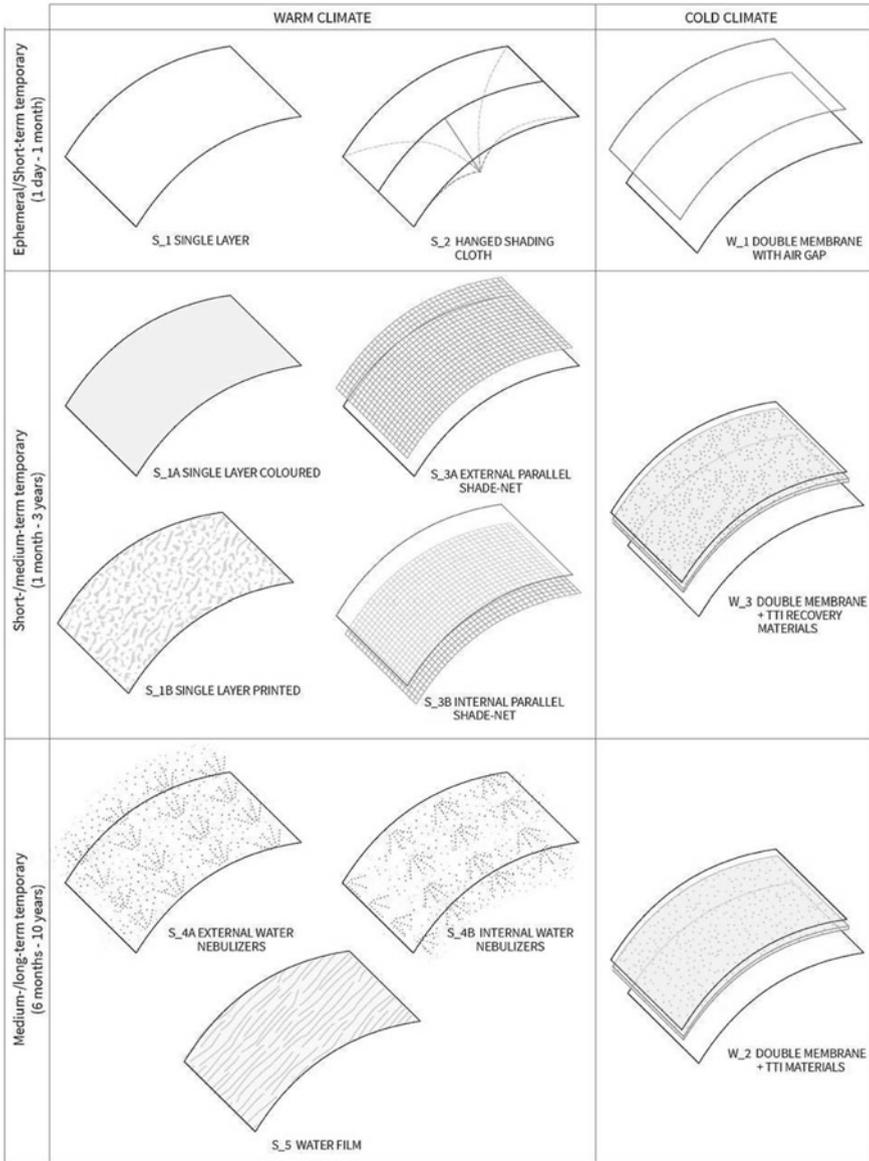


Fig. 4 Technological solutions and strategies to improve TemporaActive’s envelope performance

for warm and cold climates. For each scenario, alternative technological systems aimed at increasing the indoor comfort condition are proposed. An accurate literature review, an analysis of significant case studies, and the previous experimental experiences of the research group TAN in the field of membrane structures have led to the selection of the technological solutions presented in the following pages.

### Warm Climate Scenarios

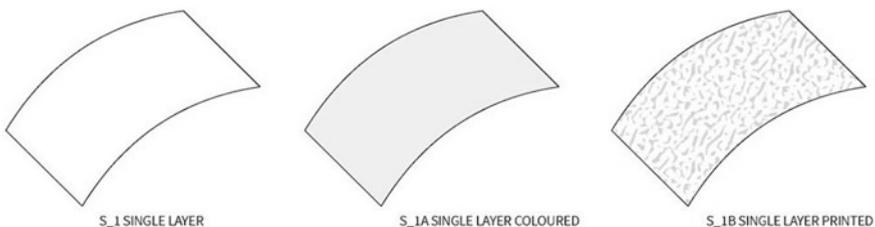
In the warm season, the lightweight envelope should meet the following requirements:

1. diffuse the light to avoid glare and provide adequate indoor lighting;
2. reflect solar radiation to prevent the inside temperature of the indoor space to go significantly above the outside temperature, i.e., green-house effect; and
3. allow for natural ventilation to prevent overheating of the membrane-enclosed space.

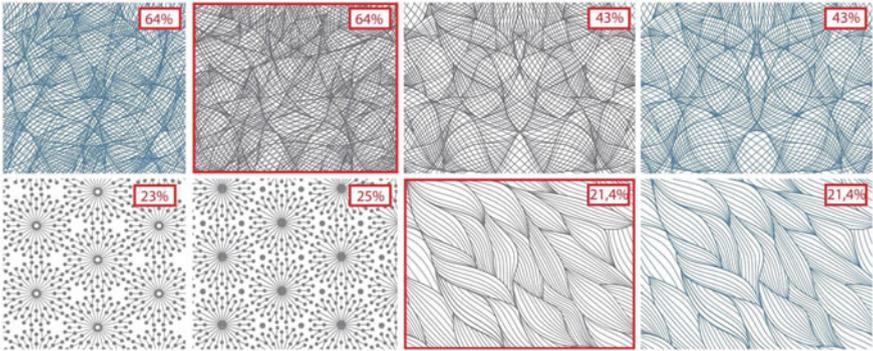
For an ephemeral or short-term temporary application (i.e., building's lifespan of up to one month) in the warm season, shading is identified as a priority requirement to avoid excessive overheating of the covered space. Considering the short lifespan, a basic single-layer envelope solution can be adopted. The envelope can be implemented afterward or replaced when the location and function change. In fact, it is also possible to upgrade and customize the material by coloring, printing, and/or applying top-coatings on the membrane to improve its performance (Fig. 5).

The envelope of the temporary pavilion TemporActive built on the occasion of a one-week event is made of a transparent foil (e.g., PVC Crystal or, alternatively, ETFE) printed with a shading pattern. To evaluate the shading capacity, different colors and patterns with increasing coverage percentages were compared and field-tested (Fig. 6). In the end, the dark gray option was chosen with two different patterns to provide adequate shading at the top and an aesthetic effect given by a gradient: the most opaque pattern (i.e., ink coverage percentage 64%) in the zenithal part and a lighter pattern (i.e., ink coverage percentage 21,4%) on the upper side, shading up to the simple transparent foil on the sides.

The membrane printing has brought a benefit when compared to the transparent single-layer foil. However, in the hottest summer hours, the shading pattern is not



**Fig. 5** Technological options for the warm season short-term scenario: (1) simple, (2) colored, and (3) printed single-layer system

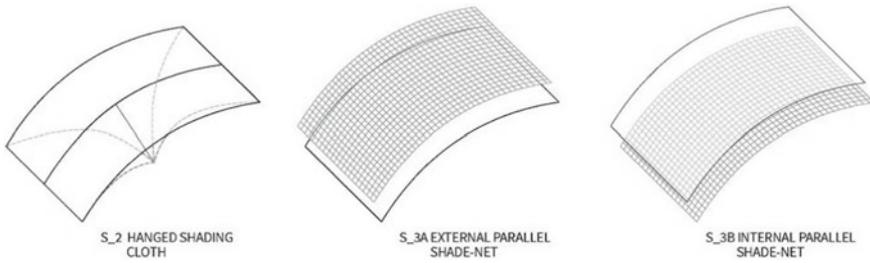


**Fig. 6** Different printing pattern options and the two selected solutions (in red)

sufficient to avoid overheating of the internal space because solar radiation is allowed to enter inside. To improve the single-layer envelope performance, it is possible to increase the percentage of ink coverage or use a metal-based reflective ink (e.g., silver fritting) that reflects solar radiation, thus preventing the membrane from overheating (Fig. 7).



**Fig. 7** Selected solution for the zenithal part (64% covering) after in the TemporActive pavilion



**Fig. 8** Technological options for the warm season long-term scenario: (1) hanged shading cloth, (2) external parallel shade net, and (3) internal parallel shade net

Shading elements are essential for ensuring an acceptable thermal performance of a lightweight building skin in a warm climate, by protecting the envelope and the indoor environment from excessive solar radiation and ultraviolet rays. Shading devices should be designed according to the location and orientation of the building, and their efficiency depends on their position relative to the waterproofing layer (Fig. 8) and the characteristics of the material that composes it. They can be made with various flexible materials characterized by different fiber components, colors, shade factors, and weights that result in diverse levels of solar protection. PVC-coated polyester (PVC/PES) open mesh and UV-stabilized polyethylene (PE) mesh are commonly used. In terms of color, darker shade nets have the best thermal insulation, causing a decrease in the internal temperature rises. Shade factors are generally expressed in percentage: the higher the value, the more coverage and performing the shade net is, and less amount of light can penetrate inside, i.e., resulting in a lower light transmittance value. The weight of the materials commonly used as shade net varies between 45 and 275 g/m<sup>2</sup> (ISO 3801:1977). In the design phase, a compromise must be found between environmental performance and other project requirements such as transportability and buildability. In fact, a more performing shade net will weigh more for transport and installation and must be considered during the structural behavior analysis.

One possibility is to hang removable mesh screens or knitted fabrics on the restrained arches inside the transparent waterproof layer. The advantage of hanging shading cloths is that they can be installed/uninstalled by the user as needed and they can constitute relevant architectural elements characterizing the interior space by shaping it with organic forms.

Alternatively, the shading elements can be integrated into a multi-layer envelope system and placed either outside or inside the waterproof layer. When the shade net is positioned outside, the shading layer absorbs solar radiation before it hits the inner membrane. For best performance, it is recommended to choose a dark-colored and dense shade net. In this case, if the climate and location of the building are favorable, there is also the possibility of making the external shade net a fog harvesting system.

When the shade net is positioned inside, the performance is reduced compared to the external solution because the heat enters the transparent surface and heats



**Fig. 9** Active strategies for the warm season long-term scenario: (1) external water nebulizers, (2) internal water nebulizers, and (3) water film

the internal air. However, when the architectural configuration is opened, as in the case of the TemporActive Pavilion, the position of the shade net has less impact on the thermal performance of the envelope because natural ventilation has a beneficial effect in dampening the external temperature.

In addition to the passive strategies listed above, some active strategies can be adopted to mitigate environmental and indoor discomfort in warm climate conditions (Fig. 9).

Experimental studies have tested the use of water to mitigate discomfort conditions in the warm season, by creating a microclimate inside buildings or in open public spaces. These studies, often still in a prototyping phase, can be an inspiration to improve indoor comfort conditions of membrane-enclosed spaces such as TemporActive.

First, Mainini et al. investigated the influence of water spray on the thermal and solar performance of a double-layer ETFE pneumatic cushion as a strategy for increasing the envelope performance during warm climate conditions (Mainini et al. 2016). In the case of TemporActive, the water can be used to create either an evaporative cooling effect with water nebulizers to cool the air outside, i.e., preventing the membranous surface from heating, or inside the building, i.e., giving an immediate thermal comfort benefit to users. Otherwise, the provision of an evaporative cooling system in the ventilated cavity of the double-layer envelope would allow for a thermal benefit and the prevention of the indoor space overheating.

Alternatively, a film of water flowing on the external side of the envelope can have a beneficial thermal effect, causing the cooling of the membranous layer and thus damping the heat coming from the solar radiation. A similar solution using a thin water film has been experimentally tested by Qahtan et al. on a glazing façade (Qahtan et al. 2011). The measurements made on a mock-up showed an improvement of the indoor comfort condition, resulting in a decrease of the surface and indoor temperature both on sunny and cloudy days.

The above-mentioned active strategies that make use of water to improve indoor comfort, even if partially experimented with prototypes or in the laboratory, require further experimental studies and tests. In fact, in addition to the technical aspects still to be developed and the assessment of the real effectiveness of these strategies,

it is necessary to consider other project-specific constraints, e.g., logistics depending on the place and context of application. For instance, active strategies that make use of water are more suited for a medium-/long-term temporary since it is necessary to foresee the installation of a closed water circuit and a water tank.

### **Cold Climate Scenarios**

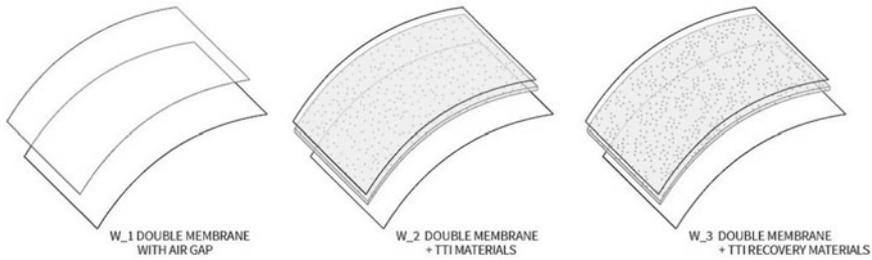
Considering the low mass of membranes which cannot guarantee an adequate level of comfort on its own, in the cold season it is advisable to opt for multi-layer solutions. Winter thermal insulation is particularly challenging because on the one hand transparency must be ensured without, on the other hand, weighing excessively on the structure or reducing the inside/outside visibility. If the use of transparent or translucent components for the envelope allows taking advantage of the free gains of solar radiation that create a green-house effect inside the air gap, the transparency and lightness of the envelope—imposed by the architect's will as one of the design requirements—significantly reduce the materials with insulating properties available.

For an ephemeral or short-term temporary application, i.e., building's lifespan of up to one month, a double-layer envelope made of two transparent or highly translucent membranes with an intermediate air gap can be created. For these conditions where the project requirements are generally limited to the essential, the insulating function of air may be sufficient to mitigate the external temperature.

For applications requiring specific thermal performance due to the location or function of the building, flexible transparent thermal insulation (TTI) materials can be inserted in the air gap to increase the envelope performance compared to the simple double-layer solution. In the last few decades, several innovative products appeared on the market as an alternative to common opaque thermal insulation materials. For example, honeycomb hollow chamber panels, spacer fabrics, or panels soaked with aerogels, to name a few. These materials are efficient in terms of thermal insulation performance and enable light permeability. However, they are expensive, difficult to find on the market, and often require special attention for installation. These characteristics, in many cases, make them unsuitable for temporary solutions or multiple assembly/disassembly cycles. Furthermore, in terms of eco-efficiency—despite being very performing during their use due to their high insulating properties and low weight—these products have substantial ecological gaps in the rest of the product's life cycle because their production requires great energy consumption, and they are hardly reusable and/or recyclable.

Considering the design principles of sustainability and the other design requirements that guided the TemporActive pilot project, alternative solutions to conventional TTI materials were sought.

Some experimental research works found in a literature review suggested the use of unconventional materials as an alternative to translucent thermal insulation materials (Trang 2014). In particular, the technological options proposed aim at increasing the winter thermal performance by inserting a number of functional layers made of highly translucent, flexible, and easily available polymeric materials with thermal insulation function inside the 30 cm double-skin air gap (Fig. 10).



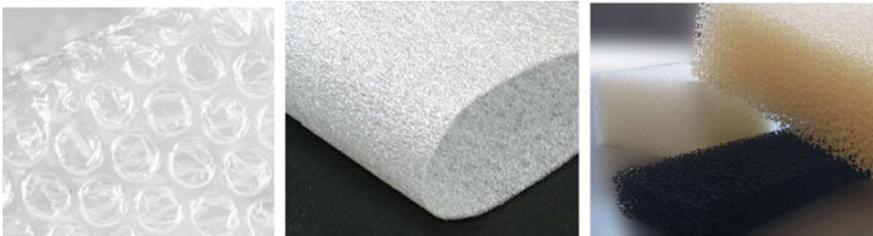
**Fig. 10** Technological options for the cold season scenario, double-layer membrane envelope with: (1) air gap, (2) conventional transparent thermal insulation (TTI) materials, and (3) unconventional recovery TTI materials

Three common products with different thicknesses have been selected to be used as translucent thermal insulation material:

1. Low-density polyethylene (LPDE);
2. Expanded polyethylene (PE); and
3. Polyurethane foam (PP).

The three selected materials, generally used in other sectors than construction, were chosen on the basis of their common characteristics: They are all thermoplastic polymers, flexible, cheap, and easily available on the market and are sold in rolls or flexible panels, i.e., an aspect that greatly facilitates installation. Given the use of these materials in everyday life, their employment of these materials opens up the possibility of using recycled materials (Fig. 11).

Several envelope stratigraphies have been proposed to assess the thermal insulation performance of the selected translucent insulating materials, using from one to three layers of material. For each stratigraphy, the thermal transmittance value ( $U$ -value) has been calculated. Although considering only  $U$ -value is a simplification that does not accurately describe the complexity of reality, this gives a preliminary idea on the insulation performance of the lightweight envelope. A similar simplification is generally made for preliminary assessments of ETFE pneumatic cushions' thermal performance. To make a more accurate study, solar radiation and



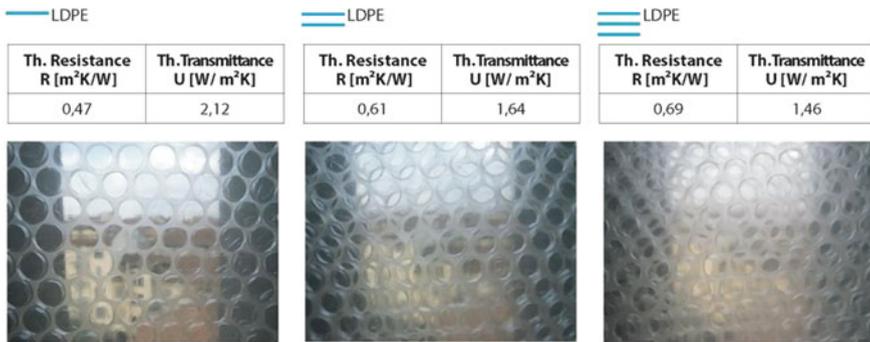
**Fig. 11** Three selected thermal insulation materials. From left to right: Low-density polyethylene (LPDE); Expanded polyethylene (PE); and Polyurethane foam (PP)

convection phenomena within the air gap should be considered in the assessment. To consider these aspects, which have great importance in the behavior of the multi-layer membrane-based envelope systems, complex Computational Fluid Dynamics (CFD analysis) simulations would be required.

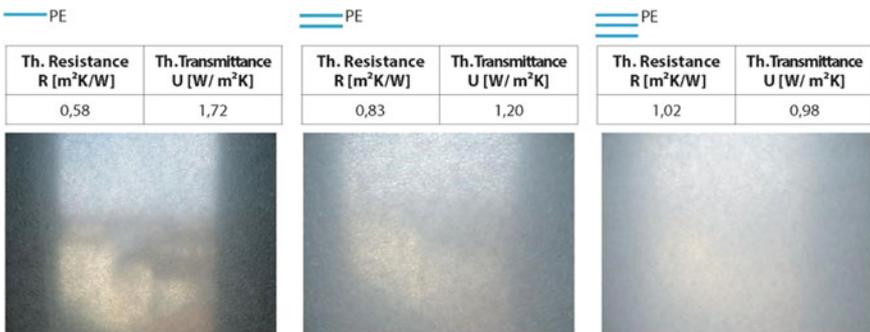
Considering the curvilinear shape of the TA envelope, the  $U$ -value calculation was made both for a horizontal and a vertical wall with an ascending air motion. The values of the two cases vary by a few decimals, and therefore, only those concerning the horizontal wall are shown below (Figs. 12, 13, and 14).

If on the one hand the increase in the number of recovery translucent insulating material's layers leads to an improvement of the envelope's performance level, on the other hand the visibility between inside and outside decreases (Fig. 15).

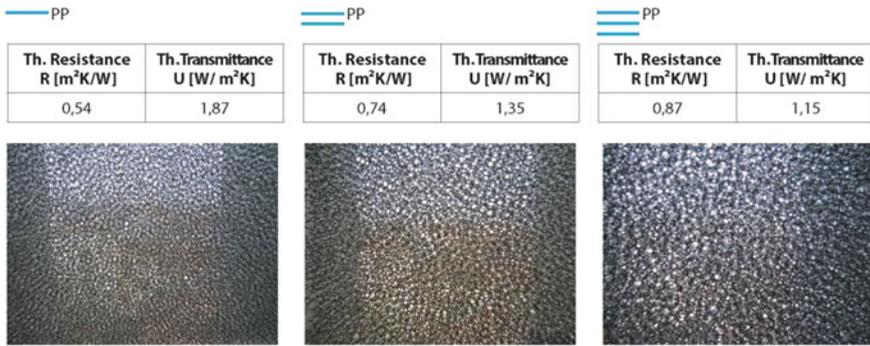
To more easily comment on the results obtained from the experimentation, the values calculated for a double-layer ETFE cushion are taken as a reference. A cushion consisting of two layers has  $U = 2.95 \text{ W/m}^2 \text{ K}$ . The  $U$ -value decreases as the number of layers and air chambers interposed increases, i.e.,  $U = 1.96 \text{ W/m}^2 \text{ K}$  for three



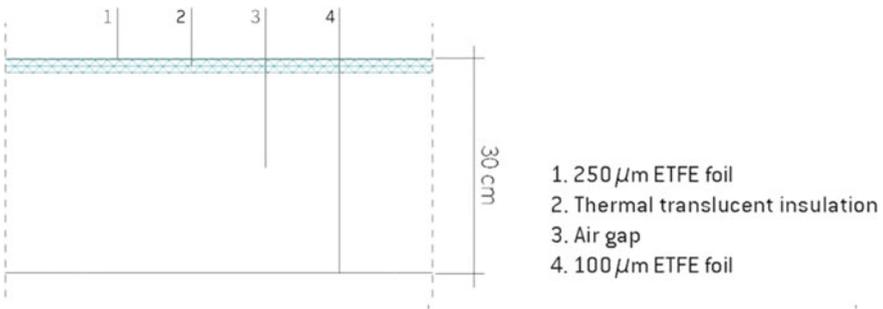
**Fig. 12** Translucency and visibility levels and thermal resistance and thermal transmittance values from one to three layers of low-density polyethylene (LPDE)



**Fig. 13** Translucency and visibility levels and thermal resistance and thermal transmittance values from one to three layers of expanded polyethylene (PE)



**Fig. 14** Translucency and visibility levels and thermal resistance and thermal transmittance values from one to three layers of expanded polyurethane foam (PP)

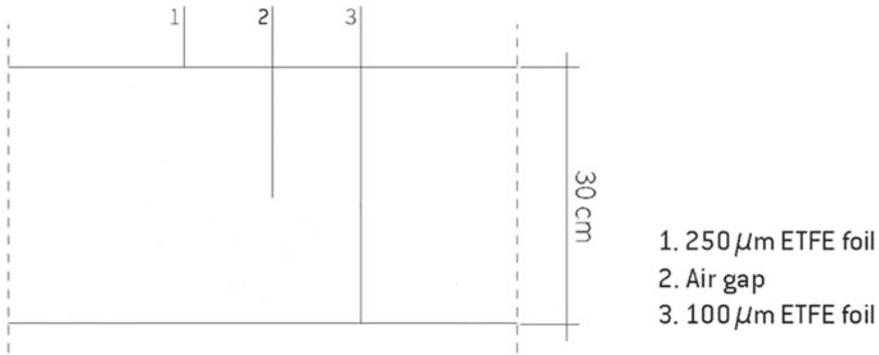


**Fig. 15** Multi-layer envelope system with thermal translucent insulation (TTI) layer inside the air gap

layers and two air chambers,  $U = 1.18 \text{ W/m}^2 \text{ K}$  for five layers and four air chambers. By comparing the thermal transmittance values of the simple double-layer ETFE membrane without inserting TTI layers (Fig. 17), this solution results in much less performance, i.e., the thermal transmittance is almost two times higher than the solutions with thermal insulation layers. As a result of a preliminary assessment, the insertion of flexible translucent materials inside the envelope seems to be a good alternative to more conventional solutions to increase the envelope’s performance of a temporary lightweight building in the cold season (Fig. 16).

### 3 Conclusions

In this chapter, the results of a research focus on the environmental comfort of temporary structures enclosed by membrane-based materials were presented. In particular, a series of technological strategies have been proposed and experimented within the



**Fig. 16** Multi-layer envelope system made of simple ETFE double-layer

— ETFE

N. of layers	Layer description	Thickness [m]	Density [Kg/m <sup>3</sup> ]	Conductivity [W/mK]	Specific heat [J/KgK]	Thermal Resistance R [m <sup>2</sup> K/W]	Thermal Transmittance U [W/ m <sup>2</sup> K]
Exterior	1/h <sub>i</sub> = 0,107 m <sup>2</sup> K/W					0,33	3,02
1	ETFE foil 250 μm	0,00025	1780	0,250	2386		
2	Air gap	0,29965	/	/	/		
3	ETFE foil 100 μm	0,0001	1780	0,250	2386		
Interior	1/h <sub>e</sub> = 0,043 m <sup>2</sup> K/W						

**Fig. 17** Thermal resistance and thermal transmittance values of the simple ETFE double-layer system

pilot project TemporActive. These alternatives have been studied and organized in relation to the building’s expected lifespan, i.e., short-term and long-term temporary, and project context.

Even if from the studies done it is possible to affirm that the technological solutions presented improve thermal and optical performance compared to a simple single-layer system, the theoretical results found require more in-depth verification.

The research can continue in several directions. At a methodological level, for example, it is possible to create a Key Performance Indicators analysis that can be used as a design tool to support the decision-making process or for case study analysis. At a technological level, a phase of field testing of these technological alternatives could give important feedback on the real effectiveness of the results found in this preliminary phase. Moreover, in the future other alternatives can be explored and tested with simulations and measurements. For example, the tunnel shape and transparency of the pavilion’s membrane envelope give the possibility of integrating flexible photovoltaic cells for the production of solar energy. The integration of PV in flexible transparent envelopes could have great potential for

applications in transportable lightweight buildings that can thus become autonomous from an energy point of view.

The preliminary research of unconventional technological solutions allowed us to step forward the state of the art of a topic such as thermal comfort of lightweight envelopes that is very challenging and still little treated in literature.

**Acknowledgements** The author of this chapter would like to thank all the people who contributed to the successful realization of the project, in particular, Bernd Stimpfle (formTL), Roberto Canobbio, and Alessandro Rizzo (Canobbio Textile Engineering) for the technical support. Moreover, the author wishes to acknowledge Prof. Alessandra Zanelli and Carol Monticelli, from the Architecture, Built Environment and Construction Engineering Department at Politecnico di Milano, for their guidance during the project development.

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# Conclusion: On the Way to New Species of Lightweight Energy-Conscious Membrane Architecture

Alessandra Zanelli

Mankind, an excellent technological animal, capable of conceiving and creating admirable architectures, supported by innovative structural concepts, has every time looked beyond the limits of its time. There is no doubt that today's designer can boast theoretical and practical knowledge based on the millennial experience of his predecessors. Today we are about 186 generations away from that ingenuity that was able to design and build the pyramids, 107 generations from the Etruscan necropolises and from the first experiences of the resistant arch shape, and only 30 generations from the builders capable of that technical refinement that has allowed the Gothic cathedrals to reach us (Zevi 1997). In other words, we can define ourselves as experts in mass construction, which exploits the heaviness of the materials incorporated in the construction to withstand the surrounding conditions. But we are only four generations who wisely and safely use steel in architecture, if, for example, we think of the Eiffel Tower or contemporary iron bridges as a turning point. Even a couple of generations ago we started introducing plastic materials into our artifacts and experimenting with their use in the construction field.

Therefore, we can perhaps still define ourselves as pioneers in the use of tensile-resistant materials and lightweight construction systems with membrane and tensile structural behavior, while even shorter is our experience in the use of fiber-reinforced composite materials based on cement and/or polymeric. This temporally short experience in the structural and architectural conception based on tensile-resistant materials must certainly encourage designers and technicians and scientists, politicians and administrators to finally follow up on that irrepressible desire for knowledge that always pushes us to learn from mistakes—whenever we cross the threshold of the known—and to refine the results, in view of the development of a new architectural, structural and constructive solution.

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There are countless examples in architecture that help us to remember that every technical innovation that has reached a certain level of reliability and relevance in the transformation of the built environment has, at a certain point, been the subject of a “species jump” that always human ingenuity had the courage and perseverance to work for the progress of society (Giedion 1941).

With this book we wanted to underline that the “species jump” of textile architecture and membrane architecture is underway, driven forward by the technical innovations that have taken place in the chemistry of materials on the one hand and by automation and electronic miniaturization on the other.

Furthermore, the research works presented in the book also wants to lead the reader to reflect on the opportunity that these great technological potentials must however be put at the service of environmental sustainability. The development of membrane architecture today can therefore only be in the primary direction of saving resources and energy, considering the scarcity of planet’s resources as the first design issue (Manzini 2012). This means to promoting design solutions that use the most advanced production and installation techniques starting from a structural and architectural conception aware of correct and economical use of non-renewable resources throughout the construction life cycle, and to finding the smartest ideas for integrating renewable ones into the building components.

Membrane architecture of the near future must be the emblem of an updated “human construction”, in the sense in which Frei Otto defined every architectural work capable of promoting peace and the co-existence of mankind (Otto 1979 in Nerdinger 2005), such as a natural artifact that self-organizes and co-evolves over time together with its users. This new generation of lightweight construction must be the result of a design-production-construction process optimized in every aspect, calibrated to maximize efficiency and minimize material, human and energy resources throughout the entire life cycle of the product.

May this lighter-weight and lighter-energetic membrane architecture contribute to a more sustainable transformation of the built environment? The question is the real challenge behind the research studies presented in the book.

The Chap. 1 aims to introduce the reader and the designer in the field of membrane architecture, presenting its potential and future challenges, the developments for a less-energetic building skin and a more interactive to the user soft, membranous building envelopes.

In the Chap. 2, the life cycle perspective in designing lightweight building systems is presented, with the final aim to demonstrate the advantages of the Life Cycle Design strategy answering to the environmental sustainability of novel lightweight skins.

The Chap. 3 introduces the approach of a programmatic “environmental lightweight” architecture. It analyzes active and passive strategies, focusing on lightweight envelope systems from a historical to a future perspective. It demonstrates the global potential of bioclimatic architecture using sun, wind, and water, both separately and in combination, as the main design drivers. Furthermore, the presented case studies show successful implementations of bioclimatic principles that can inspire future developments. The chapter argues that environmental design should be embedded into the building design process to use visible and invisible

natural resources that surround us. Moreover, doing so is possible with lightweight technologies that produce minimal environmental impact and have the possibility to reach net or plus-zero targets. Therefore, only a careful balance of energy harvesting and lightweight solutions could make a successful and accelerated transition towards a sustainable future.

In Chap. 4, the advancement in material science enabling enormous developments of Photovoltaic technologies are presented. From an architectural integration viewpoint, the mechanical flexibility of the Photovoltaic products represents another key consideration, rather than only cost and energy conversion efficiency. The chapter presents descriptions of flexible substrates and thin film Photovoltaic, deepening the two key choices for the flexible Photovoltaic in buildings, the thin film, as well as organic one. The potentials and limits are highlighted: considering building applications the higher transparencies upon visible lights, the multiple color choice are important requirements.

Starting from Chap. 5 on, several industrial developments and applied researches are presented, with the aim to show concrete case-studies and multidisciplinary advancements on the main designing and production domains described in the first part of the book.

In Chap. 5, SOFT-PV research is presented. The work deals with a coupled mechanical and electrical characterization method to monitor the correlation of OPV electrode resistance and cell performance upon tensile strain and to verify the deterioration effect and reason for the tension strain on the OPV performance response.

In Chap. 6, the industrial research project TIFAIN is presented. It addressed a broad range of performances, paving the way toward an integrated design methodology for BIPV facades. The progress was made from the original Tile 1 design towards TIFAIN Diamond that improved both design and performance. Multiple experimental tests were carried out on small and 1:1 scales to validate simulations and demonstrate manufacturing feasibility.

The Chap. 7 aims to analyze fog and dew harvesting's system as a powerful and efficient alternative water resource. A comparison between two areas that are characterized by the fog phenomenon, Chile and Italy are investigated. Moreover, the fog harvesting structural device has been studied to develop an experimental project related to a master thesis dealing with the dew collection in Milan. Furthermore, on-site and in the Lab, the ongoing investigation is also presented.

Finally, in Chap. 8, the pilot project TemporActive is presented as main the result of a research path focused on the environmental comfort of temporary, membrane-based enclosed space. Alternative and unconventional solutions have been studied and organized in relation to the building's expected lifespan, i.e. short-term and long-term temporary, and project context.

Through the presentation of updated knowledge, case-studies of applied research and pilot projects, the book wanted to outline the fundamentals of a light construction of a renewed conception, designed starting from energy saving, and artfully built to be safe and durable, but not eternal. Rather than last indefinitely, the light-energy construction of the future will have to be resilient to changes—even to those currently

outside the predictive capacity of designers and standards—and adaptable over time, to meet the changing needs of humankind that will follow and will be able to enhance it.

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