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Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings

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ABSTRACT

The present article is a critical review about ETFE (ethylene tetrafluoroethylene) material, with emphasis on building applications since ETFE is promising for the building sector, offering multiple advantages (elastic and low-weight structures, etc.) from different points of view. Selected references about ETFE properties are presented, revealing that ETFE material presents resistance to temperature/aging, mechanical strength and chemical resistance. In addition, studies about light transmission/insulation of ETFE material for building applications are included, showing that ETFE cushion insulating characteristics can be further improved by utilizing additional layers while some studies refer to ETFE decay in terms of light and solar transmittance performances after some months of exposure. Investigations which compare ETFE with glass are also presented, revealing that ETFE offers many advantages, in comparison with glass, from different points of view. A separate part of the article is about ETFE environmental profile and the literature review demonstrates that most of the investigations (which include LCA (life cycle assessment)/environmental issues about ETFE) evaluate embodied energy (the findings show values from 26.5 to 210 MJ/kg). Concerning ETFE applications, the literature review reveals that ETFE can be used for different applications (roofs, façades, atria, in combination with PV (photovoltaic) technology, etc.). Moreover, additional issues (acoustics, shading, etc.) are presented and critically discussed. Furthermore, a separate part with case studies is included. In this way, the present article offers useful information about ETFE, based on different factors, focusing on ETFE applications for buildings and constructions.

1. Introduction

Plastics in buildings offer lightweight and low-cost alternative solutions to glass and other claddings; in this way, plastic materials are useful for building applications, for example for commercial buildings [1]. During the last years, new plastics have been developed, resistant to UV radiation and without showing decoloration, and there is a growth in the variety of the plastics while their lifespan and quality increase. Among these plastics, ETFE (ethylene tetrafluoroethylene) is a promising material that can be adopted as cladding for buildings (and, in general, for multiple architectural constructions), offering around 95% light transmission, flexibility and inspiration for new concepts influencing building structural design [2]. Nowadays, ETFE is considered as one of the most innovative materials in the frame of modern architecture [3] as well as in lightweight architecture with creations of spectacular buildings of various geometric and unusual forms [4].

The development of ETFE, and in general the development of fluoropolymers (polymer materials containing fluorine atoms in their chemical structures), has started several years ago. An overview of the history of fluoropolymers, from the discovery of the polytetrafluoroethylene (30 s) till nowadays has been presented by Teng [5]. Moreover, in the work of Teng [5] it was noted that the existing products can satisfy most of the requirements for industrial applications and the current efforts give emphasis on the reduction of the production cost as well as on the expansion of the market.

List of symbols and abbreviations: BI, Building-integrated; BIPV, Building-integrated photovoltaic; BIPVT, Building-integrated photovoltaic/thermal; CFD, Computational fluid dynamics; CML, CML method; ECTFE, Ethylene chlorotrifluoroethylene; ETFE, Ethylene tetrafluoroethylene; FEM, Finite element method; FEP, Fluorinated ethylene propylene; IR, Infrared; LCA, Life cycle assessment; LED, Light-emitting diode; PE, Polyethylene; PET, Polyethylene terephthalate; PTFE, Polytetrafluoroethylene; PV, Photovoltaic; PVB, Polyvinyl butyral; PVC, Polyvinyl chloride; PVDF, Polyvinylidene difluoride; PVT, Photovoltaic/thermal; TFE, Tetrafluoroethylene; THV, Tetrafluoroethylene-hexafluoropropylene-vinylidene fluoride; TPO, Thermoplastic polyolefin; UV, Ultraviolet

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In the literature several studies about ETFE material have been presented. These studies examine ETFE from different points of view. For example, some investigations give emphasis on ETFE mechanical behavior [6–9] while other studies focus on issues related with light transmission and insulation [10–13]. In addition, some authors examine ETFE material from LCA (life cycle assessment)/environmental point of view [14–17]. On the other hand, in the literature there are some works which: 1) compare ETFE with glass [15,18], 2) present issues about the acoustics of ETFE structures [19,20], 3) examine shading and thermal comfort of ETFE structures [21,22], 4) discuss issues about the inspection of ETFE foils [23]. In terms of ETFE applications, several studies have been presented, including multiple applications such as ETFE façades [24], ETFE roofs [14], ETFE atria [25] as well as configurations which combine ETFE with PV (photovoltaic) technology [26–28].

Based on the above mentioned, it can be seen that ETFE material presents interesting characteristics and useful applications, including the building sector. In the literature, there are few review articles about ETFE: Hu et al. [29] presented an overview about buildings with ETFE foils with emphasis on material properties, architectural performance, structural behavior and sustainable ETFE structures; Hu and Jiang [30] conducted a review about the production and the market of ETFE; Chilton [31] presented a state-of-the art about lightweight envelopes based on ETFE. Thereby, there is a need for more review articles which present an overview of ETFE material from different points of view. In the frame of this scope, the present article is a critical review about ETFE material, discussing different issues:

1) General characteristics for high-performance materials/configurations for buildings.
2) Requirements specifically for membrane configurations (roofs, façades, etc., in terms of aspects such as material selection for membranes).
3) Mechanical and other critical properties of ETFE material (light transmission, insulation, etc.).
4) Acoustics related to structures which are based on ETFE.
5) Shading issues about configurations including ETFE components.
6) Inspection of transparent construction materials.
7) Issues about ETFE material from LCA/environmental point of view.
8) Applications (requirements in terms of claddings; studies about ETFE façades, roofs and atria; combination of ETFE with PV or PVT (photovoltaic/thermal), etc.).
9) Case studies based on ETFE systems (for buildings and architectural constructions) that have been already developed.

In addition, a critical discussion is provided and by considering that:

1) There is a need for reduction of the energy consumption in the building sector in order to reduce CO_2 emissions. Passive design approaches can offer multiple advantages (energy savings with low extra investment, etc.) towards green buildings and sustainable constructions [32].
2) ETFE is a promising material in the frame of environmentally-friendly buildings and constructions [2].
3) In the literature there are few review articles about ETFE, it can be seen that the present study provides useful information about ETFE, based on different points of view.

More specifically, in the present article, the major part focuses on building applications and environmental issues, taking into account the importance of eco-friendly constructions in the building sector. Within the frame of this concept, multiple ETFE configurations and examples which combine ETFE with PVs are presented, highlighting the role of renewable energy sources in the frame of sustainable constructions and buildings. Finally, the part of the case studies verifies, based on projects that have been already developed and applied in practice, the connection of ETFE material with renewable energy systems and eco-friendly constructions.

2. Literature review

2.1. Characteristics of high-performance materials/configurations for building applications

Paech [24] noted that structural high-performance materials present high ratio of structural strength to dead load and the application of these materials is optimal when they are under pure tension (utilizing the full structural capacity by omission of bending moments and any stability issues). However, high-performance is not only about the structural properties. High-performance is also related, for example, with the fact that a material or composite of materials is designed and produced to have specific characteristics (e.g. specific color, acoustic damping, transparency or translucency, air permeability, etc.). Moreover, Paech [24] mentioned that selective coatings are sometimes part of high-performance materials in order to affect the properties of a specific building (example: coatings for the improvement of the interior climatic conditions).

Related with the above mentioned factors, some additional issues are following presented:

- Design considerations for the roof-to-wall interface (the roof and wall design should be able to resist the fundamental forces as outlined by the applicable building code. Parameters such as building overall height, use, roof slope, location, structural type and shape should be taken into account for the development of the roof-to-wall interface) [33].
- Heat, air and moisture factors (for the protection of the quality of the interior environment and building enclosure assemblies from the deleterious effects of moisture and air) [33].
- Adaptive or moveable elements impose specific demands in terms of the selected materials (sometimes it is necessary to have specific geometrical arrangements) [24].
- Adopting membrane materials for façades is a more economical solution than using traditional cladding materials, especially when there are reduced requirements on the envelope system (for example, pure shading or balancing of thermal peak loads and simple wind or visual barrier) [24].
- Use of advanced façades which are cost effective and they offer environmental quality, life-cycle savings and energy efficiency [34].
- Façades should be able to respond and adapt to the variable exterior conditions and to the needs of the occupants [34].
- Special requirements depending e.g. on the height of the building (specific case: for example, high-rise buildings) are necessary for certain cases [34].
- Adoption of solutions which combine façade with ventilation [34].
- Use of systems that include combination of a façade with production of energy (active façade systems) [34].
- Utilization of façades that offer solar control and/or daylighting [34].

The degree of influence of the above mentioned parameters is associated with the specific case of a building/construction. As a general comment it can be said that the high-performance materials/configurations in the building sector include multiple issues, ranging from the structural strength of the materials to strategies which propose multifunctional façades (for ventilation, daylighting control, energy production, etc.).

In the report of BASF [1] it was noted that the envelope of a building should control heat flow, moisture flow and air flow and at the same time it should offer structural integrity and protection from wind, rain, snow, hail, dust, pollutants, allergens and pests. A high-performance building envelope is defined by its ability to achieve these goals [1].

Based on the above mentioned issues, it can be seen that there are different factors which influence the performance of materials for buildings/constructions such as their structural strength, acoustic damping, heat/air/moisture factors, color/transparency, type of application (façade, roof, etc.), size of the building and cost. Furthermore, it should be taken into account that usually membrane materials offer more economic solutions than other types of cladding materials.

2.2. Requirements specifically for membrane configurations (roofs, façades, etc.)

2.2.1. Material selection for membranes

Paech [24] noted that different products have been developed in the field of membranes that can be used e.g. for façade applications. In general, there are two types of membranes: 1) textile membranes (consisting of a woven-based cloth), 2) foils (very thin extrusions with a thickness less than 0.4 mm). It was mentioned [24] that since single-layer membrane configurations have relatively low mass and thickness, they present a relatively high U-value and thereby, the single-layer structural membranes are mainly adopted as exterior sun screens, for wind and rain protection, as skins for semi-air-conditioned zones or to create a visual barrier between the interior and the exterior. Certainly, multi-layer membrane configurations show better thermal performance (in terms of the U-values). The multi-layer systems can be, for example, inflated membrane cushions or two-layer systems (with intermediate insulation) [24].

Additional issues/concepts, related with membrane architecture, have been presented in the report of Dyneon [35]. Some of these are following presented:

- Translucent membranes which absorb and reflect daylight with a unique fashion.
- Transparent air-filled membrane cushions (including ETFE).
- Configurations with different shapes (rectangular, etc.).
- Membranes with weatherproofed surfaces.
- Films made of ETFE which allow light and UV permeability.
- Glass fiber membranes.
- Highly-transparent films made of ETFE.
- Membrane spans.
- Membrane awnings.
- Structures composed of concave elements.
- Elastic structures.

In the frame of membrane architecture, Dyneon [35] proposed some film membranes made of 3M™ Dyneon™ ETFE which offer multiple advantages such as:

- High transparency.
- Printability.
- High UV transmission.
- Freedom of design.
- Low weight.
- Cost-effectiveness.
- Long lifetime.
- Self-cleaning surface.
- Weather and UV resistance.
- Resistance to fire.
- Wide temperature range in use phase.
- Variety of colors.
- Recyclability.

In addition, IASO proposed ETFE films (for "transparent architecture" applications) with the following advantages/characteristics [3]:

- Low weight.
- Possibility of coloring, printing and light guiding.
- High transparency (95% for the visible light and 85% for UV light).
- Excellent behavior in terms of the fire.
- Impermeable, self-cleaning with rainwater, low maintenance.
- Permeable to UV-A rays (but they do not allow UV-C rays to pass).
- Extremely durable and recyclable.
- Good resistance in terms of hail, etc.
- No visible mechanical damage, no discoloring, no hardening.

On the other hand, in the work of Kawaguchi [36] it was highlighted another important advantage of ETFE: the fact that ETFE components are lightweight means that they provide protection in case of earthquakes (in contrast with the heavy ceilings).

By taking into account the above mentioned issues, it can be noted that the requirements for membranes for buildings include different parameters, ranging from characteristics which are important during use phase (thermal performance, temperature range, lifetime, self-cleaning, transparency, shape, elasticity, weatherproofing, etc.) to characteristics which are important at the end-of-life/disposal (recyclability, etc.).

2.2.2. Textile membranes

Different types of textile membranes can be found, depending on their "mesh". Mesh membranes can be adopted for applications such as sun screens but also for architectural building envelopes. Different patterns of meshes can be found, various colors (for certain cases) and some products are printable and they present different strength classes [24]. During the last years, laminated open mesh membranes have been developed: for example, glass/PTFE (polytetrafluoroethylene) (mesh membrane with a continuous lamination of a transparent fluorpolymer (ETFE, PTFE, etc.)). For this case, the advantage that they offer is relatively high transparency (> 50%) in combination with material strength [24].

2.2.3. Foils

Foil, primarily in the form of ETFE, is a membrane material that offers new design possibilities and an alternative solution to woven fabrics [37]. In the work of Zhao et al. [38] it was noted that as a construction and building material, ETFE foil is widely-used. However, it is still a new material compared with other materials (steel, wood, concrete, etc.). It was also mentioned that when ETFE foil is adopted for structures, it is often used in the form of inflated cushion [38].

Robinson [2] presented a work about ETFE foil cushions as building cladding. It was noted that ETFE foil cushions consist of alternating layers of ETFE film and air cavities and an inflation system pressurizes the foil cushions. It was highlighted [2] that ETFE cushion is a lightweight plastic which shows considerable benefits in comparison to traditional cladding materials. Moreover, ETFE foil cushions are highly transparent to light, self-cleaning, resistant to weathering. In addition, they can be manufactured in almost any shape and size, offering an efficient and low-maintenance structure for the building (alternative to glass for cases such as atria and shopping malls) [2].

With respect to foils, Paech [24] noted that ETFE offers thin films with very high transparency (up to 96%), but in comparison to textile membranes, ETFE has significantly reduced strength and the material properties are more sensitive under conditions of elevated temperatures. The thickness of the ETFE foils for the case of architectural applications is between 100 and 300 μm, while individual foil segments can be welded and seemed in order to form larger panels. In addition, ETFE foils allow printing. On the other hand, an alternative solution to ETFE foils are ECTFE (ethylene chlorotrifluoroethylene) foils. In the field of architectural applications, this is a relatively new product with abrasion resistance, excellent corrosion resistance and very good fire resistance. In general, ECTFE has similar material properties to ETFE but the major advantage of ECTFE is that the material has higher solar transmission and clarity [24].

Toniolo and Carella [39] present a work about ECTFE film for new buildings structures and it was noted that Halar® High Clarity ECTFE films from Solvay are the ideal substitute for glass and they outperform ETFE while currently they are considered as the best polymeric alternatives.

2.3. Mechanical and other properties of ETFE material

2.3.1. Mechanical properties

Galliot and Luchsinger [6] investigated the mechanical behavior of ETFE foils under uniaxial tension, standard biaxial extension and bubble inflation. The experiments which were conducted based on a biaxial machine showed that the load ratio has no influence on the elastic properties at small strains and there is no major advantage of using biaxial testing over uniaxial testing for the evaluation of the material initial behavior. It was also noted [6] that uniaxial tensile tests are easier to conduct and they do not require much material and time. It was highlighted that the main disadvantage of the uniaxial tests is the fact that with standard equipment it is not possible to evaluate Poisson's ratio. This can be solved by using an additional device in order to measure the transverse strain in the sample. Another issue related with uniaxial tests is that the failure happens at very large strains which are not representative of the strains that the foil undergoes under large biaxial stresses [6]. On the other hand, bubble inflation tests should be adopted in order to study the biaxial failure of the foil. For design analysis, a linear or bilinear elastic model can be utilized as a first estimation of the material behavior up to the second yield point. For more accurate predictions, it is critical to include rate- and temperature-dependent behavior. The experiments [6] showed that the material behavior is non-homogeneous after the second yield point. It is also expected that the material behavior becomes anisotropic because of the reorientation of the molecular chains at large strains. Finally, it was noted that further studies are necessary to better understand the viscoelastic and plastic behavior of ETFE foils and using prestressing of the foil to increase the first yield stress would be interesting for the improvement of the load-bearing capability of ETFE foil structures [6].

Charbonneau et al. [7] conducted an experimental study about the mechanical behavior of ETFE foils. Creep tensile tests for different stress levels and for different time frames as well as tensile stress–strain tests were performed. Moreover, a one-dimensional creep model based on multi-Kelvin and power law modelling was presented. ETFE films show short-term creep under levels of stress expected in structural applications and the creep strain of the foils increases with the stress level. More analytically, at 2 MPa very little creep strain (0.015–0.033%) occurred in a basis of 24 h. Nevertheless, at 14 MPa the 24-h creep strains were 3.6–10.4%. Moreover, differences between the responses of films tested in the longitudinal and transverse directions were observed. In general terms, the films tested in the transverse direction experienced higher elastic and creep strains. It was noted [7] that the extrusion of the films and the molecular structure of ETFE could be the reasons for this behavior. In addition, the different types of film presented differences in terms of the creep behavior. Moreover, constitutive models were developed in order to represent the observed creep behavior. Furthermore, nonlinear viscoelastic and viscoplastic models were developed for each creep test and for the 24-h tests the viscoelastic models showed a very close representation of the data for all the studied cases. The viscoplastic models offered a good representation at low stress levels; however, often deviated from the results at higher stress levels. Furthermore, tensile tests on the ETFE film were performed. In general, the findings showed that the films yielded and failed at higher stresses in the longitudinal direction than the transverse direction, but they were more ductile in the transverse direction. In terms of the average yield stresses, for all the films these ranged from 24 to 29 MPa (the average failure stresses ranged from 42 to 70 MPa). In Fig. 1, a schematic of an ETFE cushion is illustrated [7].

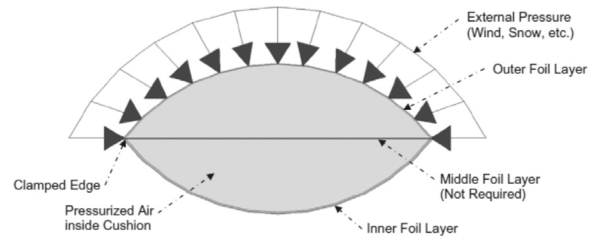

Fig. 1. A schematic of an ETFE cushion. (Source: Charbonneau et al. [7]).

Zhao et al. [38] demonstrated the technical feasibility of the flat-patterning method, as an efficient technique to find the form of ETFE cushion with the advantages of material cost efficiency, simple fabrication and easy installation. The main findings of Zhao et al. [38] are the following:

1. During the process of the whole form-developing, the stresses and strains of the ETFE cushion were found to be non-uniform. The maximum stresses were in the region from the center part to the middle parts of the three edges.
2. In terms of the creep phase, the internal pressure of the ETFE cushion was constant, but the rise and shape were increasing under the constant internal pressures of 4 kPa.
3. During the phase of creep-recovery, the shrinkage of the ETFE foils was proved by the variations in terms of the rise, internal pressure, stress and strain.

Wu et al. [40] carried out a model experiment on ETFE foil spring cushion. A temporary experimental hall using ETFE foil cushions as its roof was also constructed. It was demonstrated that the new structural system is easy in terms of the construction, it needs no air supply and control equipment, no running energy and low maintenance. Moreover, during the service time period of the experimental hall, the ETFE foil was tensioned very well by the compressed spring and no wrinkling of the foil was observed.

Hu et al. [8] investigated the uniaxial cyclic tensile mechanical properties of ETFE foils that are widely adopted in the frame of mechanical and construction industries. The experiments included eight cases with loading stress amplitudes from 4 to 21 MPa. The experimental findings demonstrated that the yield stress is a main mechanical property as the hysteresis loop and ratcheting strains become remarkable after the yield stress and that the elastic modulus, hysteresis loop and ratcheting strains evolve with the number of cycles and loading stress amplitude. In order to quantify these mechanical properties, a Matlab model was also developed [8].

Moreover, Hu et al. [9] presented a work about uniaxial tensile mechanical properties and model parameters determination of ETFE foils, adopted in structural engineering for membrane structures such as claddings and roofs. A series of uniaxial tensile tests under a wide range of temperatures and constant loading speeds were performed. The experimental findings were processed with mathematical methods in order to evaluate mechanical properties, such as first yield stress and elastic modulus. It was found that the first yield stress and elastic modulus decrease with increasing temperature but increase with the increasing loading speed. It was demonstrated [9] that the effect of temperature on the mechanical properties is stronger than that of the loading speed when considering the normal working conditions. In addition, a constitutive model based on viscoelasticity–plasticity of semicrystalline polymers was adopted for ETFE foils. The numerical results were in good agreement with the experimental findings. Related with the above mentioned issues about ETFE for building applications, in the work of Attipou [41] it was noted that ETFE is resistant to different temperatures and pressures.

ETFE foils present very high durability (in comparison to other transparent plastic materials). The basic characteristics of ETFE foils are: high tensile strength, high tear and impact strength. Moreover, ETFE is a very ductile material and it shows good failure behavior because of its large deformations before breaking point. In addition, ETFE foils are alkali resistant and solvent resistant (to a great extent) [42].

In the study of McKeen [43] it was noted that ETFE is a fluoroplastic with excellent electrical, chemical and mechanical properties. It was also highlighted that ETFE is especially suitable for applications which include high mechanical strength and adequate chemical, thermal, and/or electrical properties for a constructive material [43]. Moreover, it was mentioned that the mechanical properties of ETFE are superior to those of PTFE and FEP (fluorinated ethylene propylene). More specifically, the following characteristics/properties of ETFE were presented [43]:

- Excellent resistance to extremes temperatures (ETFE presents a wide range of working temperatures: from −200°C to 150°C).
- Mechanical strength (ETFE shows excellent tensile strength and elongation and it presents superior physical properties in comparison with most of the fluoropolymers).
- Excellent chemical resistance.
- Low smoke and flame characteristics.
- High resistance to weather and aging, excellent dielectric properties and nonstick characteristics.

In the study of McKeen [43] it was also mentioned that manufacturers and trade names include: DuPont™ Tefzel®, Asahi Glass Fluon® and 3M Dyneon™. In addition, uses and applications include: stadium roofing, electrical and fiber-optic wiring, liner in pipes, tanks and vessels.

In Table 1, selected literature references (years: from 2011 to 2016) about ETFE properties (with emphasis on the mechanical properties) are presented. From Table 1, it can be seen that:

1) There are different studies which examine ETFE properties, with emphasis on its mechanical properties, and these studies are based on different methods.
2) A considerable part of these investigations is about ETFE foils appropriate for cladding and roofing applications.
3) The results show that ETFE material shows resistance to temperature/aging as well as mechanical strength and chemical resistance.

2.3.2. Issues related with light transmission and insulation

In terms of the impact of longwave transmission on the total heat transfer, in the literature there is a study about energy modelling of ETFE membranes in building applications [10]. A mathematical model was developed, focusing on the maximum potential effect during a warm summer day. The results showed that the impact of longwave transmission is insignificant for the case of a warm sunny day [10].

With respect to insulating issues, a standard three-layer ETFE cushion presents around 1.95 W/m^2 K U-value that is remarkably better than triple glazing when used horizontally. Cushion insulating characteristics can be further improved by the adoption of further layers. In this way, U-values below 0.6 W/m^2 K can be achieved. On the other hand, ETFE foil absorbs a big part of infrared light transmitted, a quality which can be used in order to improve the energy consumption of the buildings [42].

Regarding light transmission, the optical characteristics of the transparent ETFE foil offer multiple advantages. ETFE shows high translucency by transmitting up to 94–97% of visible light (380–780 nm) and 83–88% of UV range (300–380 nm). This is an important issue for the well-being of humans and plants [42]. Moreover, the almost natural daylight makes the indoor environment more enjoyable for activities such as shopping (for the case of shopping malls) and swimming (for indoor swimming pools) and for places such as atrium roofs, markets, football stadiums and tennis courts. Another interesting issue is the fact that ETFE cushions can be lit internally with LED lighting in order to make them glow or projected onto externally (e.g. giant cinema screens) [42]. The utilization of ETFE material for roofs of swimming pools has been also examined in the work “Piscine publiques: sobres en énergie (2011)” [51].

Mainini et al. [12] proposed an alternative dynamic solar-gains-mitigation strategy for a double layer, non-cushion, ETFE panel for façades. A water spray system was located in the air-gap between the parallel ETFE foils in order to reduce surface temperatures and solar access. It was mentioned that the results are preliminary; however, it was noted that a reduction of up to 10% in total solar gains could be achieved as well as a reduction of 10°C in surface temperature.

Moreover, Mainini et al. [11] presented a work about measurements and evaluation of soiling effects of spectral light and solar transmittance decay of ETFE membranes (after three and six months of exposure; Milano city outdoor urban conditions; different tilt and orientations). The obtained values where utilized in order to evaluate thermal and solar properties of a multilayer ETFE panel. It was noted that after six months of exposure (urban outdoor conditions), ETFE showed decay in terms of light and solar transmittance performances. It was also mentioned that visible light transmittance is the most influenced performance. Soiling influences light transmission and solar heat gain coefficient of a double-layer ETFE; however, the average percentages of reduction are 4–8%. The maximum soiling was observed after 6 months of exposure, but soiling after three and six months were similar. The maximum performance reduction was found for the surfaces exposed on horizontal and the minimum for the vertical surfaces. The average value that was calculated for the thermal conductance was 5.158 W/m^2 K.

In addition, Ahadi et al. [13] proposed an improved transient-plane-source method for measuring the thermal conductivity of thin films. It was noted that the conventional transient-plane-source method cannot accurately evaluate bulk thermal conductivity of thin films and coatings due to the inclusion of thermal contact resistances in the results. A new modified transient-plane-source method was proposed, offering accurate measurement of bulk thermal conductivity of thin films and coatings. The results, based on the proposed method, showed thermal conductivity values of 0.174 ± 0.002 W/m K for ETFE [13].

Lau et al. [52] proposed an experimental approach in order to investigate the luminous environment in lightweight fabric structures. It was concluded that the selective use of transparent and translucent components in the ETFE envelope can offer well balanced, yet dynamic lit scenes. Furthermore, by combining single-skin ETFE foil and double-layer or triple-layer ETFE cushion and by introducing ETFE cushions with different light transmittance to the building envelope, improvement of the overall visual and luminous environment can be achieved [52].

In the literature there is also a study about the experimental assessment and thermal characterization of ETFE foils [53]. The study [53] focused on the evaluation of heat transfer through ETFE membranes as well as on issues such as heat losses and solar gains.

Regarding transmittance, the spectral transmittance of semi-transparent materials appropriate for protective covers of solar concentrators has been measured [54] and the results showed yielding solar-weighted normal transmittance values of 0.913 and 0.946 for 100 μm thin films of ETFE and FEP, respectively.

Based on the above mentioned literature studies about light transmission/insulation of ETFE material for building applications, it can be seen that, for example, ETFE cushion insulating characteristics can be further improved by using additional layers. Concerning light transmission, the optical characteristics of the transparent ETFE foil are very advantageous; however, it should be taken into account that in practice, after several months of exposure, ETFE shows decay in terms of light and solar transmittance performances.

Table 1
Selected studies about ETFE properties, focusing on mechanical properties.

Study/year	Main content of the study	Studied material	Methods/tests	Findings	Additional comments/results
Galliot and Luchsinger (2011) [6]	Uniaxial and biaxial mechanical properties	ETFE foils e.g. for claddings and roofs	Three commonly used test methods were compared: uniaxial tension, biaxial extension of cruciform samples, bubble inflation (bursting test)	All methods showed very similar results (the selection of a test procedure depends on its advantages and limitations)	Uniaxial tensile tests: the strain-rate in the material varied in the range of 0.4–200%/min; the elastic modulus of the material was between 1000 and 1200 MPa and the first yield stress between 14 and 20 MPa
Charbonneau et al. (2014) [7]	Mechanical properties of ETFE foils, based on testing and modelling	ETFE foils e.g. for claddings and roofs	ASTM D882-09 standard test method for tensile properties of thin plastic sheeting	At 2 MPa, very little creep strain was presented, in the range of 0.015–0.033% in 24 h (nevertheless, at 14 MPa, 24-h creep strains showed values of 3.6–10.4%)	Average yield stresses for all the films varied from 24 to 29 MPa (average failure stresses varied from 42 to 70 MPa)
Zhao et al. (2016) [38]	Mechanical models of ETFE cushion based on flat-patterning method	ETFE foils (inflated cushion)	Forming design method of flat-patterning	Over the whole form-developing process, the stresses and strains of the ETFE cushion are non-uniform, with the maximum stresses in the region from the center part to the middle parts of the three edges and the minimum stresses in the three corners of the ETFE cushion	During the creep phase, the internal pressure of the ETFE cushion is constant (nevertheless, the rise and shape are increasing under constant internal pressures (4 kPa) and as a result, the stresses of the ETFE cushion are decreasing)
Wu et al. (2011) [40]	ETFE foil spring cushion structure and its analytical method	ETFE foil cushion structures (for greenhouses, sport facilities, etc.)	Analytical method, numerical method; Loading test	The structural behavior of the spring cushion system was experimentally studied; It was found that the new structural system is easy in construction, needing no air supply and control equipment, little maintenance	During service period of the experimental hall, the ETFE foil was tensioned very well by the compressed spring (no wrinkling of the foil was observed)
Hu et al. (2014) [8]	Uniaxial cyclic tensile mechanical properties of ETFE foils under eight loading cases	ETFE foils for mechanical and construction industries	Methods in the MATLAB program; Uniaxial cyclic tensile test	The experimental results revealed that the yield stress is a major mechanical property as the hysteresis loop and ratcheting strains become noticeable after the yield stress	The fact that the first loading elastic modulus differs from subsequent loading/unloading elastic modulus gives explanations to the discrepancies found between the numerical findings calculated based on the uniaxial mechanical properties and the experimental results under field loading conditions
Hu et al. (2015) [9]	Uniaxial tensile mechanical properties and model parameters for ETFE foils	ETFE foils e.g. for claddings and roofs	Mathematical methods, numerical; Uniaxial tensile tests	The effect of temperature on the mechanical properties is stronger than that of loading speed for normal working conditions	Uniaxial tensile tests were conducted and the experimental findings were processed with mathematical methods in order to evaluate the mechanical properties
Blum et al. (2016) [44]	Elastic range, yielding conditions, break and the influence on the analysis of ETFE-structures	Structures made of ETFE films	Uniaxial tensile test; Biaxial tensile tests: square samples; Multiaxial tests on circular samples	Biaxial tensile tests (square samples): a cross sample always has a tendency to deform into the shape of a circle; Multiaxial tests on circular samples: the tests on the cross samples were found to be unsatisfactory since the homogeneity of the stress state could not be proven	The stress-strain behavior of ETFE films can be divided into a linear elastic region and a plastic range
Yoshino and Kato (2016) [45]	Viscous characteristics of ETFE film sheet (under equal biaxial tensions)	ETFE membrane film structures for applications in construction	Biaxial tensile test; FEM	The behavior under biaxial tension test was expressed sufficiently accurate by the proposed theory; however, for the prediction of the biaxial creep strains for long-term, further improvements of the viscoelastic coefficients used in the proposed formulation are needed	The validity of the proposed constitutive equation was verified
De Focatiis and Gubler (2013) [46]	Thermal and mechanical response	Several commercial grades of ETFE copolymer films	Differential scanning calorimetry; Mechanical testing	The thermal analysis showed that, even if the films have similar degrees of crystallinity and melting temperatures, there are obvious differences in terms	Ways in which biaxial stretching could lead to improvements in terms of the properties across the plane of the film were proposed and

(continued on next page)

Table 1 (*continued*)

Study/year	Main content of the study	Studied material	Methods/tests	Findings	Additional comments/results
				of the melting endotherms and crystallisation exotherms	discussed in the frame of production of polymer electrolyte membranes for energy applications
Hirschmann et al. (2014) [47]	Thermo-mechanical characterization of fluoropolymer films	Fluoropolymer films with emphasis on applications for solar concentrators	Differential scanning calorimetry, dynamic mechanical analysis and tensile testing	FEP and THV could not fulfil the thermo-mechanical requirements in terms of glass transition temperature and yield strength at application relevant temperatures; As most appropriate materials, ETFE copolymers were recommended even if no ETFE film fulfilled all of the requirements	Five transparent fluoropolymer films were characterized: three different ETFE, one FEP and one THV; The goal of the study was to find an appropriate material for utilization as transparent layer in a pneumatic pre-stressed sun-concentrator made of polymer films
McKeen (2016) [48]	Tribology of fluorocoatings	Several fluorocoatings	ASTM D1894-08 standard test method for static and kinetic coefficients of friction of plastic film and sheeting, etc.	Static coefficient of friction of Chemours Tefzel® HT-2004-25% glass fiber reinforced polyethylene tetrafluoroethylene: 0.31 (static coefficient of friction) for pressure 0.69 MPa	Tribological properties are most often useful when the materials are used in dry lubrication applications but the tribological properties are often considered for other types of applications
Liu et al. (2016) [49]	Solar radiation properties of common membrane roofs	Membrane roof materials (ETFE, PTFE, PVDF, TPO and PE were examined)	Numerical simulations (CFD), specimen tests	ETFE and PE membranes show high solar radiation transmittance (up to 0.8) and this can be modified for example by printing silver dots	The temperature of the steel structures below ETFE and PE membrane roofs was found to be over 61.7°C during summer (at least 27.7°C higher than the ambient air temperature)
Ebnesajjad (2015) [50]	Chemical properties of fluoropolymers	Fluoropolymers	Several methods (exposure to boiling water, etc.)	The hydrolytic stability of ETFE is indicated by retention of its physical properties after an extensive exposure to boiling water: Tensile strength and elongation changed little after an exposure of 3000 h of unfilled ETFE to boiling water	ETFE presents excellent resistance to many chemicals: it is somewhat influenced by oxidizers, chlorinated solvents, (however, it resists acids, alkalis as well as organic solvents)

2.3.3. Lifespan

Flüeler and Aller [55] presented a work about long-term expectations and experiences of ETFE membrane constructions and it was noted that ETFE-membranes show an excellent physicochemical long-term performance, exceeding 30 years. During use phase (results based on three buildings) it was observed damage by hail (22 years of use). It was highlighted that such constructions should be protected against hail, impact of sharp objects and against vandalism [55].

In subsection 2.7, more details about ETFE lifespan and other issues which also influence the environmental profile of an ETFE system are presented, based on several literature studies.

2.3.4. ETFE vs. glass

In comparison to glass, ETFE film has lower weight, it transmits more light and it is resilient. Its properties such as self-cleaning (thanks to its nonstick surface) and recyclability at lower cost are superior [42]. For the case of pressurized pillows, it is possible to have control of sunlight transmission and effective insulation. Furthermore, ETFE material does not cause annoying echoes indoor. In addition, unlike glass, ETFE film is shatterproof [42].

Candemir [15] presented a work about an inflatable pillow system, based on ETFE, as a glass substitute for building envelope. The following issues were discussed:

- Regarding light transmittance, it was noted that double-layer ETFE and triple-layer ETFE present lower light transmittance in comparison to single-layer. Nevertheless, both double-layer and triple-layer ETFE pillows show higher values than double-glass glazing. However, it was highlighted that pillow system can interrupt the vision because of its curved nature. Glass and ETFE foil can glare and lose their transparency for high amounts of sunlight [15].
- In terms of thermal transmittance, it was explained, based on certain examples, that multi-layer ETFE configurations present better insulation properties than glass [15].
- Concerning acoustical performance, ETFE pillows may influence the internal comfort in a positive or in a negative way, depending on its use and design. The designer should be aware of the acoustical performance of the materials and even if ETFE pillows sound-reduction index is lower than the one for glass glazing, the use of double-glazing does not mean that double glazing contributes to the acoustical comfort [15].
- With respect to other issues, the advantages of ETFE in comparison to glass are the considerable reduction of the weight, the flexibility of the configurations and the increase of module «productivity» by transmitting the total sunlight spectrum (from UV to IR) to the solar cells (for the cases which combine PVs with ETFE configurations) [15].
- By taking into account building performance (including heating, lighting and mechanical equipment costs) membrane-glazing systems are found to be better than glass. The energy efficiency, along with the durability and the flexibility of the pillows can be adopted for several applications, offering advantages for the building [15].
- In terms of the cost (for the system itself, for the construction and for the maintenance and transportation), membrane configurations offer cost-effective solutions in comparison with conventional structures (based on conventional materials e.g. glass) [15].
- From environmental point of view, ETFE foil presents considerably lower embodied energy per m^2 of surface (in comparison to glass) [15].

In the frame of the comparison ETFE vs. glass, in the work of Kronenburg [18] it was noted that extruded as a film, ETFE is lighter and stronger than glass, and its original architectural application was for replacement of greenhouse glass.

Based on the above mentioned literature studies, it can be noted that ETFE shows many advantages, in comparison with glass, from different points of view (building, environment, etc.): lower weight, flexibility, self-cleaning, recyclability in lower cost, shatter-proofing, good transmission of the sunlight (possibility for combination of ETFE with PVs), cost-effective membranes, etc.

2.4. Acoustics related to structures with ETFE

Acoustics is one of different design issues that should be taken into account in order to assess if a lightweight, tensile fabric is suitable for a building enclosure. Materials such as ETFE and PTFE are widely used, offering multiple advantages (UV resistance, high reflectance, flexibility, waterproofing, light transmittance, etc.). However, further research studies should be conducted, by taking into account the suitability of the materials based on space use and occupancy [20]. Lightweight fabric membranes such as ETFE pillows present interesting acoustic properties because of the inherent thickness, weight and airspace. The benefit of this acoustic transparency is the fact that the reflected sound can enhance the acoustic energy back into the space. An example of this effect can be found in stadia where the noise from the crowd can enhance the sense of excitement. Nevertheless, a disadvantage is that the reverberation and noise build-up from the middle to high frequencies is difficult to control for speech intelligibility. On the other hand, the noise that it is generated from the inside of a space enclosed with a membrane skin façade may disturb nearby people and buildings. In addition, environmental noise (for example from aircrafts, cars and railways) may easily be heard inside the space and it may be distracting for the occupants [20]. Moreover, rain noise is another issue for lightweight fabric membranes. The impact from rain falling on a lightweight fabric system can cause a drumming noise inside the space and usually noise mitigation is needed in order to minimize the effect of this impact noise. In this way, manufacturers of ETFE and PTFE materials are aware of this issue and they offer integral acoustic solutions so as to reduce rain noise [20]. For example, there are ETFE roofing systems with rain suppressors [56]. Related with the above mentioned issue, Toyoda and Takahashi [19] investigated rain noise from an air-cushion-membrane structure with ETFE films and it was noted that the results (theoretical and experimental) demonstrate the possibility of attenuating the noise by adding absorptive layers and/or damping materials.

Based on the above mentioned issues, acoustic design evaluations should be conducted at early design stages in order to examine if a lightweight tensile fabric system is appropriate for example for a building enclosure [20]. Some parameters related to this issue are: noise survey (sound measurements of external ambient noise, etc.), mechanical and electrical noise assessment, feasibility of speech intelligibility requirements. Finally, it should be noted that designers should know that different façade membrane products present different acoustic performances related to mass and material [20].

2.5. Shading issues about ETFE configurations

The material is very transparent and ETFE foil can be treated (by means of different ways) in order to manipulate its transparency and radiation transmission characteristics. In the frame of this concept, several strategies can be adopted such as the addition of more layers, tinting, printing, surface treatments and radiation [42]. Moreover, in the frame of «clever shading», it is also possible to control the amount of light that it is transmitted to the inside by adopting a combination of one translucent with two printed ETFE films into a three-layer configuration and by moving the middle layer up and down. In this way, maximum shading or reduced shading can be obtained (when it is required). Thereby, it is possible to make a building skin which is reactive to the environment through changes in climate [42]. It should be noted that the middle layer is programmed to rise and fall (by using the air pressure) in order to increase and decrease the percentage of printed area and thereby, to control the solar gains [42].

Cremers and Marx [22] presented a comparative study of a new IR-absorbing film for the improvement of solar shading and thermal comfort for ETFE structures. It was noted that standard ETFE foils show a very high solar transmission and this can create overheating and thermal discomfort. In this way, a new material infrared-absorbing was proposed by Nowofol (Nowoflon ET 6235 Z-IR). Cremers and Marx [22] presented a comparison between conventional ETFE constructions with clear (transparent) film or with silver printing (65%) and ETFE constructions of one layer with the new material Nowoflon ET 6235 Z-IR. The new IR-absorbing ETFE film is not fully neutral in terms of the color (its transmission and reflection is slightly blue/greyish). In the study [22], the upper membrane was replaced by the new IR absorbing foil. The meteorological data of Stuttgart (Germany) were adopted. For summer, the thermal comfort showed an improvement of approximately 10% compared to a conventional ETFE construction. The savings in terms of cooling energy were 5–8%. Different climatic zones were examined [22].

With respect to the above mentioned issues, a single layer of NOWOFLON ET 6235 Z-IR-Film offers reduced heat transfer [57]. In addition, the transparency is completely maintained through linear light transmission and there is no color distortion. The annoying reflections can be reduced by more than half. Regarding UV, the transmission of UV-light is reduced to UV-A. Moreover, this ETFE film presents longevity, flame resistance, mechanical strength and it can be printed with a wide variety of designs [57].

In addition, Martin et al. [21] presented a work about the thermal and lighting performance within an ETFE structure. The findings of the field studies revealed that the temperature within an unventilated enclosed ETFE-panel structure can become too high for occupant comfort (during the summer). On the other hand, the enclosure may need heating during winter. The necessity for ventilation and shading in order to extend the time periods of comfort was discussed. The overall brightness within the structure was found to be acceptable but rather high for the occupants during intense insolation. It was noted that plants would prosper under slightly diffused light [21].

2.6. Inspection of transparent construction materials

Hinz et al. [23] presented a work about an image engineering system for the inspection of transparent foils, in particular ETFE foils. The developed bursting test, including the photogrammetric recording and image analysis system, offers possibilities for the evaluation of transparent materials, such as ETFE foil, in the multi-dimensional viscoelastic range up to the breaking point. It was highlighted [23] that the system can acquire precise 3D and 4D information. It was also noted that the calculated results are adequate to study the strain behavior of the foils quantitatively at early and middle stages. Moreover, it was mentioned that the point accuracy should be improved in order to evaluate the strains at later stages [23].

2.7. Issues about ETFE from LCA/environmental point of view

In the study of Robinson-Gayle et al. [14] it was noted that ETFE is sold by manufacturers in granules and it is heated to its softening temperature (170°C) in the hopper of an extruder. Then, the extrudate is blow moulded into large sheets and the sheets are heat welded together in order to form the three-layer cushion. Moreover, the pneumatic cushions are suspended in aluminium or steel frames. A critical issue is the very high heat input necessary to cause the raw materials combination. In addition, there are significant gaseous by-products (such as CO_2, SO_x and NO_x) [14]. Furthermore, embodied-energy values of 26.5 GJ/t and 27.0 MJ/m^2 (for ETFE foil) and 20 GJ/t and 300 MJ/m^2 (for glass) were presented [14]. Related with the above mentioned issues, in the work of Candemir [15] it was highlighted that, ETFE foil presents remarkably lower embodied energy per m^2 of surface (comparing to glass). On the other hand, Cremers [16] highlighted that in the literature there are big differences in terms of the proposed values of ETFE embodied energy, ranging from 26.5 MJ/kg [14] to 210 MJ/kg [17].

In the work of Monticelli et al. [17], details about the ETFE embodied energy were presented. The case examined was the embodied energy in order to obtain 1 kg of an extruded ETFE film. The system boundaries were from the retrieval of the raw material to the cushion make up, taking into account the extrusion process. The embodied energy during the cushion manufacturing phase was around 210 MJ/kg:

- 173 MJ are because of the generation of the raw materials; it was noted that (for ETFE) there are gases (ethylene and R22) which are introduced in the polymerization process: 80% of this amount is due to the production process of the chlorodifluoromethane (because of the utilization of natural gas and brow coal during its creation process), which produce TFE (tetrafluoroethylene) by pyrolysis [17].
- 28 MJ are because of the polymerization process and granulation of the raw materials into ETFE pellets (53% is the energy rate from steam, 35% is from electricity and 12% from gas) [17].
- 9 MJ are due to extrude ETFE pellets in thin films [17].

Maywald and Riesser [58] examined (from environmental point of view) the use of glass and the use of ETFE (Texlon® ETFE) in the frame of two projects in Germany (Berlin and Aachen), based on LCA. A lifespan of 30 years was considered for both cases (ETFE and glass). The selected standard foil cushion consists of three layers of NOWOFLON® ET foil. The selected glass includes double-glazing with panes, laminated with a PVB (polyvinyl butyral) film. The method of CML was adopted for the LCA, based on 1 m^2 of roof for both claddings. It was noted that globally, the results of the environmental impact assessment are better for the Texlon® roof than for the glass roof, except of the impact category of Ozone layer depletion. The production of Texlon® cushions requires much less energy in comparison to glass production, and less structure materials are needed in order to support the whole system (thereby, there is less impact during manufacturing phase). It was highlighted that ETFE foil membranes can be considered as a more ecological solution in comparison to glass [58]. Results about the environmental impact for the production of 1 m^2 of a representative foil cushion (average values from 2012) for NOWOFLON®ET foil have been also presented in the report “epd-norge.no” [59], based on “environmental product declaration”.

In addition, in the work of Viguier [60] it was highlighted the fact that ETFE is a recyclable material, a characteristic that shows interest (from environmental point of view): for example in the frame of the evaluation of ETFE systems over their lifespan, end-of-life and disposal.

Flexible PV modules (flexcell) from amorphous silicon covered with an ETFE layer of 0.1 mm thickness have been evaluated, based on Ecological Scarcity 2006 method [61]. The findings of the study showed that the supply chain of ETFE has a major contribution to the environmental impact of the Flexcell modules. In the frame of a sensitivity analysis, the effect of a thinner ETFE coating on the environmental performance of the modules was examined. The coatings of 0.05 mm ETFE and those of 0.025 mm ETFE respectively, were compared to the standard thickness of 0.1 mm ETFE and the results revealed that by using half thickness, the environmental impacts of a module are reduced by a percentage of 18% [61]. It was noted that the chlorofluorocarbon emissions during the phase of production of the ETFE feedstock (R22) remarkably influence the results of different indicators. Moreover, it was mentioned that the data quality of the ETFE production was medium (because of the lack of production data, the material consumption and certain emissions were modelled theoretically) [61].

In addition, it should be noted that information in terms of life-cycle inventory data about ETFE have been analytically presented

Table 2
Selected literature studies which include LCA/environmental issues about ETFE.

Study/year	Materials	Environmental issues studied	Expected lifespan, durability, etc.	Additional information
Robinson-Gayle et al. (2001) [14]	ETFE foil cushions	Embodied energy: 26.5 GJ/t and 27.0 MJ/m^2	Current tests have run for 25 years; ETFE is very stable and it can resist chemicals and UV; its optical properties are not diminished over time	A comparison with glass was included, showing embodied energy for glass (6-mm float glass) 20 GJ/t and 300 MJ/m^2
Monticelli et al. (2009) [17]	ETFE film	Embodied energy to obtain 1 kg of an extruded ETFE film: 210 MJ/kg	ETFE pillows show outstanding durability, reducing the needs of replacement	The greatest part of the embodied energy is due to the generation of the raw materials introduced in the polymerization process
Monticelli (2010) [64]	ETFE cushions	The multi-layer ETFE cushion involves less energy (159.6 MJ/m^2) than other roofing systems	ETFE pillows show remarkable durability (40 years)	ETFE-cushion roof requires less energy (than other roofs) because it is lightweight and it needs less quantities of materials
Maywald and Riesser (2016) [58]	ETFE foil vs. glass	CML method; ETFE foil membranes can be considered as a more ecological solution in comparison to glass	A lifespan of 30 years was considered for both materials (ETFE and glass)	Selected materials: standard foil cushion of three layers of NOWOFLON® ET-foil; Glass: double-glazing with panes, laminated with a PVB film
Jungbluth et al. (2012) [62]	ETFE, at plant	Inputs and products; Energy demand; Water use; Transportation; Infrastructure and land use; Emissions to air; Emissions to water; Solid waste	ETFE: its resistance to chemicals and solvents is excellent (strong acids and bases have no effect on ETFE resins)	Unit process raw data and uncertainties for ETFE copolymers (at plant) were presented
Zeh (2009) [65]	ETFE membranes	Durability, etc.	ETFE: it is supposed to have a guarantee of 30 years	Two structures roofed in PVC-coated polyester and one structure roofed in ETFE were compared

(including unit process raw data and the uncertainties for the production of 1 kg ETFE) in the report of Jungbluth et al. [62]. Moreover, Monticelli and Zanelli [63] presented a review about life-cycle design and efficiency principles for membrane architecture, including information about ETFE environmental profile.

In terms of the production of ETFE, ETFE is produced by mixing tetrafluoroethylene and ethylene monomers and the copolymerization of these monomers is very energetic. The copolymers of tetrafluoroethylene and ethylene can be prepared based on aqueous, non-aqueous, or mixed systems [62]. In the work of Jungbluth et al. [62] it was also noted that ETFE can be reinforced by using glass fibres. The operating temperature of ETFE resins is from around −100°C to (at least) +150°C. ETFE is a good insulating material and ETFE resins are non-flammable in air [62].

In the literature there is also a study about LCA of polymer solar cells [28]. Several scenarios were examined, including encapsulation steel-foil/EVA/ETFE, in analogy to flexible PV modules manufactured on metal substrates [28].

In Table 2 information about ETFE that is related with the environmental profile of an ETFE system over its life-cycle, is presented. From Table 2 (studies conducted from 2001 to 2016) it can be seen that:

1) Most of the investigations examine embodied energy, showing values ranging from 26.5 to 210 MJ/kg, depending on the assumptions/boundaries adopted for each study.
2) Several types of ETFE appropriate for building applications (foils, cushions, etc.) have been examined.
3) Some studies compare ETFE with glass and the results reveal that, in general, ETFE configurations can be considered as more environmentally friendly than glass-based systems.
4) ETFE material is resistant, with lifespans ranging from 25 to 40 years.

2.8. Applications

2.8.1. Requirements in terms of claddings

Before presenting studies about ETFE façades (and, in general, about ETFE for buildings), it is necessary to present some information about the requirements for the case of claddings. In the work of Paech [24] several critical issues were presented:

- Protection of the interior of the building from the external environmental conditions (rain, temperature, sun, wind, etc.).
- Creation of private interior spaces.
- Withstanding of the outer loads (maintenance loads, temperature, wind, etc.).
- Good thermal performance and good performances with respect to solar radiation and light management and response.
- Good fire behavior of the materials.
- Acoustic performance.
- Durability.
- Aesthetic value and appearance of the surface (in terms of translucency, color, etc.).
- To allow complex architectural geometries (for certain cases).
- Weight of the materials.
- Cost of the materials.
- Installation issues (regarding costs, time, etc.).
- Maintenance requirements.
- Recyclability of the components and sustainability.

Paech [24] noted that since the cladding is the main component of a façade, the materials and their specific requirements should be examined during the initial stage of the design. Given the fact that building projects are very distinctive (in terms of their location, their purpose, etc.) it is impossible to list all the demands for each application with claddings. However, the above mentioned factors present some critical issues.

2.8.2. Studies about ETFE façades, roofs and atria

Paech [24] presented a work about structural membranes used in modern building façades. General demands about façade systems were analyzed. Material and system options, properties, limits of membrane façades, case studies and multiple solutions including typical material combinations (ETFE, glass-PTFE, PVC polyester, glass-PTFE mesh, multi-layer insulated systems) were also discussed.

Robinson-Gayle et al. [14] presented some examples of ETFE foil roofs. It was concluded that ETFE foil is an appropriate technology for specific building applications, especially for the cases where the volume of the space is large and there is a need for high levels of light. In addition, it was highlighted that ETFE foils can improve the environmental performance of a building and they can reduce the overall environmental burden related to the construction process as well as the burden of the building over its lifespan [14].

Afrin et al. [25] presented results based on on-site monitoring of foil surface temperatures and thermal environment within two atria configurations covered with different compositions of ETFE foil cushion roof (1: two-layer, 2: three-layer) and different ventilation regimes. A strong vertical stratification in both atria was found. Moreover, it was demonstrated that the foil surface temperatures respond rapidly to high solar radiation with the internal layer being hotter than both the external layer and the adjacent internal air. Furthermore, it was found that during night the surface temperature of the external foil follows the ambient external temperature closely and the internal layer temperature follows approximately the mean of adjacent internal temperature in the atria and external temperature [25].

Masih et al. [66] presented the results of a field work about the luminous environment of an atrium enclosed by ETFE cushion roof and a test structure constructed with ETFE-encapsulated panels. A theoretical study was also conducted. The goal was to examine how the typical homogeneous and dull luminous environment can be improved. It was found that the selective use of translucent and opaque components in the frame of ETFE enclosures can offer good lighting conditions [66]. In addition, the selective positioning of these components in different parts of the ETFE structures can enhance the visual perception. Different case studies were examined. One of these case studies is based on the Engineering and Science Learning Centre at the University of Nottingham, including student support office, graduate center, learning and teaching spaces as well as a multi-functional central atrium. The atrium roof consists of three-layer ETFE cushions with extruded aluminium frames connected to the primary steel truss structure. The geometry of the above mentioned building has an arc-shape in plan and the atrium roof offers daylight for all the internal spaces. In addition, a glazed aperture on the top of the south-west façade provides supplementary daylight (Fig. 2) [66].

In addition, configurations with ETFE for roofs/atria have been presented in the following works: INRA [67], Tanno [68], Découverte en avant-première du pôle de Commerces et de Loisirs Confluence [69].

2.8.3. Combination of ETFE with PV or PVT

Zhao et al. [70] conducted field experiments and numerical modelling in order to study the temperature of an amorphous-Si PV system which is combined with a three-layer ETFE cushion roof. The experiments were done for four typical weather conditions (winter sunny, winter cloudy, summer sunny and summer cloudy). The results showed that the temperature variation under cloudy condition was more significant than that under sunny condition. Comparisons between experimental and numerical results were presented. For the temperature characteristics, a good agreement between experimental and modelling findings was observed.

Hu et al. [71] presented a work about experimental studies on summer performance and feasibility of a system which combines BIPVT (building-integrated photovoltaic/thermal) with ETFE cushion. The proposed system offers collection of thermal energy due to enclosed cushions. An experimental mock-up of a three-layer ETFE cushion and amorphous-Si PV modules was developed. Experiments were performed during summer, (especially for sunny and sunny-to-cloudy conditions). The results based on the experiments demonstrated that the system operates smoothly and steadily. One-day and three-day evaluations of the system were done. The findings showed that for energy, the average stored electricity was 61 Wh. In addition, the average temperature difference between the air temperature inside and outside of the cushion was found to be 18.1°C [71]. In this way, system electricity feasibility and potential in solar energy utilization were verified. For cushion structures, the temperatures on structural ETFE membranes used to resist external loads were within the acceptable range and the pressure performance was found to be satisfactory. Thus, the structure feasibility was demonstrated. Hu et al. [71] noted that their study reveals the technical feasibility of ETFE cushion structure integrated with PV and it was mentioned that their study provides a way to extent BIPVT/cushion applications [71]. Furthermore, there is a study [72] which examines the performance of organic PV layers on architectural membranes. It was noted that organic PVs are promising due to their low cost and easy fabrication. Several cases in terms of organic PVs in combination with architectural-membrane materials were discussed [72]. It was highlighted that ETFE printed Ag layer conductance is a little less sensitive than PET (polyethylene terephthalate)-printed one with large strains, which is highly favored for the use of ETFE as a substrate of organic PVs [72].

Additional studies which include ETFE combined with PVs have been presented by Hu et al. [26], Hu et al. [27], Lenzmann et al. [28] as well as in the frame of the ETFE-MFM project [73]. In Fig. 3 the experimental ETFE-PV mock-up (Fig. 3a) and the PV arrangement (Fig. 3b) studied by Hu et al. [26] are illustrated.

2.8.4. Several configurations which include ETFE

In the frame of the project “Emballage de la Rotonde” [74] for “La Rotonde de Saint-Etienne”, in France, several plastic materials were examined (based on different criteria: economic, environmental, mechanic). It was noted that a double ETFE membrane around the construction of “La Rotonde de Saint-Etienne” can provide multiple benefits (e.g. insulating effect by means of a recyclable material) [74].

Within the field of agricultural applications, ETFE material can be

Fig. 2. The external and internal views of the Engineering and Science Learning Centre at the University of Nottingham. (Source: Masih et al. [66]).

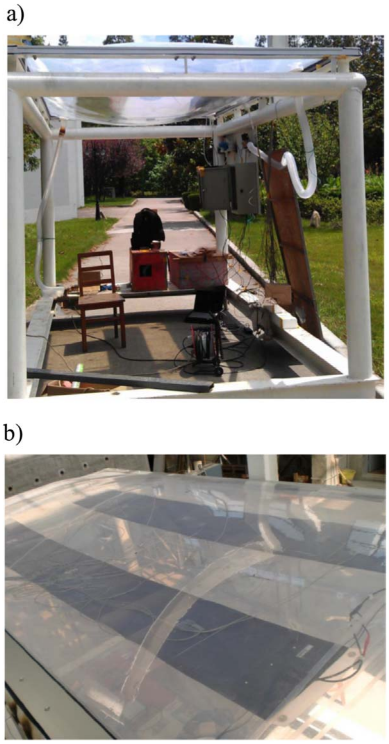

Fig. 3. a) Experimental ETFE-PV mock-up and b) PV-arrangement. (Source: Hu et al. [26]).

also adopted for greenhouses [15,18,66,75]. In the work of Masih et al. [66] a test structure with ETFE-encapsulated panels (two-layer 150 µm ETFE foils) as external skin built at the garden of a detached house (near Grantham, UK) used as an outdoor room and a greenhouse for plants (Fig. 4), was presented. In addition, in the study of Waaijenberg et al. [76] about a highly insulated greenhouse design with an inflated roof system with PVDF (polyvinylidene fluoride) or ETFE membranes, it was noted that new materials such as PVDF and ETFE-membranes offer an opportunity to create a double inflated structure, which has a light transmittance comparable to single glass thanks to the very high initial light transmittance of these films.

Another type of ETFE applications refers to solar thermal collectors. Beikircher et al. [77] presented a work about a flat-plate collector for process heat with full surface aluminium absorber, vacuum super insulation and front foil. It was noted that between the glass cover and the absorber of the collector it is added a transparent ETFE foil for the reduction of the heat loss coefficient. Related with the above mentioned study, Beikircher et al. [78] presented a review about advanced solar flat-plate collectors with full area absorber, front side film and rear side vacuum super insulation.

Other types of applications include ETFE for fuel cells [79–81], ETFE for inflatable tubes [82], ETFE as materials to protect for example reflectors of solar concentrators [54], ETFE for electrical and fiber-optic wiring, liner in pipes, tanks and vessels [43].

2.8.5. Discussion about ETFE applications

Based on the literature it can be seen that ETFE can be adopted in the frame of different applications: for example for roofs, façades, atria as well as in combination with PVs. Except of the building sector, ETFE has also agricultural applications, e.g. for greenhouses. Moreover, ETFE can be used as additional component for the development of solar systems (solar thermal collectors, etc.).

Regarding ETFE-PV combination, it can be noted that ETFE shows interest for example for organic PVs, for flexible amorphous-Si PVs, for BI (building-integrated) applications. ETFE provides a protection (from weather conditions) for the PV cells and specifically for BIPV (building-integrated photovoltaic) systems, configurations with ETFE can offer multiple advantages: enhancement of the use of BIPV systems in constructions, development of innovative façades with different lighting possibilities, etc [73].

For the specific case of adopting ETFE as cladding, certainly, certain requirements (which are requirements, in general, for cladding materials) should be fulfilled: good thermal performance, durability, high aesthetic value, low weight, good performance in terms of solar radiation and light management and response, etc.

2.9. Case studies

In the present subsection several case studies based on ETFE material, with emphasis on buildings and architectural constructions, are presented (Table 3). From Table 3 it can be seen that:

1) The case studies refer to several countries with different climatic conditions (Spain, UK, France, Germany, etc.).
2) Multiple ETFE configurations have been presented (membranes, inflated cushions, with/without lighting, transparent or printed, etc.).
3) The constructions are for different uses (commercial, sports, etc.).
4) ETFE configurations offer multiple advantages (they can be manufactured to any size and to fit any shape, they can be combined with modern constructions as well as with buildings of historical character, etc.).

In general, the case studies demonstrate that ETFE can play an important role in the building sector, offering multiple configurations. For example, the combination of ETFE with PVs (e.g. AWM Carport [73]) is an interesting solution, taking into account the importance of PVs towards the development of net zero energy buildings [97] which provide advantages from energetic as well as from economic point of view [98]. Another example is the combination of ETFE with different types of lighting, pleasing from aesthetic point of view [73]. In addition, ETFE configurations offer possibilities for ventilation and temperature control [3,90] as well as natural daylight illumination [3,89].

Fig. 4. The external and internal views of a structure with ETFE encapsulated panels: external skin built at the garden of a detached house used as an outdoor room and a greenhouse for plants. (Source: Masih et al. [66]).

Table 3
Selected case studies with constructions which include ETFE material.

Name of the construction and reference	Location	ETFE configuration	Use of the construction	Additional information
Memorial [83]	Madrid, Spain	Glass cupola in combination with ETFE	Memorial	The memorial includes 2 parts, related: the glass cupola and the room underneath it (from the room, the visitors can see the inside part of the cupola)
Millennium Dome [73]	Valladolid, Spain	ETFE in combination with lighting	Multiple activities	ETFE can be combined with different types of lighting
Centre de loisirs Vitam'Parc [84]	Neydens, France	ETFE in combination with a wooden construction	Sports, commercial	The aquatic center has a wave-shaped roof
L'heure tranquille [85]	Tours, France	Inflated ETFE cushions	Commercial center	The construction includes arcs which are combined with ETFE
Grand Stade du Havre [86]	Le Havre, France	Dyed ETFE-membrane, four specially developed shades of blue	Stadium	A stadium forming a uniform and integrated whole
SMAC de Nîmes [87]	Nîmes, France	Façade composed of ETFE cushions	Music hall	The north façade looks like a huge “eye”
Lyon Confluence [88]	Lyon, France	Double-layer ETFE cushions	Shopping and leisure center	There is an enormous illuminated membrane roof
Hampshire Tennis and Health Club [89]	Hampshire, UK	The cladding system over the Tennis Center consists of opaque white Texlon ETFE foils within an exterior tensile structural system	Tennis and health club	The cladding system over the Tennis Center is an elegant and economic; The opaque white foil offers diffusion of the natural daylight and natural ambient illumination ideal for sporting events
Chelsea and Westminster Hospital [90]	London, UK	Texlon® ETFE inflated panels	Hospital	A Texlon® ETFE roof needs no external cleaning because it is self-cleansing (under the action of rain), in this way, there are savings in maintenance costs; Texlon® ETFE roof system offers effective ventilation and temperature control, important for a hospital
King's Cross Station [91]	London, UK	Glass, ETFE, polycarbonate	Railway station	The intelligent use of glass and translucent products offers a contemporary railway architecture
Kingsdale School [92]	London, UK	“Variable skin” ETFE roof enclosure	School	An inspiring mixed-use space based on various design interventions is offered
Olympic Swimming Pool, Munich [93]	Munich, Germany	A flexible façade connection includes a pneumatic tube made of ETFE foil	Swimming pool	There is light-flooded appearance of the swimming pool
Festo headquarters [94]	Esslingen, Germany	Texlon® ETFE inflated panels, Texlon® ETFE shading system	Offices	The design includes six finger-like buildings connected by means of a central spine. Three of these spaces are covered by Vector Foiltec state-of-the-art Texlon® ETFE variable shading system – Vario® – and in this way, they offer dynamic multi-function atrium spaces
Allianz Arena [73]	Munich, Germany	ETFE in combination with lighting	Football stadium	ETFE can be combined with different types of lighting
AWM Carport [73]	Munich, Germany	ETFE in combination with PVs	Vehicle services	The combination of ETFE with PVs can enhance the use of BIPV
Masoala Rainforest Zoo [95]	Zurich, Switzerland	Membranes of ETFE foil	Zoo, tropical house	The size is 14600 m^2
Shopping Mall Dolce Vita Tejo [31]	Amadora, Portugal	Multi-layer ETFE cushion roof	Shopping mall	Innovative building envelope
Commercial center Arena [3]	Valencia, Spain	ETFE double-layer cushions	Commercial center	The cushions include printed and transparent configurations
Malls/Caraba square Islazul [3]	Madrid, Spain	ETFE double-layer cushions	Malls, square	The cushions include printed and transparent configurations
San Mamés New Stadium [3]	Bilbao, Spain	Monolayer ETFE membrane	Stadium	The ETFE membrane is of white color; The façade is composed of more than 2700 membranes

(continued on next page)

Table 3 *(continued)*

Name of the construction and reference	Location	ETFE configuration	Use of the construction	Additional information
Urban space station, Museum of Modern Art Reina Sofía [3]	Madrid, Spain	Transparent ETFE film	Urban space station, museum	The ETFE membranes can be adapted to any type of project, including new applications
Pavilion (for banquets) in the Restaurant Les Cols [3]	Olot, Spain	Double-layer ETFE	Pavilion in restaurant	The ETFE layer is printed and transparent; There is a space with a special atmosphere thanks to the combination of shadows, light and trees above the ETFE cover
Hotel Villa de Laguardia [3]	Laguardia, Spain	Triple-layer ETFE cushions	Hotel	The ETFE layers are printed and transparent; ETFE is used for a semi-circular cover which attenuates the entry of light and solar radiation
Commercial center Vallsur [3]	Valladolid, Spain	Triple-layer ETFE cushions	Commercial center	The solar control system moves the intermediate layer up or down, in this way it changes the passage of light and the solar radiation inside the building
Ancient church of Sant Pere [3]	Corbera d'Ebre, Spain	Monolayer ETFE	Church	The transparent ETFE cover offers a perfect integration with respect to the historical character of the building and it provides a multifunctional space
Commercial center Leclerc Les Portes du Valois [3]	Le Plessis Belleville, France	ETFE: Triple-layer cushions for the building and monolayer for the accesses	Commercial center	At the level of the access to the building the transparent domes are constructed with a monolayer system of ETFE membranes; During the day, natural light floods into the interior space
Allianz Riviera stadium [3]	Nice, France	Monolayer ETFE; Exterior and inner ring	Stadium	The complex structure of wood and steel is visible from the outside through the transparent ETFE enclosure
Le Nuage [96]	Montpellier, France	ETFE cushions for façades and covers	Sport center	Surface: 2200 m^2
School of Health Sciences, University of Aveiro [3]	Aveiro, Portugal	Double-layer ETFE for the building and monolayer ETFE for the footbridges	University	Footbridges: The transparent enclosure allows natural ventilation through openings
Central train station of Luxembourg [3]	Luxembourg	ETFE membranes printed	Train station	ETFE covers show a natural integration with the neo-baroque architecture of this building
Aqualibi water park [3]	Wavre, Belgium	Triple-layer ETFE cushions, transparent	Water park	The ETFE configuration offers conditions close to those of outdoor conditions

3. Conclusions

By taking into account that in the literature there are few review studies about ETFE material, the present article is a critical review about ETFE, with emphasis on building applications.

Selected literature references about ETFE properties (focusing on mechanical properties) are presented and the results show that: 1) the investigations are based on different methods, 2) a considerable part of these investigations is about ETFE foils for claddings/roofs and 3) ETFE material presents resistance to temperature/aging, mechanical strength and chemical resistance.

On the other hand, studies about light transmission/insulation of ETFE material for building applications are included, showing that ETFE cushion insulating characteristics can be further improved by utilizing additional layers. Regarding light transmission, the optical characteristics of the transparent ETFE foil are very advantageous but after several months of exposure, ETFE shows decay in terms of light and solar transmittance performances.

In addition, investigations which compare ETFE with glass are cited, revealing that ETFE offers many advantages, in comparison with glass, from different points of view (building, environment, etc.).

A separate part of the article is based on literature studies about ETFE environmental profile/LCA and the results demonstrate that: 1) most of the investigations evaluate ETFE embodied energy, showing values ranging from 26.5 to 210 MJ/kg, 2) different types of ETFE for building applications (foils, cushions, etc.) have been investigated, 3) certain studies compare ETFE with glass and the comparisons reveal that, in general, ETFE can be considered as more environmentally friendly than glass, 4) ETFE material is resistant, with lifespans ranging from 25 to 40 years.

Concerning ETFE applications, ETFE can be used for different applications: roofs, façades, atria, etc., in combination with PVs (interesting for cases such as BIPV systems and organic PVs), for buildings as well as for greenhouses.

Additional issues (requirements for adopting ETFE as cladding, acoustics, shading, inspection of transparent materials, etc.) are presented and critically discussed. A separate part with case studies is included, along with a discussion.

By considering the fact that ETFE is a promising material for the building sector, with multiple advantages (structures of low-weight, flexible structures with different shapes, etc.), the present article offers useful information about ETFE, based on different points of view.

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