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ENVIRONMENTAL IMPACT OF MEMBRANE AND FOIL MATERIALS AND STRUCTURES – *STATUS QUO* AND FUTURE OUTLOOK

WPŁYW MEMBRAN ORAZ MATERIAŁÓW I STRUKTUR FOLIOWYCH NA ŚRODOWISKO – *STATUS QUO* I PERSPEKTYWY

A b s t r a c t

In early times and until the 1970s most of the membrane structures built were meant to be temporary. This applies to early Roman shading systems, military, nomad and circus tents, as well as to Frei Otto's early oeuvres. The global building sector as a whole, is of great importance with regard to a future sustainable use of our planet's resources: Here, approx. 50% of all primary resources and 40% of all primary energy are used, and 30% of all green house gases are produced. Also, the sector is responsible for up to 40% of all solid waste[1]. This paper[2] provides an overview on the complex aspects of environmental impacts of membrane materials and structures, and how to meassure them using life cycle assessment methodology. It briefly shows where this kind of information is used (e.g., for building assessment systems/rating schemes) and finally indicates the current status in the membrane sector.

Keywords: Membranes, PTFE/glass, ETFE Foil, PVC/PES, Photovoltaics (PV), Life Cycle Assessment (LCA), Grey Energy, Environmental Product Declaration (EPD), Building Assessment Systems, Building Rating Schemes

S t r e s z c z e n i e

Aż do 1970 roku większość konstrukcji membranowych było traktowanych jako tymczasowe. Odnosi się to do wczesnych rzymskich systemów osłon przeciwsłonecznych, wojskowych, pasterskich i cyrkowych namiotów, jak również do wczesnych konstrukcji Freia Otto. Globalny sektor budowlany jawi się jako niezwykle istotny w kwestii przyszłego zrównoważonego wykorzystania zasobów naszej planety. Jest odpowiedzialny za wykorzystanie około 50% pierwotnych zasobów naturalnych, 40% pierwotnej energii i za produkcję 30% gazów cieplarnianych. Z nim jest związana również produkcja 30% stałych odpadów. Artykuł stanowi kompleksowy przegląd aspektów wpływów środowiskowych materiałów i konstrukcji membranowych, jak również porusza zagadnienie sposobu ich charakterystyki metodą oceny ich cyklu życiowego. Wskazuje również, gdzie taka informacja jest wykorzystywana (np. w systemach oceny budowlanej, metodach klasyfikacji) i ostatecznie ocenia obecny status sektora membran.

Słowa kluczowe: membrany, PTFE/szkło, folie ETFE, PVC/PES, ogniwa fotowoltaiczne, ocena cyklu życiowego (LCA), szara energia, deklaracja produktu środowiskowego (EPD), systemy oceny budynków, systemy klasyfikacji budynków

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[1] According to M. Atif, Chairman IEA Buildings & Communities, CISBAT 2007.

[2] This paper builds on material partly published before in [1–4], it reflects the status on the subject of mid 2013.

1. Introduction, key environmental issues affecting architectural fabric structures and the global picture

Increasing energy efficiency in the operation of buildings is a major challenge of our time. This normally refers to the energy demand (non-renewable) to run the building. But we also have to focus on the energy consumption ("grey energy") and environmental impact of the materials and structures used for our buildings, with regard to their full life cycle, from the production to recycling or disposal. This means, to add the topics of limited resources, waste and environmental impacts of materials and processes to the balance sheet and therefore, to the agenda. It is important to understand that the effects of our planning decisions extend deeply into the future. And with increasing energy efficiency, the relative impact of 'grey energy' of building materials and processes becomes much more important (cp. Ill. 2).

Most buildings using foil and coated textile materials today are meant to last for decades. The membrane industry is proud to also offer this perspective to its clients when they embark on its materials and structures. In parallel, the planet's resources are shrinking and become more and more contested and hard-fought. Compared to other industry branches, the building sector is still lacking efficiency in the use of materials and rationalization because the overall recycling rate is very low.

With regard to the membrane industry we see a two-faced discussion:
On the one hand, we apply polymers that use of the enormous amounts of energy for their production. They contain a high amount of primary energy in relation to their mass and emissions from some of the materials, can present dangers for the environment and users. This is a global issue: Membrane materials a perceived as being part of the world of polymers ("plastics"). And plastic debris is everywhere – on land and at sea, and on different scales: from big and visible things like PET bottles and plastic bags to extremely small, sand-sized things which get into the food chain and become a threat to many animals (fish, birds and others). And in contrast to a common expectation, polymers in the environment are a very long lasting type of material.

On the other hand, they have an undoubted potential for generating resource and energy savings through types of construction that utilise these materials very efficiently.

2. Traditional reasoning why membrane strcutures are beneficial to the environment

When it is argued that membrane structures and materials are environmentially friendly, people commonly refer to the very low mass per area of membrane material. There is a significant weight reduction compared to alternative transparent or translucent materials:

ETFE foil	~ 0,5 kg/m^2
coated fabric	< 1,8 kg/m^2
PC/PMMA (6–8 mm)	~ 5 kg/m^2
glass (10 mm, laminated)	~ 25 kg/m^2
membrane/foil vs. PC	~ 1:3 up to 1:10
membrane/foil vs. glass	~ 1:10 up to 1:50

But there are more reasons why the use of membrane material potentially reduces the weight of a building structure per square meter:
The use of membranes as a cover material allow for high deflection within the primary structure. This applies to the buidling envelope, i.e. facades, but most of all to roof structures. Membrane materials themselves are far lighter than rigid alternative materials. This leads to a reduction of downloads, also in combination with snow loads and thus to a lighter primary structure. Compared to other translucent materials, secondary structures can be significantly reduced (due to larger span potential and/or reduced safety issues). Typically, increase of secondary steel of a non-membrane solution[3]: 100–200%.

Combining membrane materials with cable structures, offer a high potential for further optimizing: Soft membrane materials allow for larger deflections compared to glass or polycarbonate (PC). They allow for large span widths of main trusses. No expansion/movement joints are needed within membrane covering compared to rigid solutions. Membrane cable structures can be designed to be virtually maintenance free depending on the proper choice of materials (e.g., aluminium extrusions, stainless steel fittings), installation procedures, etc. This might be a key benefit, as later maintenance work on conventional structures tend to be a great deal and effort (for example, at the interface of trusses and covering materials). These benefits of combined cable and membrane structures are commonly used and have lead to a great variety of projects using this technology (cp. Ill. 1).

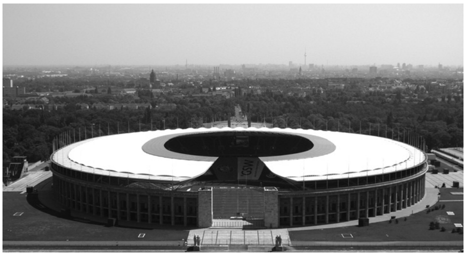
Here, some selected stadium examples are listed. When looking at the resulting figures for roof area related weight, different boundary conditions have to be taken into account: Differences in size of the roof, in applying snow loads (Maracana: none, Warsaw: very high), additional loads (video screen cube at Warsaw) or fixed/retractable roof structure. As a result, the weight figures provided can not be compared one to one. The sample projects also show very clearly that the 'engineering intelligence' of a structure, additionally holds a high potential to save weight (and therefore drastically reduces its environmental impact).

Other aspects of membrane structures also have an influence on the life cycle assessment of a membrane structure. These are, for example, the expected life-time, demand on cleaning and maintenance:

- Service life-time of different potential cover materials:
  - Polycarbonate (in challenging climate like Middle-East, Brasil) < 15 years,
  - PTFE/glass, ETFE foil ~ 30 years,
  - Glass lasts longer, but requires complex and costly sub-structure,
  - Metal sheet roofs are cheap, but not translucent and therefore require artificial lighting, also maintenance for water proofing,
- Cleaning/Maintenance;
  - PTFE/glass and ETFE foil are 'self-cleaning' (if there is rain),
  - other materials which require cleaning (water, energy, cleaning agents), might lead to faster aging (PC, for example),
  - Glass and PC roofs might need significantly more maintenance after 10–15 yrs, compared to PTFE/glass and ETFE (mainly due to aging of the watertight joints, as compared to a homogeneous membrane surface).

[3] Sample calculation based on: Main trusses at a distance of 15 m, membrane arches ~10 kg/m^2, PC incl. sec. struct. ~30 kg/m^2.

Olympic Stadium, Berlin (2004)



- 27 000 m² PTFE-coated glass fabric, 28 000 m² Mesh fabric, 6000 m² glass
- cantilevered structure, two membrane layers
- weight of support structure excluding cladding (33 000 m² roof)

~ 106 kg/m²

Gottlieb Daimler Stadium, Stuttgart (1993)

- 34 000 m² PVC-coated polyester fabric
- spoked-wheel structure, secondary arch structure
- weight of support structure excluding cladding (incl. compression ring)

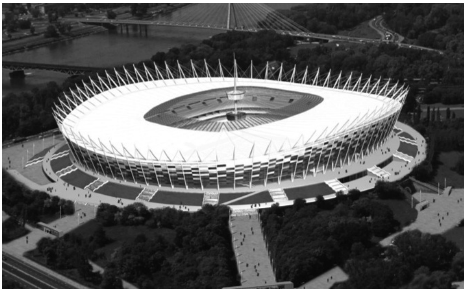
~ 91 kg/m²

Stadium Mário Filho (Maracanã), Rio de Janeiro (2013)

- 43 800 m² PTFE-coated glass fabric/roof area 45 500 m²
- steel and cable structure 2900 t + 840 t = 3740 t
- weight of support structure excluding cladding (incl. compression ring)

~ 82 kg/m²

National Stadium, Warsaw (2011)

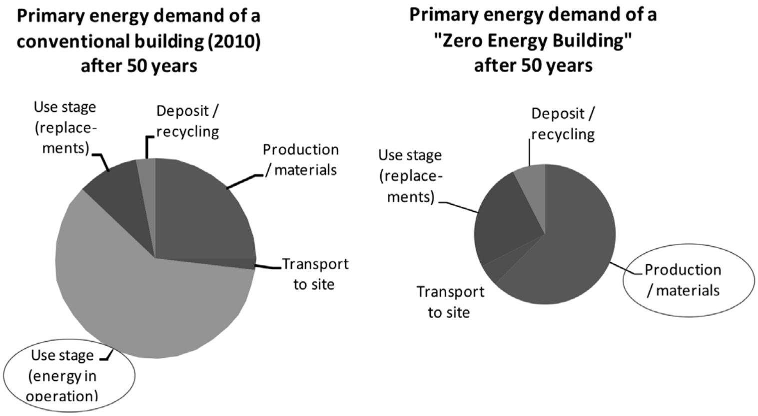


- 55 000 m² PTFE-coated glass fabric, 10 000 m² PVC-coated polyester fabric
- spoked-wheel structure, secondary arch structure, large retractable roof
- weight of support structure excluding cladding, including pillars and facade substructure

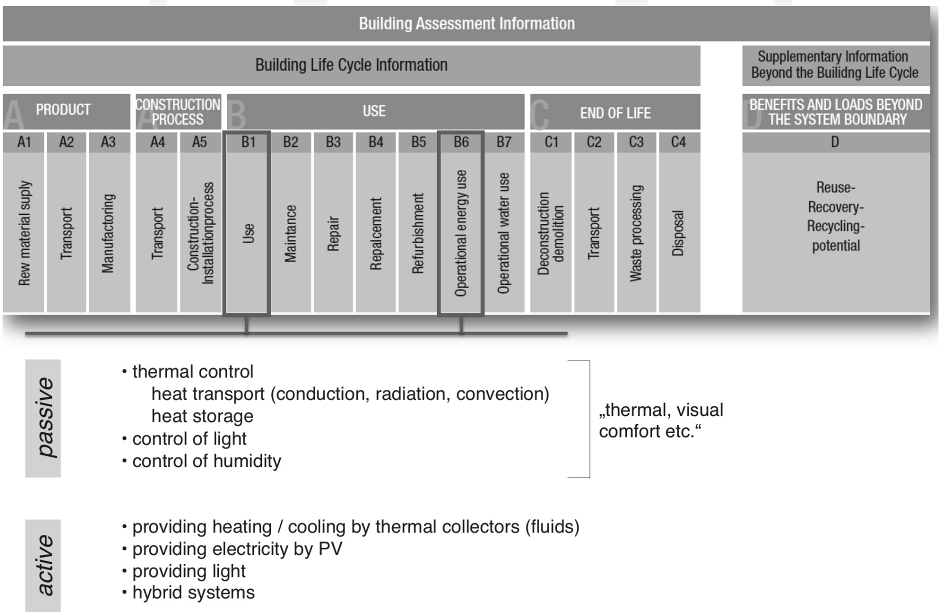
~ 200 kg/m²

Ill. 1. Comparison of selected stadia projects: Weight of roof structure per area. Data Source: Hightex GmbH and Knut Göppert, sbp – Schlaich Bergermann und Partner (5–2013)

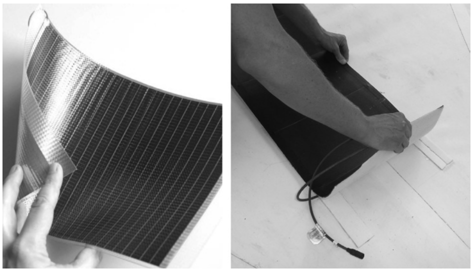
In the discussion of life cycle assessment, energy efficiency etc., the aspect of a material or technology's performance, must not be forgotten. This represents the one side of the coin which could be called 'value' (vs. 'price' on the other side). The performance is part of the 'use' stage (cp. Ill. 3). Here, membrane materials provide a lot of potential which can not be described here (e.g., light transmission in a broad range, high strength, durability, etc., cp. [5]). This includes innovative functional coatings on membranes (e.g., transparent low-E-coatings), even active solar technology which can be integrated in coated textiles and ETFE foils (cp. Ill. 4).



Ill. 2. The Relevance of construction materials grows
(source: J. Cremers/ PE International 2012)



Ill. 3. Aspects and Importance of the Use Stage for Membrane Materials and Structures
(source: J. Cremers)



Ill. 4. Flexible PV integrated on ETFE (left)
and PTFE/glass (right)
(source: J. Cremers/Hightex GmbH)

Ill. 5. Shopping Mall Dolce Vita Tejo, desgined by Promotorio Architects. Realized and low-E-ETFE-development by Hightex GmbH. Photograph: Hightex GmbH, Bernau

2. Life Cycle Assessment (LCA)

In 2011, a new Tensinet working group has been founded by an initiative of the author, which focuses on the subject of Life Cycle Assessment (LCA) in the membrane industry. The aim of this group is to review the current status on membrane materials and typical membrane structures with regard to LCA issues, which can be used as a key evaluation criterion, in the objectification of the discussion on membrane materials that the industry is based on. The LCA approach aims for a transparent evaluation of the complex environmental impacts of products and processes involved. It looks at the stages of material or structure's life, such as obtaining the raw materials, production, processing and transport, and also use, reuse and disposal if applicable. LCA measures environmental impact across a range of issues such as impact: on air quality, on water usage and water quality, on toxicity to human life and to ecosystem functioning, on impact on global warming as well as resource use (cp. Ill. 6). There are not only "cradle-to-grave" assessments that investigate the entire life cycle of a product, but also "cradle-to-gate" assessments that consider only the life of a product up to the time it leaves the factory. DIN EN ISO 14040 describes the LCA method which can be split into four phases: definition of goal and scope, inventory analysis, impact assessment and interpretation. Finally, all results like reports and declarations have to be scrutinised by an independent group of experts, which is essential, if comparative statements, e.g., with respect to rival products, are to be made or the results to be publicized.

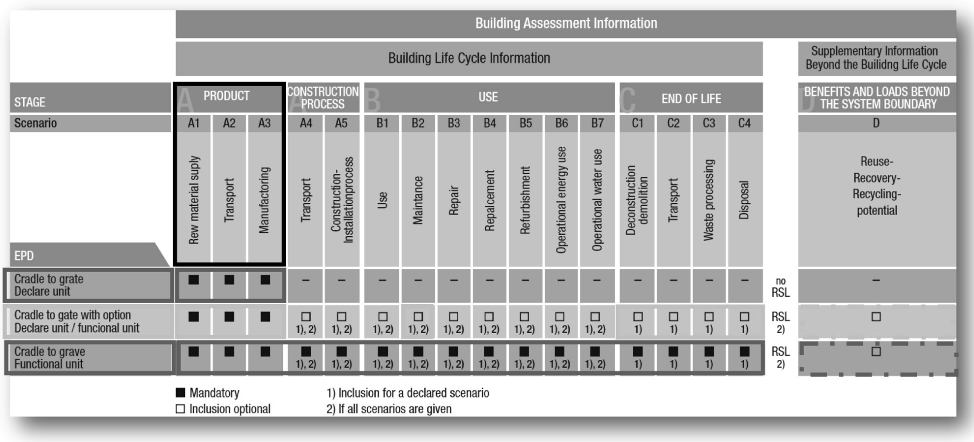
3. Environmental Product Declarations (EPD)

Drafting a product LCA is a time-consuming and expensive process that is generally carried out for the product manufacturer or a group of manufacturers by a specialist company. The ecological characteristics of a product are communicated in the form of environmental declarations. According to the ISO 14020 family, these environmental product declarations (EPD) are classified as so called "type III" environmental labels, which are highly regulated. Here, the most important environmental impacts of products are described systematically and in detail. The starting point is a product LCA, but further indicators specific to the product (e.g., contamination of the interior air) are also included. In this form of declaration, it is not the individual results of measurements that are checked by independent institutes, but rather conformity with the product category rules (PCR) drawn up to ensure an equivalent description within that product category. An EPD describes a product throughout its entire life cycle – all relevant environmental information (cp. Ill. 7. They are third party verified and guarantee reliability of the information provided. Calculation Rules for EPDs are defined by EPD program holders – for building products, EN 15804 is introduced as a respective standard in Europe.

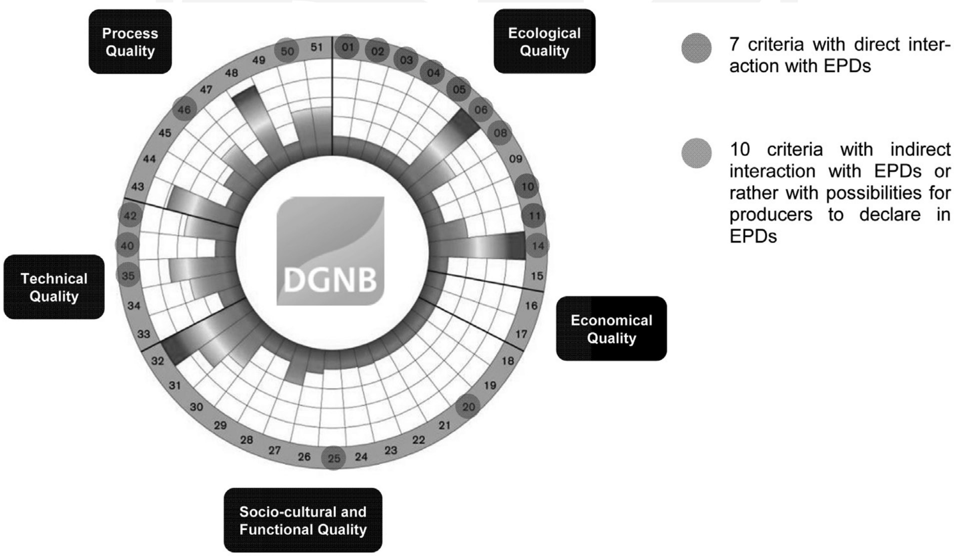
Life cycle impact assessment indicators	Global warming potential (GWP) Depletion potential of the stratospheric ozone layer (ODP) Acidification potential of land and water (AP) Eutrophication potential (EP) Summersmog potential (POCP) Abiotic depletion of non fossil resources (ADP elements) Abiotic depletion of fossil resources (ADP fossil fuels)
Energy indicators	Non renewable primary energy, excluding feedstock Input of non renewable feedstock Total input of non renewable primary energy Renewable primary energy, excluding feedstock Input of renewable feedstock Total input of renewable primary energy
Water indicator	Input of net fresh water
Use of recycled materials	Input of secondary material Input of renewable secondary fuels Input of non renewable secondary fuels
Waste indicators	Hazardous waste disposed Non hazardous waste disposed Radioactive waste disposed
Exported materials	Components for re-use Materials for recycling Materials for energy recovery Exported energy

Ill. 6. Life Cycle Impact Assessment/Environmental Indicators according to EN 15804 (source: J. Cremers, EN 15804)

EPDs help in early planning stage, they show environmental performance of a product or a product group, they are often used in political discussion and can be a basis for a company's internal benchmark and improvement.



Ill. 6. EPD Framework – EN 15804 (System boundary and modularity of product life cycle). Types of EPD with respect to life cycle stages covered and life cycle stages and modules for the building assessment (source: Jan Cremers/PE International)



Ill. 7. Sample Result of DGNB assessment and interaction of criteria with EPDs (source: DGNB/PE International)

4. Impact of LCA to the Membrane Sector

There are a number of drivers to pre-actively address the LCA issue now, for example:

- Building assessment systems with country-specific priorities for indicating the building's, like for example, LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method) and DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen/German Sustainable Building Council). The latter, was one of the first methods to prescribe a certification system that looks at the entire life cycle of a building and also includes a type of building LCA based on EPDs of the individual construction products (cp. Ill. 8). This puts the focus of planners, users and investors to the environmental impact of a whole building (including the LCAs of construction products). "Green Building" is a highly growing market share.
- Competitive situation by comparing membrane materials and structures to alternatives with LCA data available.
- Defence against prejudices based on missing, insufficient, misleading or wrong LCA data.
- Customers awareness. Communication, on environmental product performance, gains importance for manufacturers and will strengthen customer relationship.
- LCA data will become more and more important in tendering and award procedures. This also applies to the use for Construction Product Regulation (CPR).
- Existing and future legal regulations on waste concerning the building industry.

Although, the importance of the various sustainability criteria may vary, issues considered to be important include:

- Energy and carbon dioxide emissions (from building operation).
- Materials and resource use (including embodied energy).
- Waste minimisation, including recycling.
- Transport (in relation to the use of the building).
- Water conservation and use (within the building).
- Land use and ecology.
- Minimising pollution.
- Construction and building management (including security).
- Health and well-being within the building.

Material and building component selection has a direct impact on the building design and performance, and hence affects the operational energy use and the health and well-being of its occupants. Therefore, the membrane industry needs to quantify these benefits in order to maximise its sustainability credentials.

5. Additional Political Background Information

With the advent of the European single market for construction products, the European Commission became concerned that national EPD schemes and building level assessment schemes would represent a barrier to trade across Europe. The EU therefore, sought a mandate from the EU Member States to develop European standards for the assessment of the sustainability performance of construction works and of construction products. This mandate is called CEN/TC 350. From 2010, European standards began to emerge from this process and Standard BS EN15804 was published in February 2012 providing core rules for construction product EPD.

The Construction Products Directive of 1989, was one of the first Directives from the EU Commission to create a common framework for the regulations on buildings and construction products. It has been replaced by the Construction Products Regulation (CPR) and is legally binding throughout the EU. The CPR includes requirements for the sustainable use of natural resources, the reduction of greenhouse gas emissions over the life cycle and the use of EPD for assessing and reporting the impacts of construction products. If an EU Member State wishes to regulate in these areas of sustainability, it must use European standards where they exist when regulating and must withdraw national standards. This means, that in the case of the CPR, a Member State must use the CEN/TC 350 suite of standards.

An EPD provides robust and consistent information that can be used in building level assessments and the guide elaborates on the variety of ways that this can be done. In addition, a number of building level tools are emerging aimed at improving decisions at the design stage by combining embodied environmental impact data and whole life cost data (i.e., economic) and link them to BIM (Building Information Modelling) data.

Across Europe, the various environmental rating schemes are seeking to harmonise the ways in which they assess products and buildings. Increasingly, models are emerging to link embodied impacts with operational data thus enabling a better understanding of the trade-off between operational and embodied impacts, and in time, benchmarks for different types of buildings will emerge. All of which contributes greatly to the goal of a low carbon, more resource efficient, sustainable built environment [7].

6. Current status on LCA on membrane materials and structures

With regard to the status on scientific research on LCA on membrane materials and structures, it can be stated that some recent publications address the issue [1, 4, 5, 12–19], but the number of publications is still very low. Also, and maybe most importantly, it becomes obvious from a study on existing literature that there seems to be a high uncertainty in the usability of the LCA data worked with. For example, the values for, total input of non renewable primary energy' for ETFE foil that can be found, differ significantly: From 26.5 MJ/kg [16:325] to 210 MJ/kg [15]. The values provided in the only EPD on ETFE published so far[4] is even higher (> 300 MJ/kg). Whereas the data situation on PCV/PES is comparably satisfying, there still is hardly any data available on PTFE/glass.

With regard to full LCA and EPDs, there are some forerunners, for example, there is a first company specific EPD on ETFE by the companies VECTOR FOILTEC, NOWOFOL and DYNEON (mentioned before). For PVC/PES, LCA-information has been already provided in 2009 provided[5] by SERGE FERRARI and was compiled by EVEA according to ISO 14040. This company is also strongly promoting a recycling process for PVC/PES called

4 EPD-VND-2011111-E, 10-2011, Source: Institut Bauen und Umwelt e.V., Webpage: http://ibu-umwelt.de [5-2013].

5 Life cycle assessment of PRECONTRAINT® 1002 S according to ISO14040 (by EVEA, 2009) (source: Serge Ferrari).

“TEXILOOP”, which is already in operation for years already and which helps to improve LCA-values. A specific website for the recycling process [10] shows the potential of the subject for marketing including a comparison-tool to show the benefit against an incineration scenario (conventional end-of-life).

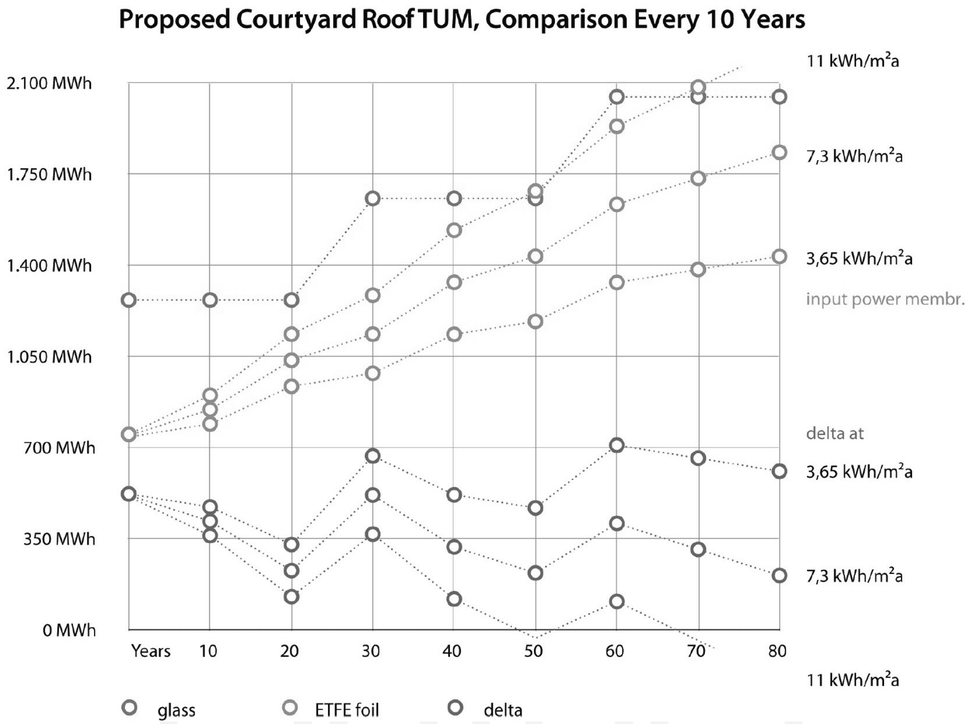
The current status (mid 2013) on the subject of recycling of the most important membrane materials is as follows: For PVC/PES there is a recycling process available which is also in use (e.g., the TEXYLOOP process which is also open to Ferrari’s competitors). ETFE, as a copolymer, can be recycled in principle. Currently, we see only downcycling from ETFE foil cut-offs and waste to ETFE tubes such as dirt, dust, etc., would limit the optical and mechanical properties of the ETFE foil. For PTFE/glass there is a lab-scale process (developed by Dyneon/3M and Bayreuth University), which is commercially not active so far, but shows the future potential. Currently, PTFE/glass, being an inert material, is currently landfilled.

On the level of structure types, there is very little published information available so far. Some single project-based calculations have been carried out, but due to the lack of proper LCA data, they are difficult to assess and compare. One example for this appoach has been conducted within a large R&D-project, in which the author has been involved in[6]. Here, a comparing calculation on primary energy intensity has been carried out for a glass-roof vs. an ETFE-cushion-roof including specificly optimised steel sub-structures (roof area of approx. 27 × 33.5 m):

	Mass incl. substructure	Primary Energy “invest” (excl. operation and replacment)
Glass-roof	180 t	1 270 000 kWh
Steel and substructure	114 t	880 000 kWh
Glazing layer	66 t	390 000 kWh
ETFE-roof	**80 t**	**693 000 kWh**
Steel and substructure	78 t	640 000 kWh
ETFE-cushions	1.3 t	53 000 kWh

In both scenarios, there is a need for maintenance, repair and typical replacement during the period of operation. Additionally, the ETFE-roof variant has a quasi constant energy demand for the cushion air supply system (keeping-up internal pressure and dehumidification). This demand highly depends on project-specific issues, i.e., fabrication quality (seam tightness), cushion geometry, type of clamping, air supply system (w/o air circulation). In the study, the energy demand therefore has been considered in three different variants (3.65/7.3/11 kWh/m^{2}a). The significance of this assumption on an 80-year-LCA calculation is depicted in Ill. 9.

[6] Cp. project website at http://www.mesg.info [6-2013].



Ill. 8. LCA-results of ETFE and glass roof variants of MESG project[7]

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