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COMPARATIVE ASSESSMENT OF LIFE CYCLE ASPECTS OF LIGHTWEIGHT AND CONVENTIONAL STRUCTURES AND THEIR INTEGRATION INTO AN EDUCATIONAL APPROACH

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Key words: teaching sustainability, sustainability concepts, lightweight structures, comparison of environmental impacts of lightweight and common structures.

Summary. The article provides information on how teaching sustainability can be applied in a practical context. A comparison of the life cycle of two roof variants and their evaluation shows how the teaching concept can be implemented.

1 CURRENT STATUS AND POSTULATED GOALS

According to a study by the UN Environment Program, in 2021 the construction and building sector was responsible for 37 percent of global energy-related CO2 emissions, which corresponds to about 10 gigatons of CO2 per year (figure 1), surpassing even the previous maximum from the year of 2019 [2].

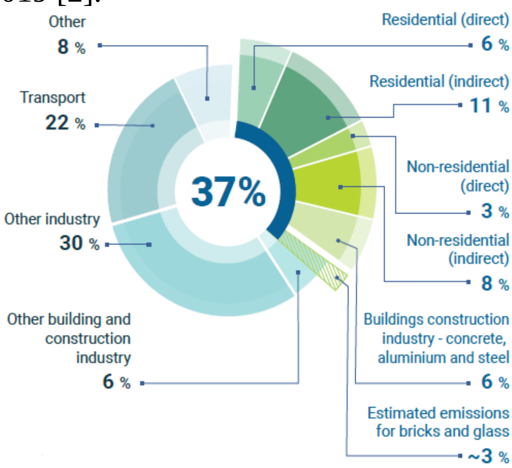

Figure 1: Share of buildings in global energy and process emissions in 2021 [5]

So how do we get back to reducing environmental impacts starting with embodied emissions from the construction of new buildings, the use of buildings and the refurbishment of existing buildings to the necessary levels to meet global environmental goals and stop and reverse the renewed upward trend in CO2 emissions?

We also have to consider that not only the emission of harmful greenhouse gases has to be drastically reduced, but also resources (e.g. water) have to be conserved, energy saved and the amount of waste reduced - and all this with an ever-growing population and people's increasing demands for comfort and standard of living.

With this goal in mind, it is the task of teachers and researchers in engineering and architecture to achieve a high level of quality, that means the harmony of form, function, construction, economy and ecology of buildings under the premise of sustainability [2], [3]. Here, the technical possibilities available to us or in prospect and the knowledge of socio-ecological relationships and long-term consequences must be taken into account. Today's design and construction has been enriched by the criterion of sustainability and has therefore also become significantly more complex [4].

2 IMPLEMENTING SUSTAINABILITY IN TEACHING OF LIGHTWEIGHT STRUCTURES

In [1] the authors of the paper have already stated that the strategy to develop a detailed and comprehensive understanding of sustainable construction methods should start in smaller units and steps from the bottom up (figure 2).

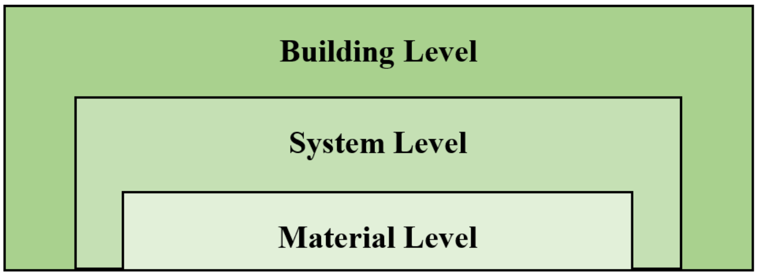

Figure 2: Building Levels of consideration [1]

The material level starts with deepened knowledge of structural materials including raw materials and their origin and availability, production processes, energy consumption, environmental impact and durability. Students will get to know and how to handle Environmental Product Declarations (EPDs) as neutral and objective considered documents including all environmentally relevant properties of the specific building materials. The content data usually covers as far as possible all effects a material has on its environment. Ideally, the entire life cycle of the material is taken into account. In this level also future perspectives may be shown. Which efforts are currently being undertaken by the building industry to improve environmental aspects of individual materials? How are these developments influencing future assessments, recyclability and lifetime of materials? Are there new materials with less environmental impacts available besides the commonly used ones [1]?

At the system level, different structures or assemblies, made of different materials or using different construction methods are investigated. This next step level will be based on the knowledge of the materials and their environmental impact previously taught. Advanced students calculate and evaluate life cycle assessments (LCA) based on the structural calculations of different structural systems. Different material designs for building components such as walls, ceilings, roofs, etc. are calculated and compared with each other. Building physics aspects, for example energy transfer and sound transmission through building components, are included in here [1].

Finally, life cycle assessments (LCA) of total structures and buildings will be carried out at the building level. Different solutions and their effects on the LCA are compared and evaluated. Here, also the interactions with the environment are intended to be taken into account.

The aim is that the students are trained to develop an understanding of the environmental impact of building materials (level 1), building systems and components (level 2) and complete building structures (level 3). Finally, the students should be able to make decisions about suitable combinations of structures and materials with regard to the life cycle assessment of a building. They will know at which points they will have to change something in order to significantly improve the LCA or a desired certification for the respective building (e.g. DGNB, BREEAM, LEED) [1].

3 TEACHING LEVELS OF SUSTAINABILITY FROM BOTTOM TO TOP ON THE EXAMPLE OF THE P&S BUILDING FOR THE AFRICAN UNION

3.1 Initial situation and comparison of common and lightweight solutions

The approx. 430.0 m² oval-shaped roof has dimensions of approx. 25.30 m x 20.00 m and is being built as a covering over the atrium of the newly built Peace and Security Building of the African Union in Addis Ababa, Ethiopia. The roof is planned as a building closure and is supported on the reinforced concrete attics. The original design envisaged a steel and glass roof variant - option 01 (figure 3).

The steel-glass roof is supported by 6 main girders, which carry the rest of the steel framework including the glass panes and transfer the loads to the edge attic construction. The glass elements are arranged at a gradient of 8° and consist of a double layer insulated glass inside and a thermally toughened safety glass outside. Due to high earthquake load zone (level IV) the steel-glass roof solution has been reconsidered.

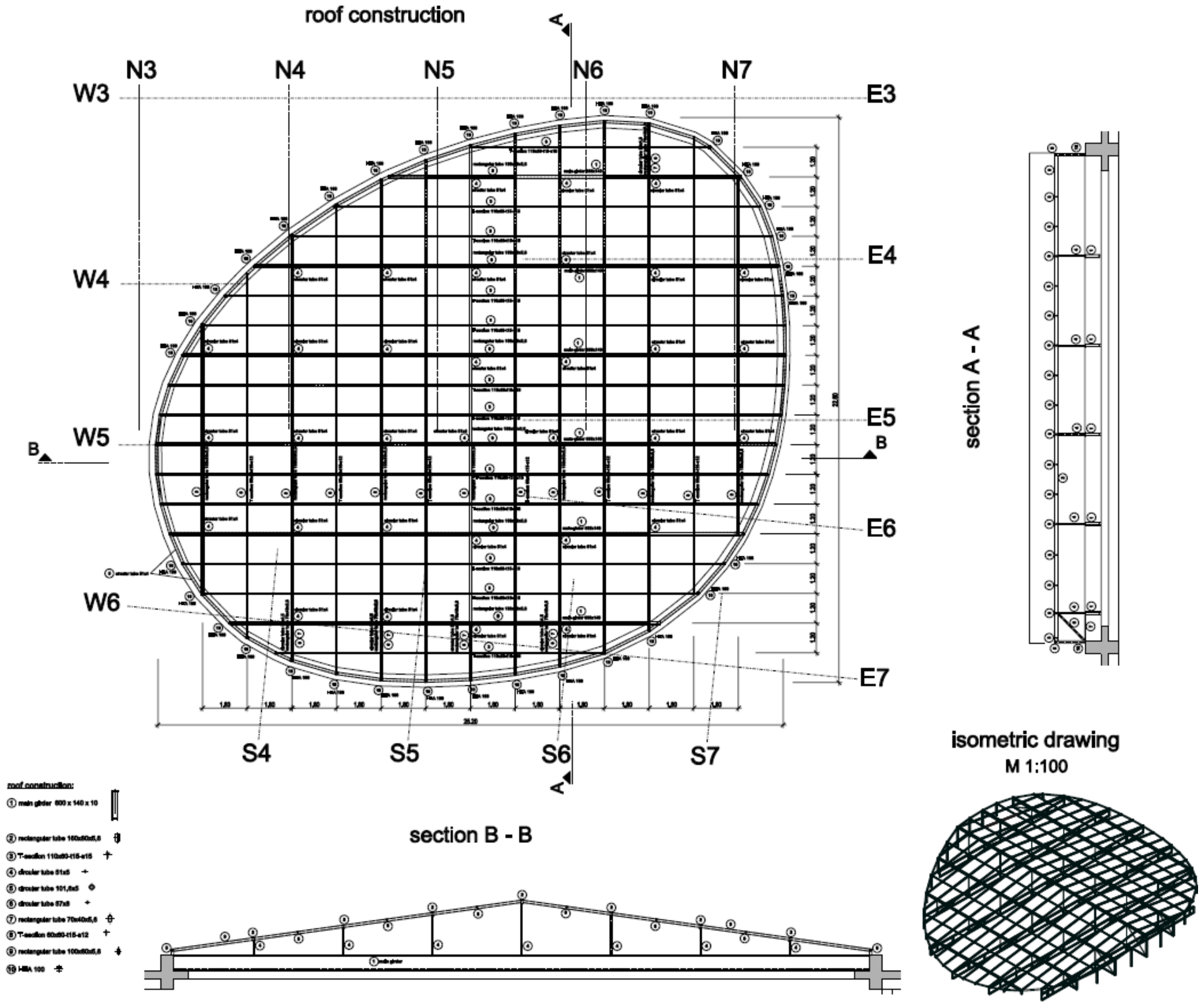

Figure 3: Option 01 – Steel-glass-roof - Position plan

In order to save material and achieve the same effect of a light-flooded atrium area, an alternative proposal was to use an ETFE cushion construction - option 02 (Figure 4 and 5).

The roof envelope consists of a 2-layer pneumatically prestressed ETFE cushions. The primary structure is a steel structure again. For this variant the steel structure consists of 5 arched beams supported by columns on the attic. The roof is intended to have a minor cantilever over the reinforced concrete attic, i.e. the roof area is slightly larger than the opening in the ceiling. The radii of the arches are different. For transverse stiffening, the arches are each braced with 3 inclined cables. In the remaining outer edge area, the cushions are braced via a jointed ring beam.

The two variants are compared and evaluated below in the sustainability categories of material, system and overall structure.

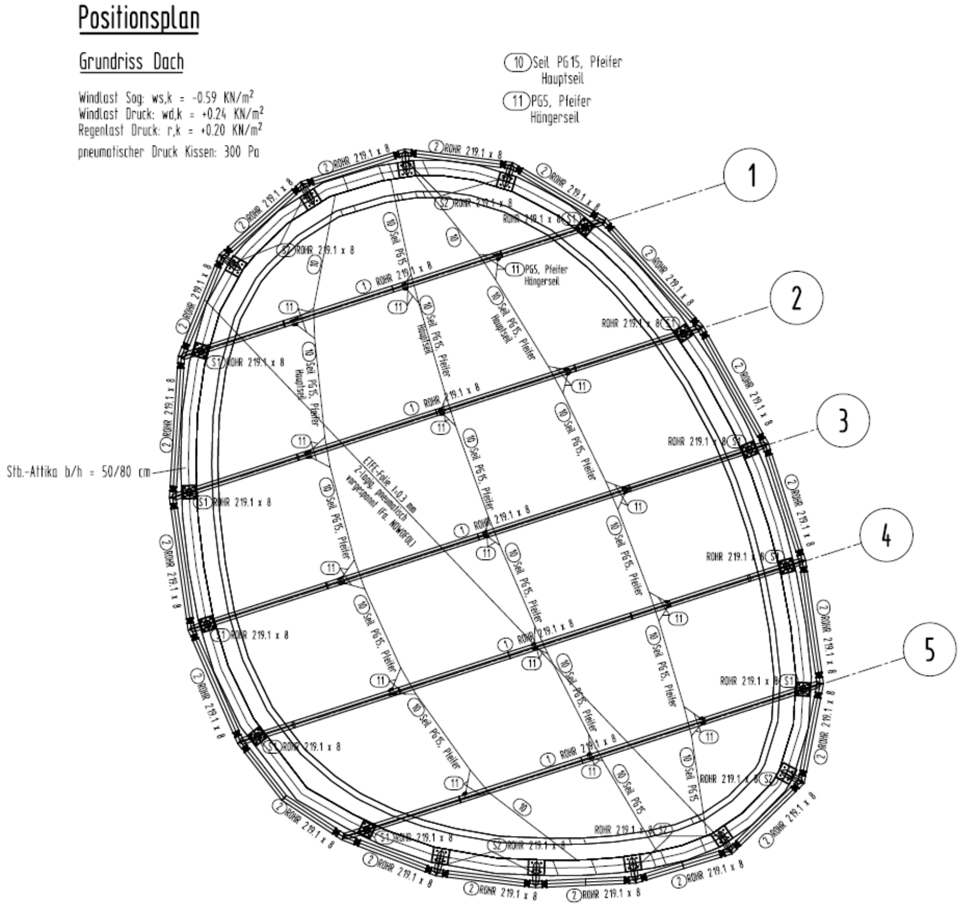

Figure 4: Option 02 - ETFE-cushion-roof - Position plan

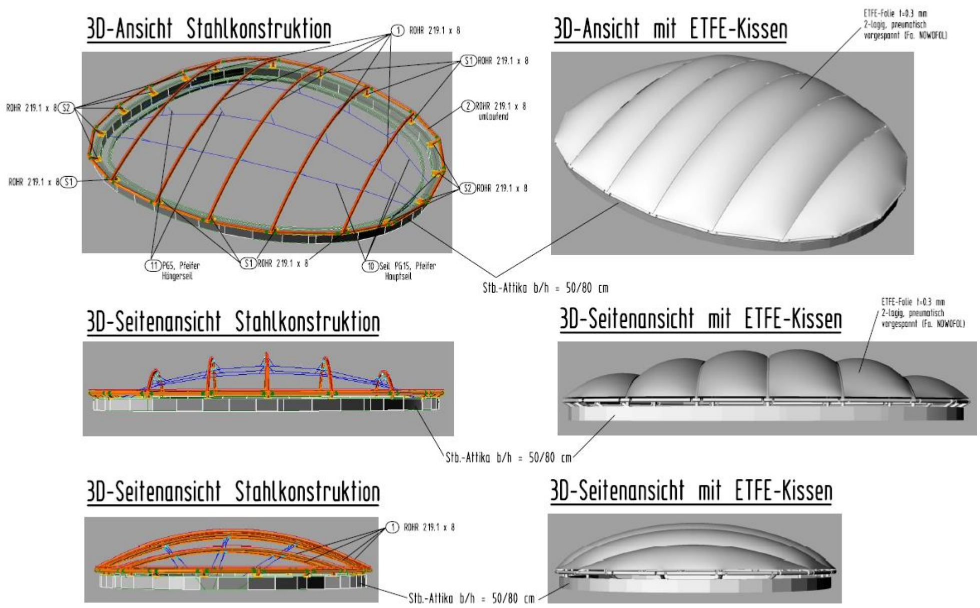

Figure 5: Option 02 - ETFE-cushion-roof - Visualisation of Cushion Structure

3.2 Comparison of a lightweight and a common structure on Material Level

The first level of evaluation is the material level. The focus of this example is on the handling of environmental product declarations, which enable a comparison between both envelopes. Lightweight construction requires materials that have high strength at the lowest possible weight. The design weight of a light surface structure, such as a membrane structure, can be significantly less than 1/10 to 1/100 of the weight of a solid structure, such as concrete or glass [2], [3]. The air-supported foil cushions form an extremely light-weight construction, because they consist of a volume of air that is enclosed airtight by at least two layers of thin ETFE-foils.

The foils in this example are each 0.3 mm thick, so that the entire cushion weighs only about 0,65 kg/m² (without the frame etc.). The glass option weighs about 30 times more than this. But weight is not the only important factor at the material level. The environmental impact of the material itself is a criterion worth considering. In order to have enough quantified environmental information about the life cycle of a product to make comparisons between products with the same functions, environmental product declarations (EPD) are used for benchmarking. An EPD is a document in which the environmentally relevant properties of a specific product (e.g. insulating glass unit) or system (e.g. ETFE cushion system) are presented in the form of neutral and objective data. This data covers, as far as possible, all the effects that the product can have on its environment. Ideally, the entire life cycle of the product is taken into account.

Table 1: LCA Analysis of the two different covering materials

	Option	Code	Product definition	Dimension	Categories		Product stage	Construction stage		Use Stage							End-of-life stage				Benefits after	Total	Total with Benefits
							A1 A2 A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D		
GLASS-COVER upper and lower layer	Thermally toughened safety glass - PG2 (exterior)	EPD-FEV-GB-61.0	1 m² area and 1 mm glass thickness	6 mm; 460 m²	GWP	to CO2 equiv.	52,54	0,75	0,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,39	0,19	-2,88	**54,10**	**51,21**
					Total use of renewable primary energy resources	MJ	57.044,60	588,80	12,32	0,00	0,23	0,00	0,00	0,00	0,00	0,00	0,00	10,64	2.921,00	385,39	-4.351,60	**60.962,96**	**56.611,36**
	AND				Total use of non-renewable primary energy resources	MJ	836.965,40	10.115,40	42,52	0,00	12,01	0,00	0,00	0,00	0,00	0,00	0,00	188,60	5.276,20	2.557,60	-42.927,20	**855.157,73**	**812.230,53**
	Double glazing: 7 mm FG, 2 mm TSG, 1 mm LSG, 16 mm spacer/cavity (interior)	EPD-MIG-61.0	1.0 * 1.0 m² - area Multi-pane insulating glass double layer config.	460 m²	Use of net fresh water	m³	199,18	0,65	0,51	0,00	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,01	2,99	0,65	-6,40	**204,01**	**197,61**
					Non-Hazardous waste disposed	to	38,87	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	13,11	-0,36	**51,99**	**51,63**
ETFE -COVER	**Option**	**Code**	**Product definition**	**Dimension**	**Categories**		**Product stage**	**Construction stage**		**Use Stage**							**End-of-life stage**				**Benefits after**	**Total**	**Total with Benefits**
							A1 A2 A3	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**		
	ETFE Foil t = 0.3 mm double layer; pneumatically pre-stressed, p = 300 Pa	EPD-TAI-20190092-ICB1-EN	Material example! 1 m² of Taiyo Europe's TensoSky®-System double layer system	460 m²	GWP	to CO2 equiv.	17,13	0,00	0,29	0,00	0,00	0,00	0,00	0,00	0,03	0,00	0,00	0,02	0,72	0,00	-3,02	**18,20**	**15,18**
					Total use of renewable primary energy resources	MJ	23.699,20	0,00	13,43	0,00	0,00	0,00	0,00	0,00	238,60	0,00	0,00	12,82	58,93	0,00	-14.200,20	**24.022,97**	**9.822,77**
					Total use of non-renewable primary energy resources	MJ	165.186,00	0,00	71,16	0,00	0,00	0,00	0,00	0,00	634,34	0,00	0,00	232,48	297,21	0,00	-38.318,00	**166.421,19**	**128.103,19**
					Use of net fresh water	m³	76,96	0,00	0,71	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,00	0,02	1,99	0,00	-35,74	**80,01**	**44,27**
					Non-Hazardous waste disposed	to	0,93	0,00	0,001	0,00	0,00	0,00	0,00	0,00	0,0004	0,00	0,00	0,00002	0,11	0,00	-0,63	**1,04**	**0,42**

An environmental assessment of the roofing materials (without the primary steel structure) based on the respective declarations [7],[8],[9] shows that the same area can be covered with an ETFE cushion construction with approx. 65% less CO_2 emission than with glass. Moreover, the evaluation shows that the energy and also the water demand over the entire service life for the ETFE roof variant is 1/3 to 1/4 of the glass variant. In addition, if we compare the waste production of the two systems, we see that with the glass roof system, only around 1-2% can be considered as positive recycling potential in the D-sector; this is much better with the ETFE roof variant, as around 60% of the so-called waste can be recycled at the end of its service life. Furthermore, the ETFE roof variant results in a considerable reduction in waste mass at the end of the service life. The comparison of all further environmental factors like the depletion potential of the stratospheric ozone layer (ODP), acidification potential of land and water (AP) or the exported electrical energy can be made on the basis of the EPDs, which can effect the selection of the available materials as well.

For a professional comparison, the expected service life must also be taken into account. Depending on the type of glass, a service life of approx. 30 to 60 years is assumed. ETFE is still a very young building material, which is why the manufacturers have so far guaranteed a service life of 25-30 years. For the current comparison, we can therefore assume that we would have to consider about two ETFE roofs during their service life. If the initial values of the ETFE roof variant are doubled, the GWP and all other comparative values are still 20-30% below that of glass. The waste production and the use of non-renewable primary energies are still significantly lower. For this reason, it is worth comparing the sustainability aspects of ETFE and glass constructions.

3.3 System Level

The glass option weighs about 15 times more than the ETFE option incl. frames, gutter, keder etc. [9] which effects the primary structure enormously. The primary supporting structure of ETFE foil cushions has therefore to transmit less load to the foundations and can be made more filigree using less weight. In addition, the span that can be achieved with such cushions is relatively large, in this case 4,00 m, which also saves weight. The steel glass roof, on the other hand, requires a support grid with a dimension of 1.80 x 1.20 m. This results in a significantly higher quantity of steel. The weight advantage is included at various points in the ecological balance (Life Cycle Assessment or LCA) of components and buildings, for example during manufacture, transport, assembly and disassembly, as well as during the preparation for reuse of the components.

Before the evaluation can take place on the basis of the material, a structural analysis must be carried out that defines the required cross-sections. Based on this, a quantity calculation of option 01 and option 02 have been carried out.

At the second level, the system level, also an intelligent selection of the structural system for each structural component of the building needs to be carried out. This means for example filigree component cross-sections that are adapted to the material, the construction and the stress. They are achieved, for example, by avoiding bending stress, by preferring tensile to compressive stress, or by short-circuiting forces (example: tension and compression ring of a spoked wheel). Supporting elements that are based on the force path of the shape-determining load case or adaptive systems reacting on the load distribution, or structures that have a density distribution corresponding to the stress profile also meet the criterion of structural lightweight construction [2], [3]. With a sophisticated static system and the difference in weight of the covering material, the values for the environmental impact of steel [10] and concrete (here without reinforcement) [11] can increase or decrease proportionally.

Table 2: LCA Analysis of the glass and ETFE cover system variants including primary structures

					Global Warming Potential [to CO_2 equiv.]																	
	Option	Code	Product definition	Dimension	Product stage	Construction stage		Use Stage							End-of-life stage				Benefits after	Total without Benefits	
					A1 A2 A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D		
GLASS-COVER upper and lower layer	Glass-Cover	see table 1	see table 1	460,00 m²	52,54	0,75	0,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,39	0,19	-2,88	**54,10**	**97,86**
	Steel Structure + 10% Surcharge	EPD-BFS-20180116-IBG2-DE	per tonne of structural steel	33,98 to	38,40	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,00	-14,03	**38,46**	
	Attica 500 x 650 mm	EPD-IZB-20180101-IBG1-DE	1 m³ Beton	24,85 m³	4,89	0,10	0,03	-0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,30	0,15	0,00	-0,53	**5,29**	
ETFE -COVER	ETFE-Cover	see table 1	see table 1	460,00 m²	17,13	0,00	0,29	0,00	0,00	0,00	0,00	0,00	0,03	0,00	0,00	0,02	0,72	0,00	-3,02	**18,20**	**36,33**
	Steel Structure + 10% Surcharge	EPD-BFS-20180116-IBG2-DE	per tonne of structural steel	10,12 to	11,44	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,00	-4,18	**11,53**	
	Cable + 10% Surcharge	EPD-BFS-20180116-IBG2-DE	per tonne of structural steel	0,07 to	0,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	-0,03		
	Attica 200 x 300 mm	EPD-IZB-20180101-IBG1-DE	1 m³ Beton	3,78 m³	0,74	0,01	0,00	-0,04	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,05	0,02	0,00	-0,08	**6,60**	
	Attica 500 x 800 mm	EPD-IZB-20180101-IBG1-DE	1 m³ Beton	27,20 m³	5,36	0,11	0,03	-0,27	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,33	0,16	0,00	-0,58		

If we add to the above compared roofing material the rest of the structure, i.e. all steel and concrete components, the difference of 60% less CO_2 emission will remain. The comparison of the global warming potential of the two solutions shall be shown below (Figure 6 and 7).

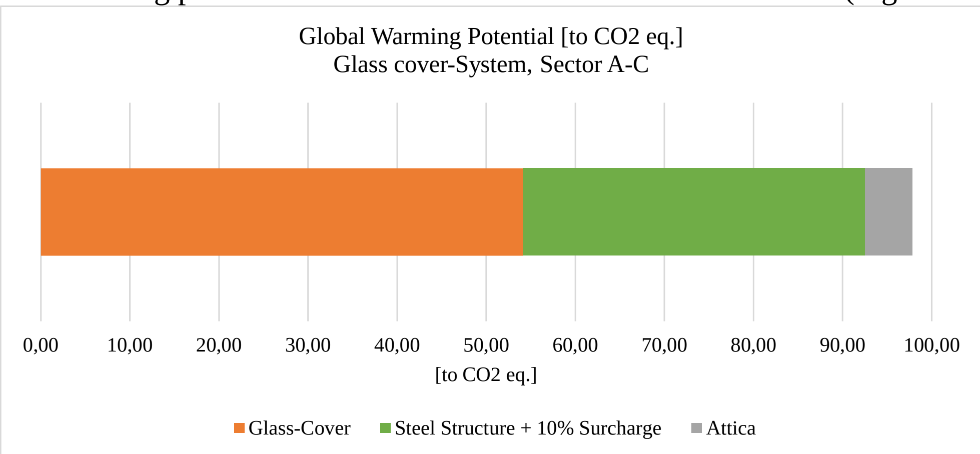

Figure 6: Visualization of LCA Analysis of the glass cover

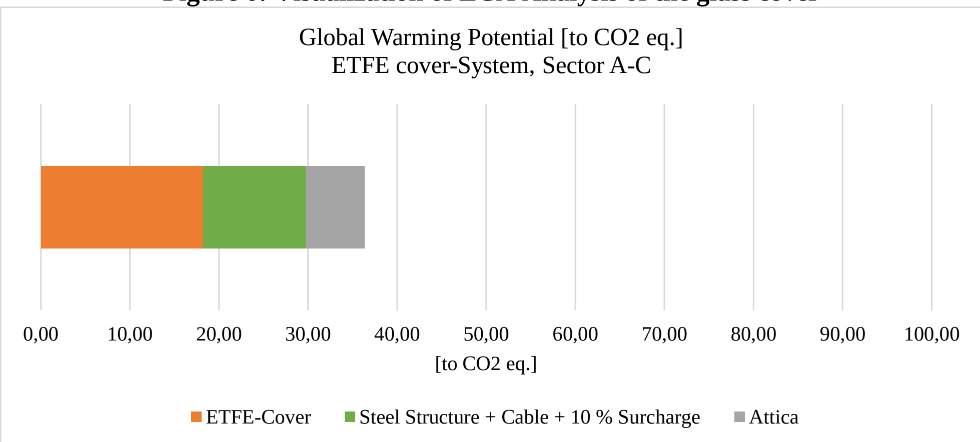

Figure 7: Visualization of LCA Analysis of the ETFE cover

This simple comparison, based on the material level, shows that a material analysis via the EPDs is already worthwhile in terms of a sustainable construction. The reduction of weight through light long-span structures has a significant influence on the primary structure and the entire building, whereby the use of resources and embodied emissions can be saved.

For this reason, the ETFE cushion will be examined in more detail as the preferred variant. The foil cushion (option 02) meets the criterion of structural lightweight construction perfectly, since they consist exclusively of tension elements and one pressure element: air. The thin foils transmit the tensile forces, the air cushion enclosed between them transfers the load via pressure into the respective load-dissipating foil (figure 8). The upper foil supports wind suction and the lower foil supports wind pressure. Bending and thus stability problems do not exist with foil cushions. The cushions are a closed system which, as long as the tensile loads at both ends of the single cushion are equal, stabilizes the steel arches. At the end cushion there is no counterpart which is why the edge beam experiences a bending stress due to the hinged support. With regard to the overall static system, this is not optimal. A continuous compression ring would be better suited as a stand-alone system to transport only compressive stresses and not bending moments. For transport and assembly, however, the division of the outer ring into individual links is helpful.

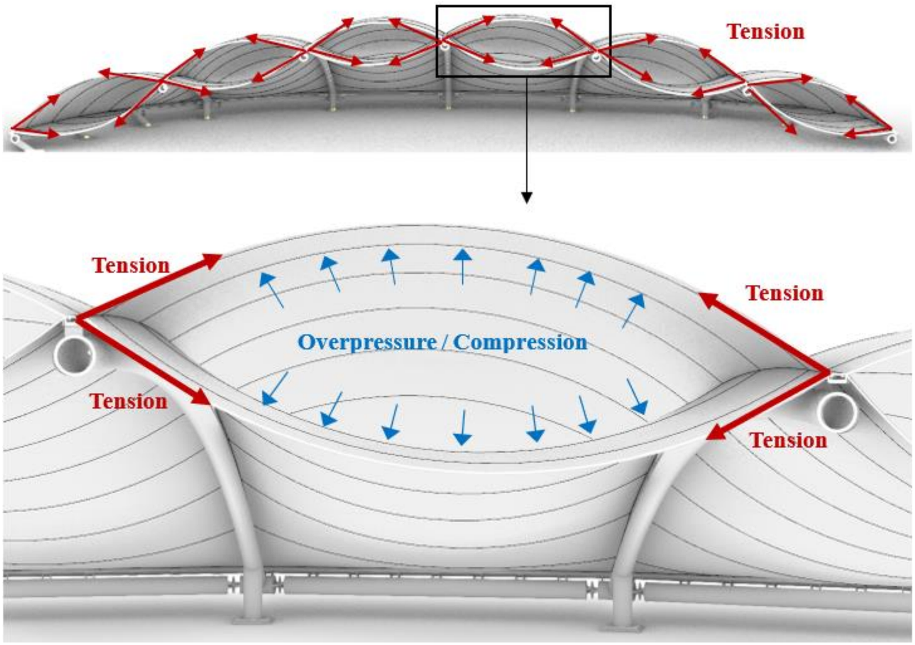

Figure 8: Structural System of a Foil Cushion

At the edge, the planner chose a rigid edge beam, which transfers the lateral tensile load of the cushions via bending moments. This is not optimal from the point of view of structural lightweight design and might in other solutions be replaced by a ring or cables.

3.5 Building Level

ETFE foil cushions can not only be used as a building enclosure with a load-bearing function, but also offer other possibilities in addition to light penetration. In this case, photovoltaic modules are attached to the cushion to generate solar energy for the pumps that regulate the internal pressure of the cushion. If the top layer is, for example, printed, pigmented or provided with a radiation-influencing coating, the solar transmission and energy transfer into the building may also be controlled. The amount of radiation that is transmitted through the cushion into the interior can be adjusted to reduce mechanical air conditioning but still allows enough light to pass through and thus saving energy (see figure 9).

Figure 9: ETFE cushion atrium roof including photovoltaic modules

The ETFE foil cushion thus fulfils the desire for a transparent supporting structure that can even control the incidence of light and shading, as well as energy generation with the use of photovoltaic modules, here by providing additionally a symbolic design option.

4 CONCLUSION AND OUTLOOK

The applicability of the bottom-up educational concept for the sustainability aspects of structures has been demonstrated using the example of the P&S building for the African Union. And furthermore a comparative study for the global warming potential of a lightweight structure made of ETFE cushion has been confronted with the one of a common glass-steel option. From the material level comparing the environmental influences of the available products, to the system level taking into account the effect of the primary structure of the two transparent atrium roof solutions and a LCA for the GWP including considerations of further optimisation possibilities the educational levels have been described up to the building level. In further studies more environmental aspects will need to be included into the LCA on the system level to the detailed investigation and calculation of certification systems on the building level. In this first study already the advantages of a lightweight structure compared to a common solution could be shown.

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