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EFFECT OF CUSHION GEOMETRY AND CONFIGURATION ON THE EMBODIED ENERGY OF ETFE FOIL CONSTRUCTION

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Summary. The low weight and high spanning capacity of ETFE foil when compared to other translucent cladding materials has potential to reduce the weight of supporting structures and energy embodied in their construction. This paper compares the embodied energy in ETFE cushion panels of different shape, size and configuration, relates these to some built examples. The results are compared with the estimated embodied energy of some built examples of ETFE roofs and from other studies. Factors that influence these are reviewed.

1 INTRODUCTION

The low weight of ETFE foil (typically less than 1kg/m^2 in three-layer inflated cushions) and high spanning capacity (with examples of up to 10m when used as a cladding material in building envelopes, for example, the Dolce Vita Tejo shopping mall, Amadora, Portugal) has potential benefits for both the extent and weight of supporting structures and the energy embodied in their construction.

A recently published Environmental Product Declaration EPD-VND-2011111-E for the Texlon® ETFE foil roof system[1] includes an assessment of the typical embodied energy per square metre of a three-layer cushion, which assumes an "...average quantity of frame material required for the assembly of the roof construction"[1]. This provides valuable information about the overall environmental impact of ETFE foil cushion construction, highlighting the individual contributions to the total of the ETFE foil, aluminium edge profile and transportation. However, this is not particularly useful to designers who may wish to minimise the embodied energy of their building envelopes, as it does not take into account the effect of individual cushion geometry or, where there is more than one, the configuration of the cushions.

To clarify this issue, the results of a recent desktop study[2] into the relative embodied energy in ETFE cushion panels of different shape, size and configuration are described. The results are compared with the estimated embodied energy of some built examples of ETFE roofs and from other studies[3,4]. Factors that influence these are reviewed.

In conclusion preferred configurations are suggested and the effects that these may have on the configuration of supporting secondary and primary structures are discussed.

2 EMBODIED ENERGY OF ETFE FOIL CONSTRUCTION

The principal components used in the construction of ETFE foil building envelopes are the foil itself and some form of aluminium perimeter profile. Published data was used to assess their relative contribution to the overall EE. However, as is demonstrated by the relatively wide range of values assessed in Hammond and Jones's Inventory of Carbon & Energy[5], estimation of the energy embodied in materials from cradle to gate is not as easy as it may seem, even for common and well-established construction materials. For ETFE foil estimates of embodied energy vary considerably, as can be seen in Table 1.The most recent is over ten times that stated by Robinson-Gayle *et al*[6] in 2001.

Table 1: Comparison of published values of embodied energy MJ/kg for ETFE foil

Source	Embodied energy MJ/kg	Notes
Robinson-Gayle *et al* 2001[6]	26.5	[p.325]
Fernandez 2006[7]	120-130	Cited in Monticelli *et al* 2009[3]
Ashby *et al* 2007[8]	100-120	Cited in Monticelli *et al* 2009[3]
Monticelli *et al* 2009[3]	210	173:28:9 MJ/kg respectively for production of raw materials, polymerization/pellet production, and extrusion
EPD Texlon® 2011[1]	337.3	Calculated from 326.2MJ/m^2 quoted for a three-layer cushion weighing 0.967kg/m^2 [p.17]

For this study the highest (and most recent) embodied energy value, 337.3MJ/kg, was used to compare the relative efficiency of different ETFE cushion geometries. Although this value applies specifically to foil material supplied by Nowoflon and incorporated in the Texlon® system[1], due to the limited number of ETFE producers and foil manufacturers, and the generally similar methods of foil cushion fabrication, in the absence of other data, this was considered acceptable. For the extruded aluminium edge clamping profile a typical value of 154MJ/kg was taken from Hammond and Jones[5], which is assumed to include an average of 33% recycled material.

3 INFLUENCE OF CUSHION GEOMETRY

In contrast to the method employed in the Environmental Product Declaration EPD-VND-2011111-E for the Texlon® ETFE foil roof system[1], which calculates the embodied energy for a nominal cushion area of one square metre, Chilton, Pezeshkzadeh and Afrin[2] have investigated the effect of changing cushion geometry and configuration on embodied energy per square metre of cushion. The results, for areas ranging from $5m^2$ to $100m^2$ and aspect ratios (length/width) from 1 to 20, are shown for individual cushions in Figure 1, for cushions sharing profiles on two (longest) edges in Figure 2, and in Figure 3 for cushions sharing profiles along all four edges. Graphs have been deliberately plotted to the same vertical scale to allow direct comparison between the embodied energy (MJ/m^2) of the different conditions.

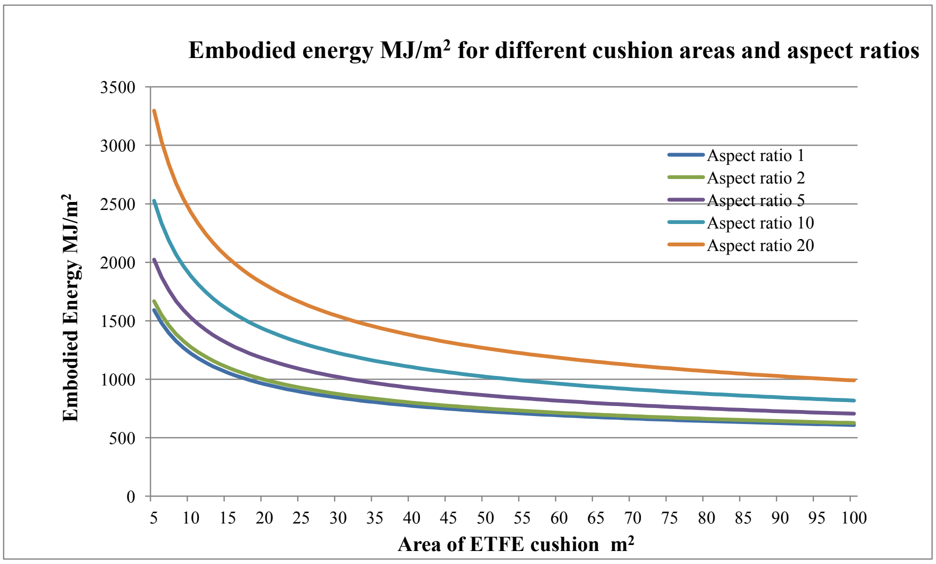

Figure 1: Embodied energy MJ/m^2 for different ETFE individual cushion areas and aspect ratios (length/width).

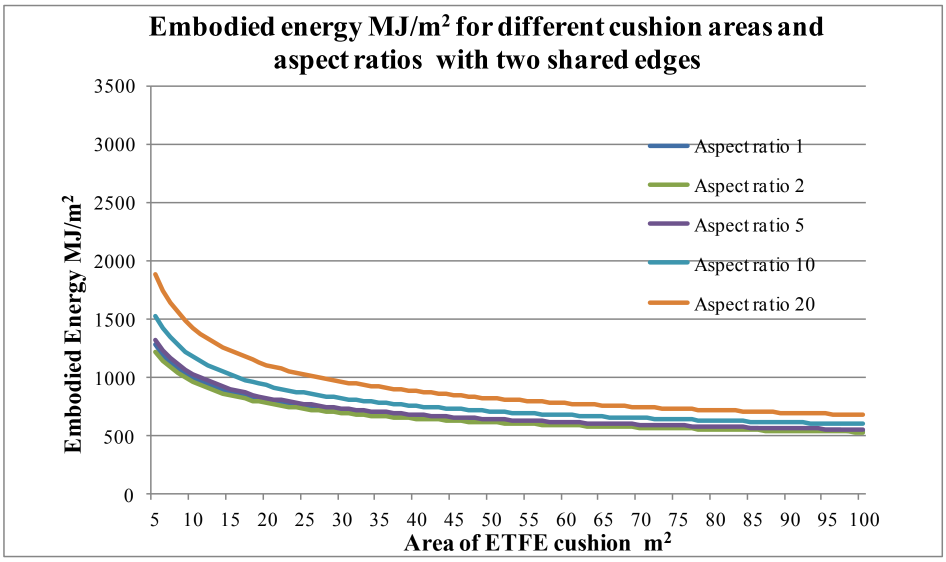

Figure 2: Embodied energy MJ/m^2 for different ETFE cushion areas and aspect ratios (length/width) with two (longest) shared edges.

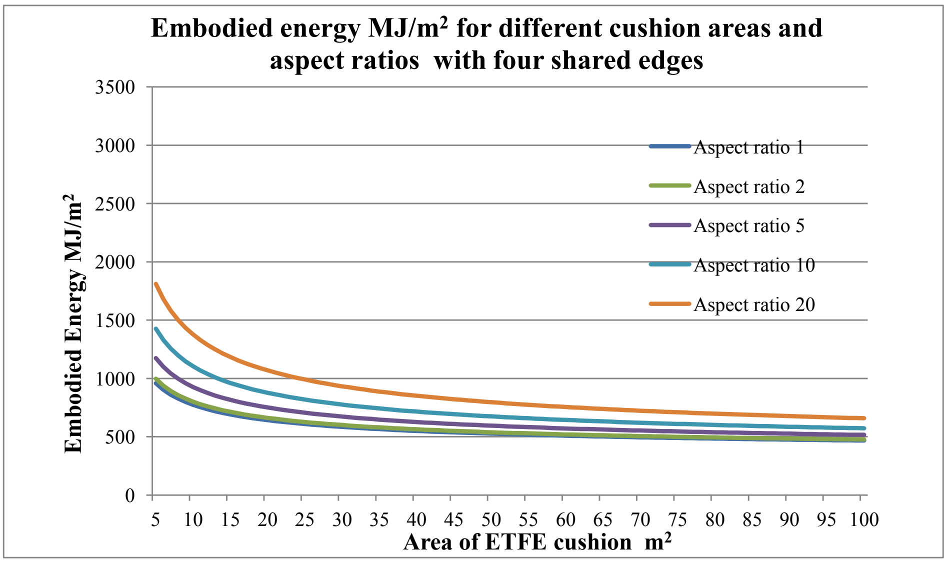

Figure 3: Embodied energy MJ/m^2 for different ETFE cushion areas and aspect ratios (length/width) with all four shared edges.

Although the foil thickness in real building envelopes will be dependent on the size of the cushion, inflation pressure and anticipated wind and snow loading, for consistency, a theoretical three-layer cushion was assumed, which has the same foil thicknesses for any size of cushion. Equally the same edge profile was used in all cases.

Comparing the three graphs, Figures 1 to 3, it can clearly be seen that, for any given cushion area and aspect ratio, isolated cushions will expend the greatest amount of energy per square metre in their production. Of these, as one would expect, square (1:1 aspect ratio) cushions consume the least energy for any given covered area – 1591MJ/m^2 for a 5m^2 cushion, compared to 3296 MJ/m^2 for a cushion of the same area but with aspect ratio of 1:20 – over twice the EE/m^2. These values should be compared with the embodied energy of 853.6MJ determined for a 1m^2 notional cushion (transportation to site excluded) according to the EPD-VND-2011111-E for the Texlon® system[1]. For cushions of 25m^2 the equivalent values are 892MJ/m^2 and 1655MJ/m^2 with a relative embodied energy ratio of 1.86. At 100m^2, the area of the square cushions used for the roof of the Dolce Vita Tejo shopping mall in Amadora, Portugal, the equivalent values are 609MJ/m^2 and 990MJ/m^2 with a relative embodied energy ratio of 1.63.

Allowing edge profiles to be shared between two adjacent on their longest edges has the greatest effect for cushions with higher aspect ratios. For instance, for square cushions of 5m^2 the EE/m^2 reduces from 1591 to 1275MJ/m^2, a reduction of 20%, for cushions with 1:5 aspect ratio the decrease is from 2024 to 1316MJ/m^2, a reduction of 35%, whilst for the cushions with 1:20 aspect ratio the decrease from 3296 to 1882MJ/m^2 represents a reduction of 43%.

When sharing edge profiles on all edges there is only a relatively small decrease in the EE/m^2 for cushions with high aspect ratio but larger savings for cushions that are closer to square. In this case, for square cushions of 5m^2, the EE/m^2 reduces from 1275 to 959MJ/m^2, a further reduction of 20%, for cushions with 1:5 aspect ratio the decrease is from 1316 to

1175MJ/m^2, a further reduction of 7%, whilst for the cushions with 1:20 aspect ratio the decrease from 1882 to 1811MJ/m^2 represents a further reduction of just 2%.

Previously the authors have reported the estimated EE/m^2 of ETFE cushions used for three roofs of different configuration: ETFE 1 - 5 x 5 grid of 25 approximately square cushions; ETFE 2 – parallel cushions of varying length but similar width; ETFE 3 - single head-ring supported conic cushion[2].

Table 2: Estimated embodied energy of MJ/m^2 for ETFE foil and glass roofed atria.

Roof		**Covered area m^2**	**Length of perimeter profile m**	**Perimeter/ covered area**	**Estimated embodied energy (MJ/m^2)**
ETFE 1		616	301.2	0.49	**582**
ETFE 2		352	187.2	0.53	**719**
ETFE 3		463	99.0	0.21	**598**

At 582MJ/m^2 the approximately 25m^2 average area cushions of roof ETFE 1, which mainly share edge profiles on all sides, accords well with the predicted embodied energy (from Figure 3) for cushions of this size and configuration (609MJ/m^2). The average, approximately 35m^2, cushion of roof ETFE 2 (with aspect ratio of around 12) has an EE/m^2 of 719MJ/m^2 which compares favourably with the predicted value of 816MJ/m^2, from Figure 2. Finally the single large cushion of roof ETFE 3 with an embodied energy of 598MJ/m^2 is within 2% of the estimated value (609MJ/m^2) for a 100m^2 square cushion.

4 IMPACT ON EMBODIED ENERGY OF THE PRIMARY AND SECONDARY STRUCTURE

Significant benefits from using ETFE foil in building envelopes, in roofs in particular, derive from savings in the number of secondary supporting elements, the material required for them and consequent reduction size of the primary supporting structure. The former is due to the spanning capacity of the foil when used as a tensioned surface – synclastic in inflated cushions and anticlastic in single layer applications. Whilst, for the latter, the minimal thickness of the foil and consequent low self-weight, typically around 1kg/m^2 in triple layer cushions, minimize self-weight actions on a roof.

Despite the apparent benefits of using ETFE foil in place of other transparent and translucent cladding materials, as noted by Cremers[7], there is little published data on the embodied energy savings that can accrue. One of the reasons for this is the difficulty of comparing like with like. Enclosures of similar size and shape often have very different supporting structures (beams, trusses, number of columns), spaced at different centres and with different environmental loading (snow/wind) and support configurations. However, Cremers[7] cites a study by Manara[8] where the primary embodied energy has been calculated for similar roofs of 27 x 33.5m clad in glass and ETFE foil alternatives. In that study the embodied energy of ETFE foil was taken to be 140MJ/kg, similar to that proposed by Ashby[7] and Fernandez[8].

For this paper the authors have estimated the embodied energy for two built examples of ETFE foil covered roofs in the UK, including the cushions, aluminium profile frames and roof steelwork but supporting column steelwork is not included. These are included with those reported by Manara[8] in Table 3, below.

Table 3: Comparison of primary embodied energy (kWh) and (kWh/m^2) for glass and ETFE-covered roofs

Structure	**Mass (t)**	**Primary Energy kWh**	**Primary Energy kWh/m^2**
1. Glass roof from Manara *et al*[8] (1320m^2)			
Steel and substructure	112.4	877,000	664
Glazing	66	390,000	295
Glass roof (total)	**178.4**	**1,267,000**	**960**
2. ETFE foil roof from Manara *et al*[8] (1370m^2)			
Steel and substructure	78.3	636,000	464
ETFE cushions	1.3	53,000	39
ETFE roof (total)	**80**	**689,000**	**502**
3. ESLC, University of Nottingham (352m^2)			
Steel trusses	16	100,400	285
Aluminium profile	1	43,300	123
ETFE cushions	0.23	21,500	61
ESLC Total	**17.23**	**165,200**	**469**
4. Nottingham Boys High School (616m^2)			
Steel trusses	19.4	125,100	203
Aluminium profile	1.38	59,100	96
ETFE cushions	0.43	40,400	66
NBHS Total	**21.21**	**224,600**	**365**

5 CONCLUSIONS

As demonstrated by Figures 1 to 3, the overall EE/m^2 of a building enclosure can vary considerably depending on the size, shape (aspect ratio) and overall configuration (number of shared edge profiles) of the ETFE cushions employed in its roof and façade construction. Although the contribution of the ETFE foil relates directly to the area of the cushion, that of the aluminium edge profile is determined by the length of the perimeter. Hence the EE/m^2 is much higher for small cushions, where the perimeter/area ratio is highest.

The embodied energy in cushions that share edge profiles is less than that for isolated cushions. With two shared edge clamping profiles the greatest benefit accrues when long, thin cushions (with high aspect ratio) are joined on their long edges.

For the designer, a slightly simplistic view may have been conveyed by the EE values quoted in the EPD -VND-2011111-E for the Texlon® system. Taking the EE for the construction of a notional 1m^2 of three-layer ETFE cushion, could understate the EE in small cushions and overstate the EE in large cushions, depending on their geometry and configuration.

For all three examples of ETFE foil covered roofs (proposed and built) the volume and weight of material consumed and the energy embodied within it is generally less than half that of the proposed glass roof. This is a demonstrable advantage of ETFE foil cladding systems which should perhaps be exploited more.

6 ACKNOWLEDGEMENTS

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