Life Cycle in Timber Facade Systems – Robust Design Patterns

Stephan Ott
Dipl.-Ing., Research associate
TU München, Chair of Timber Structures and Building Construction
Germany
ott@tum.de

Stefan Winter,
Prof. Dr.-Ing.,
TU München, Chair of Timber Structures and Building Construction,
Germany,
winter@tum.de

Short Summary

Scope of the paper is the environmental system declaration and improvement of environmental properties of the prefabricated TES EnergyFacade retrofit system on product level. It is the fundamental step towards the description of ecologic quality of a smart envelope refurbishment method. The task is a comparison of various dependencies between the technical requirements and the material effect, which is relevant for the environmental characteristics. The outcome shows a high influence on environmental impact results from different technical and functional requirements to facade elements.

Keywords: Refurbishment; energy efficiency; resource efficiency; system declaration; environmental product declaration; environmental impact; life cycle assessment; reference service life;

1. Objective

Sustainably built and modernized buildings must be economically, socially and ecologically sustainable. In addition to organizational and technical aspects, as well as the optimization of the planning and construction process, fire protection, or the hygro-thermal building physics, is therefore the life cycle-oriented consideration of ecologic quality of vital importance for the development of new modernization solutions [1]. The ageing building stock in Germany and most of Europe is in a change phase. An amount of around 45% of the existing buildings from the age class of 1950 to the eighties of the last century is dedicated to a fairly renewal, that goes beyond ordinary maintenance and repair. The building performance neither fulfils the actual technical and functional requirements nor the demand of owners and tenants.
The currently usual answer to this need for renewal is the application of external thermal insulation compound systems made of mineral fibre or for economic reasons polystyrene hard foam. The installation of these systems is little ergonomic, dependent on weather, will be more difficult with increasing insulation thickness and leads to dust and noise pollution for an extended period of time. These market dominating insulation systems are manufactured from non-renewable raw materials and are energy-intensive in the production and assembly. In polystyrene rigid foam there are risks in terms of the environment and human health, especially by contained hazardous flame retardant which can reach different pathways into the environment.
Energy efficiency measures must be out of social, environmental and process planning considerations carefully considered and compare different solutions; it must be ensured a balance between the environmental impact of the manufacturing phase and the reduction of environmental impacts during building operation. Even if the energy efficiency related refurbishment, mainly targets towards reduction of greenhouse gas emissions in the building operation, so the LCA of a reorganization measure itself, i.e. the primary energy use or greenhouse potential in production, as well as possible risk and hazardous material loads may be considered during production, processing, use and end of life.

Hence it remains a contradiction between improving the ecological properties of existing buildings and the use of fossil based resources to achieve the first goal. In order to realize a better energy efficiency of the building stock there is the need to (1) bring down buildings energy demand by changing the heating system and fuel, (2) improving the building envelope (windows, wall, windows, ground floor, roof) and additional (3) minimize impact from refurbishment by conserving useful substance of the existing fabric, prolonging service life, choice of durable and multifunctional (flexible solution) by consequently use an off-site process before facade elements are assembled and wrapped around the existing fabric.

Scope of the paper is the preparation of basic environmental system declaration and record of environmental properties of the prefabricated TES EnergyFacade retrofit system on product level. TES is synonymous with Timber-based Element System for the energy efficient refurbishment. It is the fundamental step towards the description of ecologic quality of a smart envelope refurbishment method. The task is a comparison of various dependencies between the technical requirements and the material outcome, which is relevant for the environmental characteristics. The main objectives for a practical application of reduced environmental impact are defined by König et al. in [2]. The impact for the most influential life cycle phases – production and end-of-life – has to be quantified for sustainability benchmarks. This information is required in certification systems and supports decision making.
TES EnergyFacade elements consist of a timber-framework construction with highly insulated cavities. The modular framework is produced off-site and assembled with an adaption layer onto existing structures or exterior walls. The cladding material and windows can be chosen as like. They will be mounted onto the wall elements and that should be done off-site as well. Due to the high level of prefabrication, the on-site process is short and inherits minimal waste production.

The dominant parts of the system have not the highest environmental impacts, because they are from renewable resources. Rather, it will be revealed that these parts make a positive contribution to the environmental impact by avoiding a high percentage of carbon. This remains very similar in various construction structures, as the dominant shares are of renewable resources. The disposal can take credits from the energy generation from wood to a substantial extent. The burdens are mainly on the account of the mineral components on the system.

2. Methodology

2.1 Facade Construction Parameters

Life-cycle optimized construction systems have four important basic requirements: the objectives are to maximize the lifespan of important components such as the primary structure [2] [3] [4], minimizing the flow of material [5], increases the possibility to reuse and recycling, as well as maximises the decommissioning. The necessary and variable components of the system are described as input variable. In a poly-hierarchical model, they are networked with the requirements and further the critical dependencies with the impact on the choice of material are derived.

There is a definition of functional properties of layers for TES element and a definition of the essential principles to ensure the design characteristics of this new facade construction [7]. TES is a self-supporting facade structure similar to semi-balloon framed timber structures with support for vertical loads and horizontal anchoring against wind loads on each floor level. Each element has a structural framework and within this framework there is the insulation which improves thermal properties of the existing exterior walls. The enclosure of framework is necessary for structural bracing and functional properties of the element as moisture safety, wind- and airtightness. For safety reasons specific panelling layers for fire safety can be applied. These mineral-based layers encapsulate and protect the insulation and structural parts of the elements.
The compulsory and variable components of the system are set as input dimensions and represent the subgroup of the *TES core* and *Adaption layer* as it can be seen in Figure 4. The structure of the timber framework consists of the wood studs that are positioned in a regular distance and butt-joint perpendicular to sill-beam and wall-plate. On this side of the element oriented towards the interior a panelling is applied for structural and airtightness reasons. Towards the outside a mineral- or a

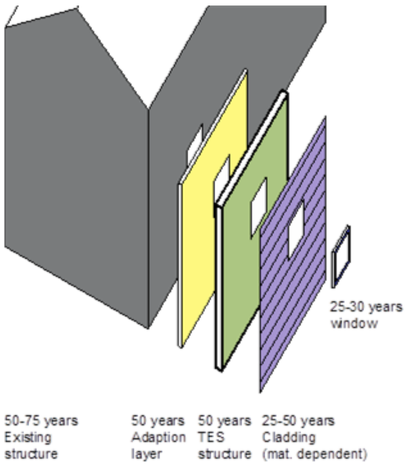
wood-based panel is fixed. A gypsum fibre board is exemplary for a fire safety layer. The partition cavities will be filled with thermal insulation like cellulose fibre.

2.2 Robust construction model

Robustness in life cycle engineering delivers constructions with minimised environmental impact at full serviceability at appropriate durability and technical functionality.
In a poly-hierarchical model, the technical parameters of the TES construction are connected with the environmental requirements derived from the objectives listed in this specific order:

a) Construction design decision leads to,
b) Differentiation of life span and
c) Influences dismantling behaviour.

For life cycle durability and service life, only qualitative empirical values can be derived from existing structures e.g. lifetime of dry wooden walls. It applies to the composition of the structures that so far no composite materials are provided in rule-compliant elements. Exceptions are the sill and the sealing of the window frame.
A selective dismantling process is possible on the element level on-site, a demolition is not necessary. All joints between the existing building and the TES are done by screws. Entire elements can be disassembled and transported for further waste management. The layers and timber framework of individual elements have to be separated and recycled off-site. The joints between the framework and layers of the element are durable and e.g. staples, nails are reversible only to a limited extent.
All relevant considerations need to be evaluated and optimized for the finding of design patterns. Hence the aim is at demonstration of appropriate layer composition instead of the detailing of smaller parts of the timber facade system. This assumption is explained with the influence of the joint part in relation to the element area. Basic assumption is an average small facade of a 4 storey town house building with eight apartments. The length of all horizontal joints is roughly 320 – 520 meters including the length of the basement and the roof eaves. This sums up to an amount of 2,2 to 3,5 m³ of wood required for all horizontal joints plus ten percent for all vertical joints. Assumed that average facade area is about 450 m² it is only 0,005 m³ of wood per square meter of the facade needed for the joint. The TES element itself requires about 0,036 m³ of wood per square meter.



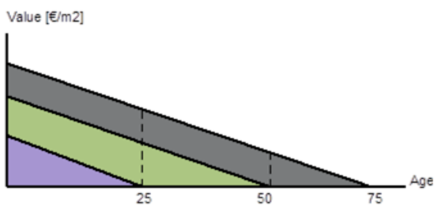


Figure 1 Differentiation of life span of TES element layers.

It is shown as an example that it is more worthwhile from an LCA perspective to optimize the structure of the element. The shape of the joint has an influence on the construction process and the later removal and thus the recovery at the end of life. These other objectives are integral in the whole life-cycle approach, and in particular in the development of the jointing.
Further goals are to maximize the lifespan of important components such as the timber framework structure, and give ability to reuse and recycling, as well as maximizing the dismantling. This is necessary to a higher degree for the exterior parts and layers compare Figure 1. The durability of

the wooden elements and the protection of the structure against climate exposure are done in compliance with hygrothermal requirements and moisture management in closed timber frame components. Thus the TES elements fulfil the requirements of use class 1, in which the wood or wood-based product is inside a construction, not exposed to the weather and wetting [8].

2.3 Life cycle assessment methodology

General LCA methodology is according to the basic rules of building life cycle assessment following the requirements and steps of ISO 14040 and ISO 14044 standard [9] [10].
Functional unit is one square meter of TES element with all layers of the timber framed element but without existing wall, cladding and other integrated components like windows. Up to now the inflow side does not include a more detailed insight in the accompanying parameters, anchoring, tie-back, and gap layer. The core element inventory, which are layers b and c see Figure 3, cuts off negligible secondary materials e.g. tapes, nails, and screws.

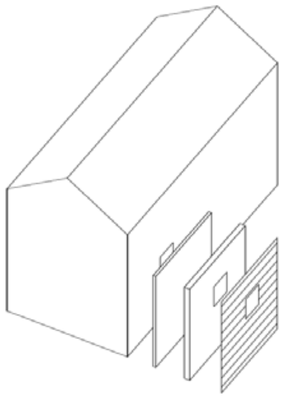


Figure 2 Assembly process of adaption layer, core element and cladding at existing structure (left to right).

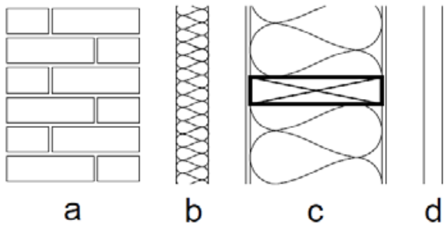


Figure 3 Cross section of existing structure (a), gap layer (b), core TES element (c), cladding layer (d).

System boundaries include the production with raw material extraction, transport, and processing into semi-finished products. The system includes the production of the raw materials and the provision at the factory gate; this is the cradle to gate part according to EN 15804 [11]. The off-site production of the conducted elements is a second factory process, but it is attributable to the construction process and related to phase A5. The transport and assembly flows in A4 are cut off from the “second” factory gate. There is still no data available for life cycle module A4-5 energy and material flows for mounting TES on existing buildings. The subsequent life cycle modules B, C and D are not examined in this article.

2.4 Data for life cycle assessment

The assumptions are set for the entire production phase of TES facade elements. They consist largely of semi-finished products for which already environmental product declarations (EPD) are available. There are so far no detailed data recorded of energy consumption and local material flows in the manufacture of TES elements. Therefore comparative figures from the off-site production of timber frame construction elements will be used, similar to new building off-site processes [12] [13].
Material input flow indicators are divided into the primary energy sources of renewable primary energy content (PER) and non-renewable primary energy content (PENR). A delicate subdivision is not possible here according to the conventions of the EN 15804, because neither the used nor currently available data from the ökobau.dat conform to this standard [14]. Upcoming EPD available on the basis of EN 15804 is also not fully well suited and have only values of the specific products. It is resorted also to EPD for the data base because there are no suitable generic records in the ökobau.dat.

Data for wood-fibre insulation material are selected on an EPD basis [15]. For the wood-fibre insulation material and other wood-based materials, the carbon sequestration is estimated on the basis of the density and the usual humidity and receives a flat-rate reduction of ten percent as either from the manufacturer unspecified base material or necessary glue is included in the final product.
The choice of the impact categories consists of accepted indicators in certification processes. Hence refurbishment will reduce the greenhouse gas emissions, is therefore an important reference value on the material side of the global warming potential (GWP). In addition the carbon sequestration (Cseq) of renewable materials is shown on the basis of the standard TC 175WI [16]. This advantage is evoked already in the global warming potential calculations for cradle to gate. But thermally recycled wood loses this advantage and gets CO2-neutral on the only material side at the end of the entire life cycle. Because the advantage of a CO2 absorption in wood in structure is an essential climate protection contribution, it is included informative in this investigation as a positive environmental impact.

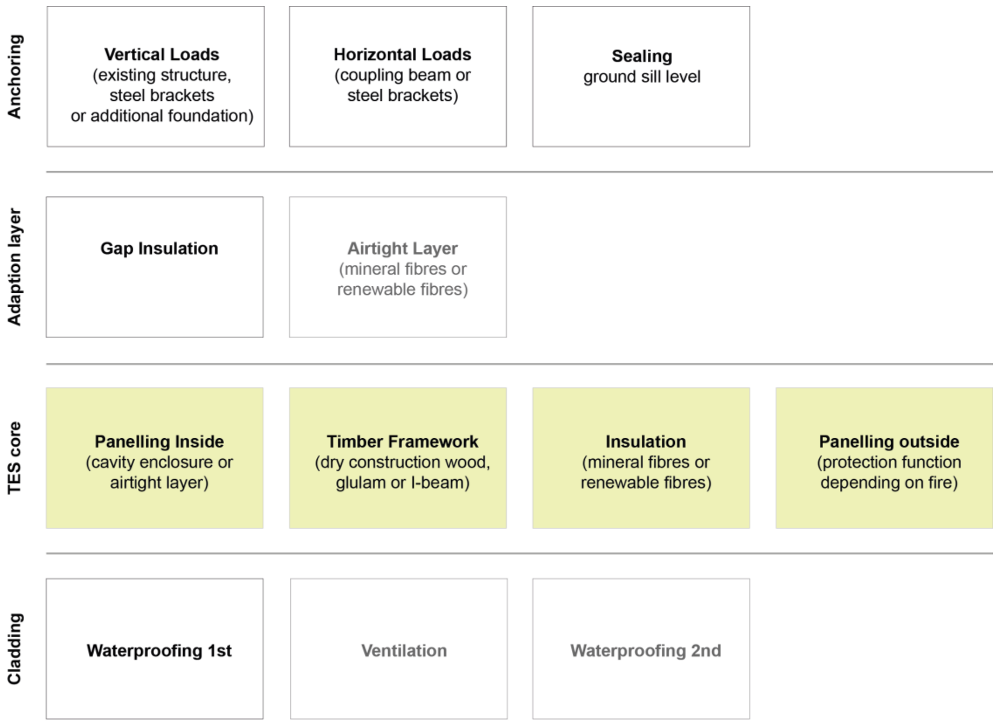


Figure 4 Matrix and basic functional unit description of a general TES system with the core parts highlighted in third row.

2.5 Demonstrators and Examples

The studies are based on nine different wall constructions that are already implemented in different projects. The projects were in Germany, in Norway and Finland. The thickness of the insulation, which is realized with these elements, is between 200 and 300 mm. The thickness of the adaption layer must be added yet, it is between 50 and 80 mm. The TES cross-sections have resulting U values of 0.14 to 0.24 W/m²K. Together with the existing walls thermal properties, total U-values can be reduced thus down to 0.10 W/m²K. By such measure the heat transmission of the facade of existing buildings can be reduced to the level of a retrofit passive house.

Table 1 Properties of TES element case A.

	Position	*Material description*	*Dimension [mm]*
1	functional layer	gypsum fibre board	25
2	gap for adaption	mineral wool	98
3	back_panelling	OSB	12,5
4	insulation	mineral wool	250
5	structure	glue laminated timber, dry	250
6	front_panelling	wood fibre board, soft	12,5

3. Result and discussion

3.1 TES solutions compared to conventional systems

The results focus on the material input and related burdens and benefits. One goal is to compare the full TES systems with the benchmark of conventional retrofit systems for facades. Another objective is taken also on the bandwidth of the inflows of primary energy and the outflow indicators for the global warming potential. Moreover, very good and very bad solutions of a TES facade can be identified and better valued. The averages for the primary content and the global warming potential give important indications of the performance of the entire system. They are also orientation values for the whole spectrum and the degree of deviation.
All TES elements compared in nine cases have the similar layer structure, only the functional layer is not included in all cases. Soft insulation is used for heat insulation and to compensate the gap. The supporting structure is made of solid wood or wood-based materials. The back side panelling requires only airtightness. The front side usually braces the element and additionally meet fire protection requirements on the front in the cases A, D, E, F, G and H.

The primary energy expenditure for TES production is high, if you look at the pure numbers in Figure 5. The ratio of renewable primary energy (PER) versus non-renewable primary energy (PENR) content is 815 MJ to 603 MJ on average. Compared to that, the primary energy content of ETICS are rather small, they have a ratio of 7 MJ PER versus 331 MJ PENR.
The renewable primary energy content of TES contains also the share of the calorific value of wood material in addition to the energy of production; it is therefore similar to or higher than the non-renewable primary energy. The fraction of the calorific value of a square meter of TES is at least 212 MJ or 55 kWh and thus over a quarter of the average renewable primary energy demand.

Table 2 Indicator overview of all nine examples with averages and standard deviation.

	Min	*Max*	*Average*	*SD*
PER	492.21	1318.37	815.38	275.74
PENR	338.27	1191.28	603.38	249.30
GWP	-0.43	-63.89	-33.78	16.67
CSeq	38.32	81.00	50.82	12.16

The benchmark of ETICS is according to the environmental system description (ESD) of the industry. It is therefore an aggregated ESD of German ETICS association and indicates PENR 331.18 [MJ/m²], PER 7.07 [MJ/m²], and GWP +14.48 [kgCO2eq/m²] [17]. The ETIC system compared is from expanded polystyrene insulation material and contains therefore prevailing fossile energy and causes greenhouse gas emissions. Meanwhile, the TES facades have a carbon sequestration potential of an average 50 kgCO2eq that is almost equal between different cases as it can be seen in Figure 6.
The GWP of nine different cases of TES is on average at -33 kgCO2eq. This value is by a factor of four below the reference value of polystyrene-based ETICS.
This shows the low environmental impact of TES facades despite their high resource demand and minor U-values. Despite high primary energy consumption, a result of the reasonable amount of

wood mass with a high calorific value, the remaining GWP of TES is still lower than for ETICS. It should be noted in particular a necessary improvement of resource efficiency in the production of the TES elements and its raw materials. However this universal statement based on the figures lacks a more detailed examination of material properties that cannot be done here.

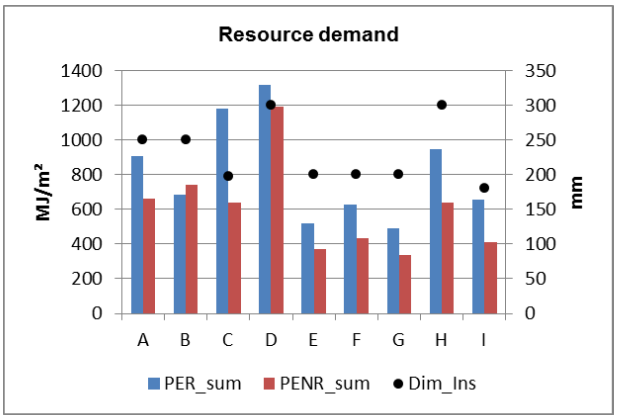


Figure 5 Resource demand of construction compared to thickness of insulation and TES element.

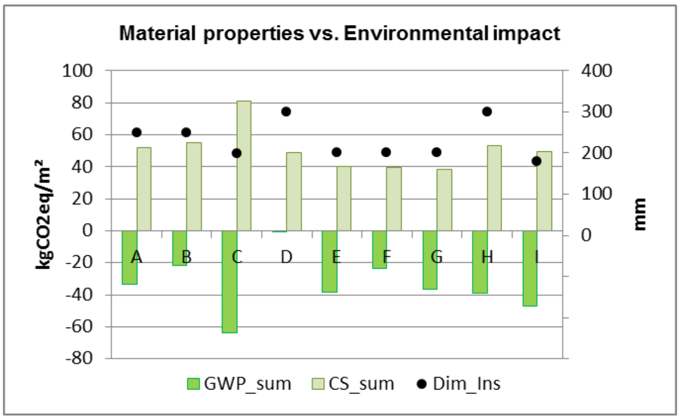


Figure 6 Environmental impact versus the carbon sequestration related to thickness of insulation in a TES cross-section .

3.2 TES layers environmental impact en detail

The analysis of the element layering is most suitable as a method and applied here. The inflow indicators by PER, PENR and carbon sequestration together with the outflows or emissions of GWP are individually calculated for each component layer. The correlation between the insulation dimension and the GWP is assessed. The sensitivity of the influence of layer materials is checked in a dominance analysis. Finally the evenness of material compositions graphs show how important certain layers are for the total amount and to the degree of environmental impact.
In principle, all layers are variable, with regard to the dimension as well as with regard to the materiality. In order to handle the possible diversity it is necessary to consider the requirements matrix and to ensure the correct choice of environmentally-friendly construction of the system. The choice of the layers in the context of the design principles makes it possible to evaluate them separately and to assess environmental impact of layers. By comparing the individual inflows and outflows makes clear, this parameterized layer affect the result of each indicator. On one hand facades such as TES can avoid or replace materials with high environmental impact in contrast to other constructional parts of a building like foundations. This is not always a simple task for wood-based materials because fasteners, adhesives, or encapsulating materials can influence the outcome (structural, safety). If the influence can be reduced the overall result will get more stable in relation to the environmental impacts. Further research will be done on this topic and first results are show in the presentation.

In Table 1, the review of the TES is given as an example element in case study A. By the global warming potential be considered it is apparent that there are positive and negative values in case A. The functional layer and the insulation are on the positive ordinate axis because they do not have carbon storage in cradle to gate phase. The wood based materials from the back panels to the front panels are on the negative ordinate axis due to their carbon storage, see Figure 6 and Figure 9. They avoid carbon emissions and contribute to a reduction of global warming therefore they have a bonus expressed in negative values for the cradle to gate phase.

It is expected that the insulation and the studs have the highest proportions and the strongest influence on the distribution of primary energy. This can be confirmed from a general perspective with the numbers in Figure 7 to Figure 8. There is also a correlation expected between the insulation thickness and the primary energy parameters. Regression of the insulation thickness with the PER and PENR is available (Lin. R-squared = 0.62). Further it is expected that there is a strong negative CO2eq for GWP as mostly wood and wood-based materials are in use. This is true for almost all investigated facade cases; compare Figure 9 to Figure 10. Mainly a mineral based panelling of the TES front side will have influence as well as non-renewable insulation. The GWP scattering at the Back_Panel layers is very low. The Back_Panel layer is only thin regard the entire cross section. Greater deviations rise with the front panelling, the Front_Panel layers, because technical requirements for fire protection or bracing reduce variability of material and dimension parameters. The carbon sequestration information will behave similarly to the GWP.

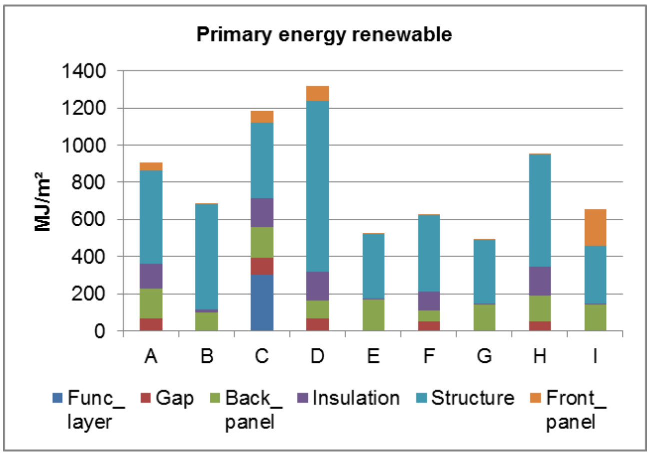


Figure 7 Renewable primary energy content of nine different TES facades, separted by layers.

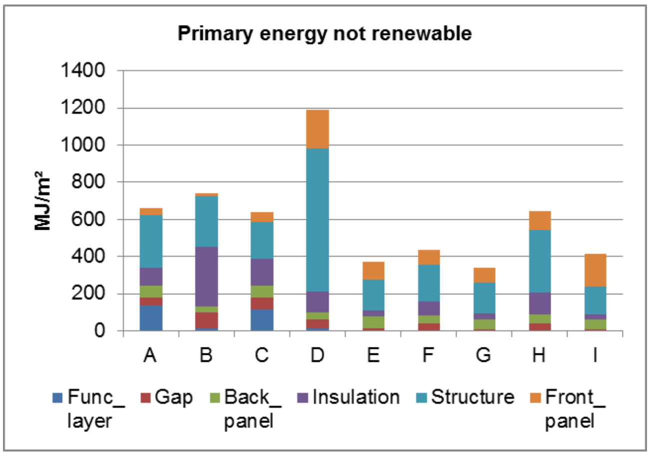


Figure 8 Non-renewable primary energy content.

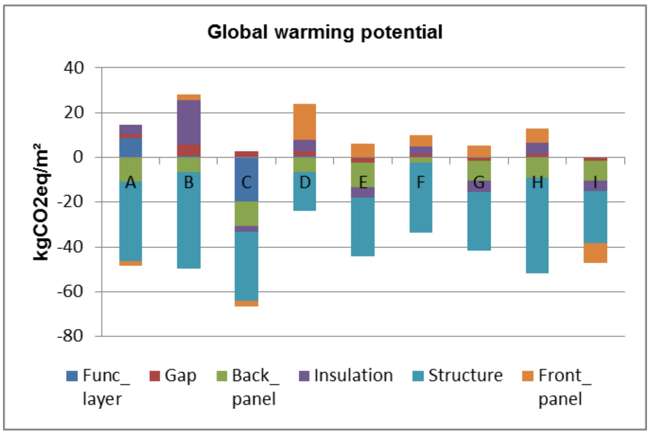


Figure 9 Global warming potential.

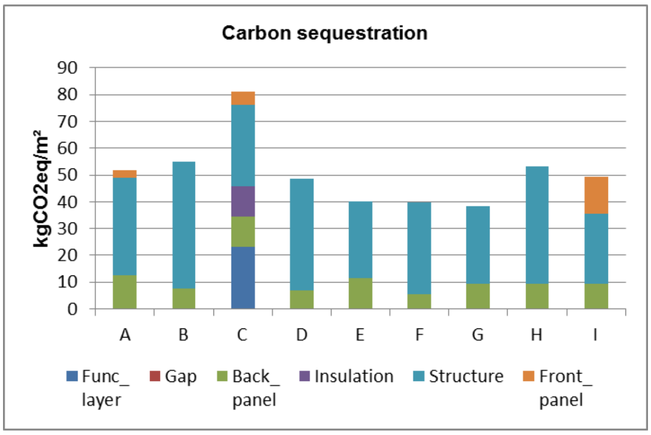


Figure 10 Carbon sequestration potential.

In the further course this article you look closer to some features. They are related to particular element production techniques and the use of certain materials associated.

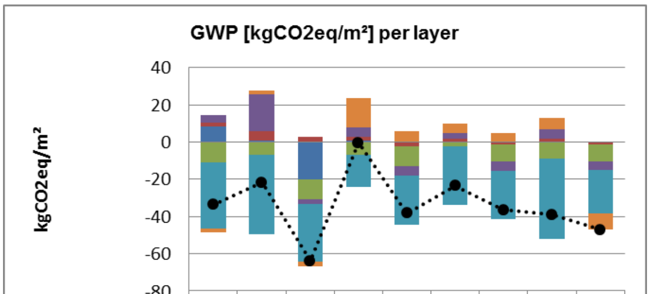
Table 3 Main material groups used in the nine cases.

Functional layer	A; B; C; D	airthightening foil or board
Insulation	A; B; D; F; H	mineral or glass wool insulation
	E; G; I	loose fill cellulose fibre insulation
	C	wood fibre insulation
Front panelling	A; D; E; F; G; H	mineral-based building board (gypsum based or cement bound)
	A; C; I	wood based panelling

In facade case C a functional layer (= shell) is included for airtightening reasons. For this layer, there is a small reinforcing effect of negative GWP, compare Figure 9.
In Figure 9 GWP shows also a distinct greenhouse potential at facade of case D, whereas the

other cases all have a smaller proportion of the positive GWP variants. The same applies to the primary energy content from case D. There is a GWP score of almost zero instead of a negative for case D. It should be noted that the load-bearing structure in this case is laminated veneer lumber (LVL). The used insulation material is mineral-based. In sum, this leads to a below-average score in all impact categories.

For its positive performance the cases C, H and I have low GWP. Another good performance in GWP value has facade case H despite high insulation thickness and not renewable insulation material. This is due to the high proportion of wood in the load-bearing structure. The layers have almost no greenhouse gas emissions with the exception of case H, because it has a mineral based insulation and front panelling. Case I is very balanced over all component layers.
Figure 12 indicates the positive influence of the structural framework on the negative GWP while the front panelling and the insulation do not have this. The structure also has the highest deviation of all scores. The even distribution of the other layers impacts apart from the front panelling is seen also in Figure 12. There is also a spike from the insulation material in this diagram. Reason for this result is a high amount of GWP for the glass wool used.
The influence of insulation and its material is a significant burden while the influence of insulation thickness is comparable low.



	A	B	C	D	E	F	G	H	I
Front_ panel	-1,77	2,406	-2,7	15,85	6,084	5,07	5,07	6,084	-8,51
Structure	-35,7	-42,9	-30,8	-17,5	-26,2	-31,1	-26,2	-42,8	-23,6
Insulation	4,172	19,75	-2,55	5,006	-4,94	3,337	-4,94	5,006	-4,44
Back_ panel	-10,8	-6,6	-10,8	-6,6	-10,8	-2,52	-9,03	-9,03	-9,03
Gap	2,019	5	2,843	2,06	-2,35	1,648	-1,47	1,648	-1,47
Func_ layer	8,45	0,753	-19,9	0,753					
GWP_sum	-33,6	-21,6	-63,9	-0,43	-38,2	-23,5	-36,5	-39,1	-47

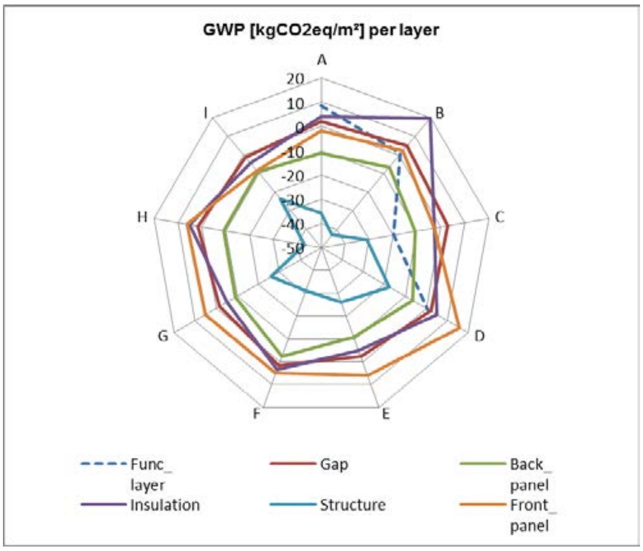


Figure 11 Global warming potential in detail compared to the total sum.

Figure 12 Dominance and evenness of GWP related to layers.

As mentioned before the module A4-5 is based on a very general assumption. It is given that the life cycle module A4-5 holds 20-30% of the total impact of module A1-3. In addition, the module A4 has a relatively high share in the module A4-5, approximately 30%. The other 60% can be allotted to phase A5 construction and phase A5 waste management in equal shares.

4. Conclusions

The TES system is analysed to, which features most of the modernization projects are sustained and what features constitute individual solutions. This inquiry is necessary to be able to use the catalogue of requirements for all projects as universally as possible. The dominant parts of the system have not the highest environmental impacts like the timber framework as structure. Rather, they make a positive contribution to the environmental impact by saving a high percentage of carbon. This remains very similar in various constructions, as the dominant shares are of renewable resources. But right selection of structure and insulation material can influence the positive properties of TES EnergyFacade to a large extent.

To sum up, it can be stated only the front cladding and insulation can deteriorate the GWP balance because they have values on the high emission side of the GWP which is a positive figure. The wood framing and the panelling of the back are renewable materials with negative figures and absorb more CO2 than the production emits. The functional layer is not always required, but it can contribute a slightly negative influence on GWP. The environmental impact of the insulation layer in the adaption layer of the gap is in contrast, constant low and almost negligible.

All TES EnergyFacade solutions are relatively homogenous regarding their global warming potential. The deviations depend severely on the material of the studs and the insulation and are more obvious on the inflow side than on the impact. The panelling has only minor influence.

The TU Munich has developed an eco-balance calculation tool for the TES facade elements and it will be expanded with complementary information. It is an extension to previously disregarded components (e.g. anchoring bolts), as well as characteristic values for the end-of-life scenario have to be captured. The cladding layer as well as integrated elements will be shown only exemplary, because they are individual chosen in each project and they are separate EPD or even ESD and therefore kept outside the system boundary. Another interesting aspect is a deeper insight in the necessary amount of energy and waste for off-site construction and the missing values for flows resulting from on-site processes. The assembly of a TES element wrap around on existing buildings is very different from new building with timber constructions and will cause further environmental impact that has to be diminished.

5. Acknowledgements

TES EnergyFacade, run from 2008 to 2009, and still running SmartTES, from 10/2011 to 09/2013 are funded in the European ERA-Net Woodwisdom-Net by the German federal ministry for research BMBF, represented by PTJ.

6. References

[1] smartTES. smartTES – Innovation in timber construction for the modernisation of the building envelope. http://www.tesenergyfacade.com. Period from 10/2011 to 09/2013, funded by BMBF, represented by PTJ.

[2] KÖNIG H, KOHLER N, KREISSIG J, LÜTZKENDORF T. *Lebenszyklusanalyse in der Gebäudeplanung*. Institut für intern. Architektur-Dokumentation, München, 2009, ISBN 978-3-920034-30-0

[3] ALTING L, LEGARHT JB. *Life Cycle Engineering and Design*. CIRP Annals — Manufacturing Technology, DOI: http://dx.doi.org/10.1016/S0007-8506(07)60504-6; 1995, Vol 44 (2), pp 569–580.

[4] THORMARK C. *A low energy building in a life cycle — its embodied energy, energy need for operation and recycling potential*. Building and Environment, Elsevier, München, DOI: http://dx.doi.org/10.1016/S0360-1323(01)00033-6; 2002, Vol 37, pp 429 – 435.

[5] OTT S, WINTER S. *Parameter Study of a Prefabricated Retrofit Facade System*. Proceedings International Symposium on Life-Cycle Civil Engineering IALCCE, 2012, Vienna, ISBN 978-0415621267.

[6] MOREL, JC, MESBAH A, OGGERO M, WALKER P. *Building houses with local materials: means to drastically reduce the environmental impact of construction*. Building and Environment, DOI: http://dx.doi.org/10.1016/S0360-1323(00)00054-8; 2001, Vol 36 (10), pp 1119–1126.

[7] LOEBUS, S, OTT, WINTER. *Prefabricated Retrofit Facade System – a Systemized Building Construction Detailing*. In: Proceedings of SB13 Graz. 2013. (to be published).

[8] EN 335:2006-10: Durability of wood and wood-based products – Definition of use classes. CEN/TC38 – Durability of wood and wood based products. 2006.

[9] ISO 14040. Environmental management – Life cycle assessment - Principles and framework (ISO 14040:2006). Berlin: Beuth, 2009.

[10] ISO 14044. Environmental management - life cycle assessment - requirements and guidelines (ISO 14044:2006). Berlin: Beuth, 2006.

[11] EN 15804:2011. Sustainability of construction works – Environmental product declarations –

Core rules for the product category of construction products.
[12] ECO2-book: www.eco2wood.com; Summer 2013 (to be published).
[13] TAKANO, A, PITTAU, HAFNER, OTT. *Greenhouse gas emission from construction process of multi-story wooden buildings.* In: Proceedings of SB13 Graz. 2013. (to be published).
[14] Ökobau.dat 2009, http://www.nachhaltigesbauen.de/no_cache/baustoff-und-gebaeudedaten/oekobaudat.html?cid=4264&did=1490&sechash=026f9f62. Last access 05.04.2013.
[15] EPD-KRO-2009212-D, Kronotherm Holzfaserdämmung, Hersteller Kronoply GmbH, 2009. http://bau-umwelt.de/download/CY1c67a99eX13aab7d9717X7ba4/EPD_KRO_2009212_D.pdf. Last access 5.04.2013.
[16] TC 175 WI: *Use of wood in buildings and the adventitious potential for the reduction of a building's carbon footprint.* CEN TC175. 2011.
[17] Muster ESD-FVW-2011511-D, WDV Systeme, Hersteller Fachverband Wärmedämm-Verbundsysteme e.V. , 2011. http://bau-umwelt.de/download/C3ddbc477X13042d4a6ffX443e/Muster_ESD_FVW_2011511_D.pdf. Last access 5.04.2013.