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The combined impact of energy efficiency and embodied energy of external wall over 30 years of life cycle

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Abstract. Decreasing the energy consumption in production and building activity is the main aim nowadays as well as in the future. Taking into account that almost 50% of European Union's final energy consumption is used for heating and cooling, of which 80% is used in buildings it is essential to minimize this amount beforehand. Looking at the energy losses we see that the main heat losses are caused due to the transmission through the envelope and ventilation system.

EU energy efficiency target for buildings to 2030 is at least 32.5%. According to this, national energy efficiency action plans were done, which mean that existing building stock need renovation and new buildings will be constructed according to the energy efficiency requirements. One important factor to improve energy efficiency is to modify thermal transmittance of the envelope. In 2017 minimum energy efficiency requirements were validated in Estonia and determined that the thermal conductance of outer wall must be less than 0.22 W m^{-2} K^{-1} (recommended range of U = 0.12–0.22 W m^{-2} K^{-1}). According to this the energy loss through the envelope was calculated over the year taking degree-days as bases. In our area this number is 4,933 degree days per year, what gives us the calculated heat loss through the envelope 10.22 kWh m^{-2} if the thermal conductance of the wall is 0.092 W m^{-2} K^{-1}. This required value of thermal conductance we can achieve using good insulation materials. Still there are possibilities to choose between insulations.

Done tests and calculations allow to conclude that energy consumption during building life cycle together with embodied energy of building materials gives us more realistic overview of the energy efficiency of the building. Our results confirm that the use of local natural insulation materials is 1.67 times more sustainable and energy saving than using industrial materials.

Key words: embodied energy, thermal conductance, energy efficiency.

INTRODUCTION

'Energy use in buildings and for building construction represents more than one-third of global final energy consumption and contributes to nearly one-quarter of greenhouse gases emissions worldwide' (GBS, 2016). Minimising energy consumption is one of the important goals in nowadays production and construction activities. Referring to Eurostat: buildings account for 40% of energy consumed (EC, 2019).

As we see from the Fig. 1 the energy consumption in building hasn't decreased since 2014 comparing to 2019. Big amount of energy losses (heating and cooling energy mainly) is caused by ventilation and through envelopes, what are not sufficiently insulated (ECS, 2016). Speaking about energy savings it is recommended to use more energy efficient products. On the whole this mean energy efficient technologies and new generation insulation materials (EC, 2019; Wang et al., 2020). Increasing concern of climate and environmental change distress people and transform the way they live to limit the impacts of everyday life on environment (Probst et al., 2014). More and more customers are seeking alternative solutions that could improve their quality of life being environmentally-friendly. One approach to sustainable building includes the use of alternative building materials (Schroeder, 2019; Cornaro et al., 2020).

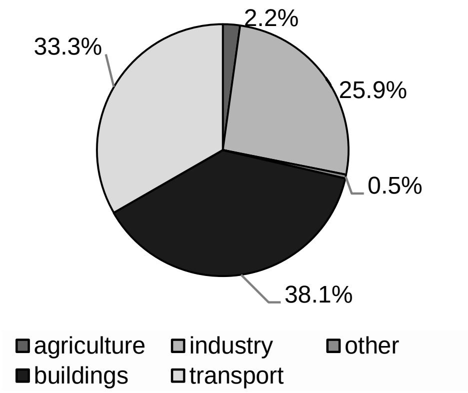

Figure 1. Energy consumption by sectors in EU in 2014 (ECS, 2016).

The possibility to obtain the energy efficiency aims planned by EU until 2030 is to build new constructions according to the demands and to renovate existing building stock as well and as quickly as possible (EPB-EU, 2016; SGF, 2014). By Estonian national energy and climate plan European Union funds are planned to use for renovating business and public sector buildings and living stock as well. The plan is to renovate totally about 290,000 m^2 of flooring (NECP 2030, 2019).

Although calculations of buildings energy efficiency don't pay attention to consumed embodied energy in building materials. B. Berge has divided the energy use during building life cycle as presented on the Fig. 2.

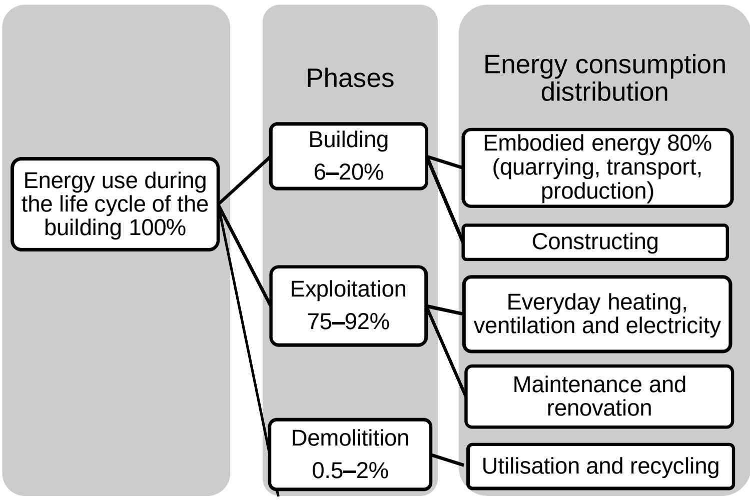

Figure 2. The energy use in different stages of the building life cycle (Berge, 2009).

From the Fig. 2 we see that in the exploitation phase the energy use is the greatest, until 92% of the total energy use. So the amount of embodied energy in the materials is in the range of 8–25%. The exploitation phase of residential buildings is considered to be 30 years. In our research and by B. Berge embodied energy of materials consists of energy used for extracting, transporting and producing materials, in other words it means energy used from 'the cradle to the gate' (Miljan, J. & Miljan, R., 2012). This method to calculate embodied energy has been used by many researchers (May et al., 2012; Fernandes et al., 2019). Embodied energy amount in building materials has been researched by Bath's University for years and done database will give the wide overview of embodied energy consumed in different building materials (ICE, 2008). One possibility to minimise energy consumption of construction materials is to use local renewable sustainable and natural materials. These materials are also considered to be healthy and improving the indoor climate quality. Renewable materials have been investigated by many researchers (Brencis et al., 2017) and results have been promising.

So one possibility to ensure good and healthy indoor climate is to improve the thermal conductance of envelopes. Problem to solve is, how to get the optimal result in minimising energy use over the buildings life cycle. Main components we shall account are: total energy consumption during exploitation, the thermal conductance of the external wall, the embodied energy in the materials of external wall.

As many of people are interested in living in sustainable buildings and in many cases local natural insulation materials are simply agricultural waste, like straw, in our research we studied them (Miljan, M.-J. & Miljan, J., 2013). In calculating energy efficiency embodied energy of materials is not taken into account. In such tense energy saving situation and in designing of nearly zero-energy buildings this calculation gives a surprising result.

MATERIALS AND METHODS

In our study we took building's life cycle equal to 30 years. In calculating heating energy consumption we used Tartu region's degree days 4,933 and indoor temperature of 21 °C (Masso, 2012).

In this study we compared embodied energy of materials and consumed heating energy over 30 years of 5 external walls. Three walls were built using local renewable building materials: timber, clay, straw and lime (Fig. 3, Table 1). The fourth structure was theoretical wall built using straw and clay plaster with steel bars and thermal conductance of the wall was calculated on the data taken from literature sources (Minke & Mahlke, 2004; Wihan, 2007). The fifth theoretical wall (Table 2) was constructed from timber frame and insulated with glass wool. In calculations we used also data from the tests done during several years in the department of rural building in Estonian University of Life Sciences and the database of University of Bath (ICE, 2008). Building physics calculations were done according to EVS 908-1

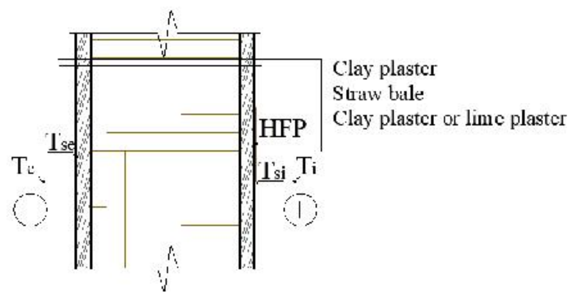

Figure 3. The scheme of external wall's structure (T – temperature sensor; HFP – heat flow plate).

(EVS 908-1, 2016). Placement of measuring devices and scheme of the walls no 1, no 2 and no 3 is presented on the Fig. 3.

Method to measure thermal conductance and temperatures was the same in all objects. The wall no 1 was a wall element built into the window opening of the laboratory (Miljan, M.-J. et al., 2013). The wall no 2 was office (case study building), built at Tammistu (Miljan, M. & Miljan, J., 2015) and the wall no 3 was sauna (case study building), built at Leigo (Miljan, M.-J. et al., 2017; Allikmae & Jurgenson, 2017). Data about structure and main results get from these objects are presented in the Table 1.

Table 1. Technical and physical indicators of external walls according to measured results on objects

Number of the external wall Measuring period Used Materials and units	Wall no 1 2009–2010 (mm)	Wall no 2 2012–2013 (mm)	Wall no 3 2016–2017 (mm)
Clay plaster (internal)	50	40	40
Straw	480	900	500
Clay plaster (external)	50	40	-
Lime plaster (external)	-	-	40
External wall - TOTAL THICKNESS	580	980	580
Thermal conductance of the external wall W m^{-2} K^{-1}	0.182	0.148	0.150

From the Table 1 we can see that measured thermal conductivity in case studies differs a lot. Results are influenced by climate, location of the building and the homogeneity of natural materials. Get results were actually not that good as we supposed basing on literature sources. From the literature data we found that thermal conductivity of straw (longitudinal fibre) is $\lambda = 0.085$ W m^{-1} K^{-1} (Wihan, 2007) and of clay plaster is $\lambda = 0.8$ W m^{-1} K^{-1} (Minke & Mahlke, 2004). Calculating the thermal conductance of external wall by these values we got that U = 0.092 W m^{-2} K^{-1}, if d_{wall} = 900 mm (later named as wall no 4).

To compare embodied energy consumption of different wall structures we constructed an theoretical timber frame external wall – the wall no 5, insulated with glass wool and with the same thermal conductance as the wall no 4. In Table 1 used materials and their building physics properties of external wall are presented.

Table 2. Building physics properties of timber frame wall no 5 insulated with glass wool

Properties of layer Used Materials	Thickness of the layer (m)	Thermal conductivity (W m^{-1} K^{-1})	Thermal resistance (m^2 K W^{-1})
Cladding (external)	0.025	-	-
Air cap	0.0025	-	-
Fixed external layer's thermal resistance	-		0.13
Wind resistance board	0.03	0.037	0.81
Glass wool	d_{wool}	0.04	R_{wool}
Vapour resistance barrier	0.0002	0.4	0.0005
Gypsum board	0.014	0.21	0.066
Fixed internal layer's thermal resistance	-	-	0.13
TOTAL			1.14

Needed thermal resistance of timber frame wall is:

$R = \frac{1}{U} = \frac{1}{0.092} = 10.87\ \mathrm{m^2\ K\ W^{-1}}$.

So the wool layer's needed thermal resistance R_{wool} = 9.73 m^2 K W^{-1}. The thickness of the wool layer should be $d_{wool} = 9.73 \times 0.04 = 0.389\ m$.

Embodied energy consumption of external walls materials' is presented in Tables 3 and 4.

Table 3. Embodied energy of the external walls (no 1, no 2 and no 3) insulated with straw

Wall	Material	Density (kg m^{-3})	Thick-ness of layer (m)	Consumed material (kg m^{-2})	Embodied energy (MJ kg^{-1})	Embodied energy of layer (MJ m^{-2})	Embodied energy of wall (MJ m^{-2})	(kWh m^{-2})
1	Clay plaster	1,700	2×0.05	170	0.09[2]	15.30		
	Straw bale	150	0.48	72	0.24[1]	17.28	50.22	13.90
	Timber*	450	-	4.50	3.93[3]	17.64		
2	Clay plaster	1,700	2×0.04	136	0.09[2]	12.24		
	Straw bale	200	0.9	180	0.24[1]	43.20	71.19	19.65
	Steel bars*	-	-	1.79	8.80[1]	15.75		
3	Clay plaster	1,700	0.04	68	0.09[2]	6.12		
	Straw bale	150	0.5	75	0.24[1]	18.00	119.60	33.39
	Lime plaster	1,400	0.04	56	1.39[3,4]	77.87		
	Timber*	450	-	4.50	3.93[3]	17.64		

*Amount of timber and steel bars is calculated to build one square meter of external wall. Indexes in the table [1] (ICE, 2008), [2] (Berge, 2009), [3] (Teor, 2016), [4] (Allikmae & Jurgenson, 2017).

In the Table 4 the embodied energy consumed in materials of the timber frame wall is described.

Table 4. Embodied energy of timber frame wall (the wall no 5) materials in the case if thermal conductance U = 0.092 W m^{-2} K^{-1}

	Material	Density (kg m^{-3})	Thickness of layer (m)	Material (kg m^{-2})	Embodied energy (MJ kg^{-1})	Material layer's embodied energy (MJ kg^{-1})	(kWh m^{-2})
1	Linseed oil (external)	-	-	-	-	13.54	3.76
2	Cladding	450	0.025	11.25	3.92	44.1	12.25
3	Distance lath	450	0.0019	0.84	3.92	3.35	0.93
4	Wind barrier	50	0.03	0.0015	7.40	11.10	3.08
5	Glass wool	40	0.389	0.015	43.00	669.08	185.86
6	Timber frame	450	0.027	12.15	3.92	47.63	13.23
7	Vapour resistance film	1,390	0.0002	0.278	83.10	23.10	6.42
8	Gypsum board	900	0.014	12.6	6.75	85.05	23.63
9	Colour (internal)	-	-	-	5.27	5.27	1.46
Embodied energy of external wall's square meter						902.22	250.62

From Table 3 we can see that embodied energy of ones square meter of external wall from alternative materials is in the range 13.90–33.39 kWh m^{-2}. Comparing this result to the result from Table 4, we see that embodied energy of timber frame wall will exceed the embodied energy of straw wall 8–18 times. Fig. 4 is compiled to illustrate this difference better.

From the Fig. 4 we can see that the wall no 4 has smallest energy consumption over 30 years and the wall no 5 (industrial materials and U = 0.092 W m^{-2} K^{-1}) consumed even more energy than walls no 2 and 3 with not so good thermal conductance as wall no 5.

In our article the calculation (formula 1) was done to find heating energy consumed during 30 exploitation years.

$$Q_k = H \cdot S \cdot 24 \cdot 10^{-3} \qquad (1)$$

where H – heat loss which is equalised with U-value; S – degree days in Tartu region, 4,933 days (Masso, T. 2012); 24 – hours in.

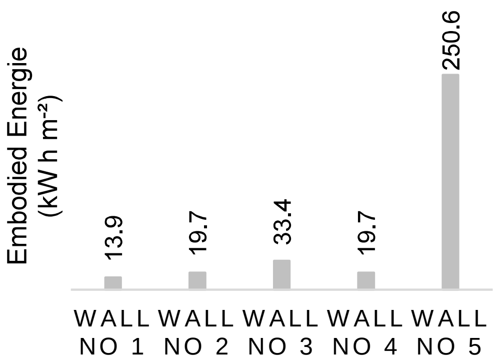

Figure 4. Embodied energy of investigated walls.

Graphs on the Fig. 5 presenting the combined impact of heat energy and embodied energy of all five investigated walls over 30 years. The consumed heat energy depends on U-value.

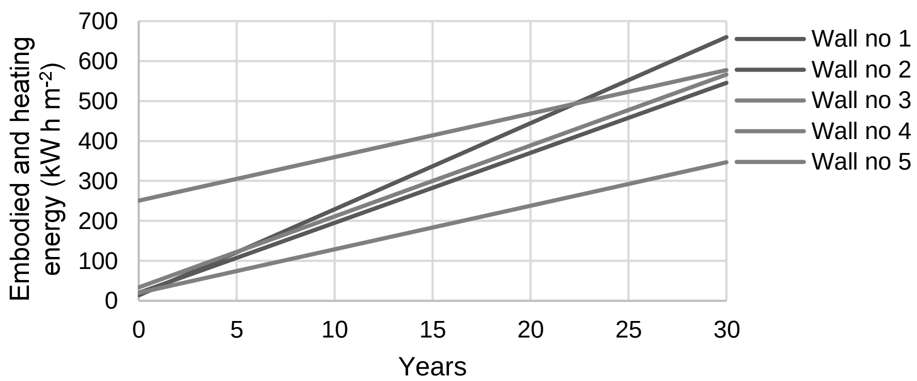

Figure 5. Combined impact of consumed heating and embodied energy of the wall's materials during 30 years.

From the Fig. 5 we can see that the wall no 5 has the best energy saving properties over 30 years and the wall no 4 (industrial materials and U = 0.092 W m^{-2} K^{-1}) consumed more energy than walls no 2 and no 3 with not so good thermal conductance as the wall no 5.

RESULTS AND DISCUSSION

Looking at the walls described in Tables 3 and 4, we see that embodied energy of the walls of local natural materials (the range is 13.90–33.39 kWh m^{-2}) is significantly smaller than that of the wall no 5 (250.62 kWh m^{-2}) constructed from industrial building materials. Comparing results the embodied energy of timber frame wall will exceed the embodied energy of straw wall 8–18 times. Even during 30 years the embodied energy together with heating energy is smaller, comparing walls no 2 and no 3 to the wall no 4. Exceptionally big difference in energy consumption is between the walls no 5 and no 4. The wall no 4 was the theoretical wall where U-value was calculated using thermal conductivity values taken from literature sources: $\lambda = 0.085$ W m^{-1} K^{-1} (straw) and $\lambda = 0.8$ W m^{-1} K^{-1} (clay plaster) and the got U value was 0.092 W m^{-2} K^{-1}. The wall no 5 was with the equal U-value and thermal conductivities of used materials were taken also from different sources. The comparison of these two theoretical walls show that the materials used in wall no 4 (natural materials) is 1.67 times more sustainable and energy saving than used materials in the wall no 5. So local natural materials are worth researching.

CONCLUSIONS

Embodied energy of external wall's materials had been evaluated for five different walls design with target to estimate 30 years' life cycle energy consumption of the envelope. Looking at the results of the article the embodied energy of external wall's building materials should be taken into account in evaluating the energy efficiency of the envelope. On the whole the suggestion is to study this phenomenon in the future to figure out the more exact conditions which may influence total energy consumption. The future plan is to continue the research of local natural building materials, so called alternative materials, for instance lime and hempcrete. Data about embodied energy of lime based on literature sources may be smaller in Estonia. In the future researches it will be fascinating to find how the recycling energy amount will influence the total amount of used energy.

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