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Environmental benefits resulting from the reduction of heating energy demand in buildings

Robert Dylewski[1], Janusz Adamczyk[2], Joanna Zarębska[3]

University of Zielona Góra, [1]Faculty of Mathematics, Computer Science and Econometrics
[2, 3]Faculty of Economics and Management
65-417 Zielona Góra, ul. Licealna 9
e-mail: R.Dylewski@wmie.uz.zgora.pl, {J.Adamczyk; J.Zarebska}@wez.uz.zgora.pl

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Abstract

The article proposes the manner of determining ecological benefits, which result from thermo insulation of the external walls of the building. In order to assign environment load the technique of life cycle assessment LCA was used, including the division into three damage categories: human health, ecosystem quality and raw materials. The production of thermo insulating materials causes the increase of the environment load, but in the thermal phase of the building usage the negative impact on the environment is reduced due to the reduction of energy demand necessary to heat. A few dozen of thermo insulation variants were examined, depending on the kind of wall, heat source and thermo insulating material. For all cases the analyzed investment turned out to be cost effective in terms of ecological aspects. In each damage category the reduction of the environment load was obtained. The ecological payback period was obtained within 0–5 years.

Introduction

In Poland 33% of final energy is consumed in the sector of households, and as much as 71% this quantity is used for heating purposes [1]. The improvement of energetic effectiveness of building objects generates first of all economic benefits, but it is also important to reduce the environment loads connected with energy consumption in the phase of using buildings. One of the most effective manners of saving energy for heating buildings in Polish conditions is thermo insulation of external building walls. Thermo insulation becomes then a great reducing potential of final energy consumption in the building sector and is economically conditioned according to McKinsey curve at the same time [2].

The investment with thermo insulation of external walls of the building should bring economic benefits, which depend to a large extent on the selection of insulation thickness [3, 4]. The article proposes the manner of determining the ecological benefits of the investment, which are obtained as a result of the reduced demand for energy to heat in the building. The method of assessing life cycle LCA was used in order to achieve it.

The environmental life cycle assessment

Investments are first of all assessed from a financial point of view. In many cases they can have a really great impact on the environment. For the ecological evaluation of investment it is possible to use so called Life Cycle Assessment (LCA). The methodology of the ecological life cycle assessment was normalized and described in two norms ISO 14040 and ISO 14044. According to those norms LCA analysis includes four consecutive stages:

- *Goal and Scope Definition*. In this article the aim of the research is the assessment of the impact of thermo insulation of the external building wall on the environment. The scope of the research referred to the process of obtaining raw materials (chain of supplies), production and utilization of thermo insulating materials, as well as the thermal phase of the building use. As a functional unit for thermo insulating materials 1 m^3 of the analyzed material was accepted. In the phase of the energetic utilization of the building the production of 1 kWh of heat was taken as a functional unit.

- LCI – *Life Cycle Inventory*. The data-in was taken from the data base of SimaPro 7.1 programme.
- LCIA – *Life Cycle Impact Assessment*. For the realization of this stage the mentioned computer programme SimaPro 7.1 was used altogether with Ecoindicators 99 procedure. This procedure enables to allocate eleven impact categories to three damage categories and, therefore, allows to conduct the assessment of impact on: human health, quality of environment and consumption of natural resources. Additionally, it enables to present a final result of LCA in so called eco-points Pt (value 1 Pt equals 10^3 of units of annual environment load per one citizen in Europe).
- *Interpretation*. At this stage final conclusions are formulated – according to the assumed aim and the scope of research at the beginning. At the same time in this phase the proenvironmental optimization is conducted – through the replacement of building materials for more environmentally friendly ones, which are characterized by a smaller value of LCA at the stage of producing them.

LCA analysis for thermo insulating materials

Thermo insulation of the external walls of the building aims at reducing the building demand to heat for central heating purposes. As a consequence, the energy consumption for heating the building and the negative impact of the building on the environment is reduced. The production of thermo insulating materials itself, however, increases the environment load.

The article takes into consideration the following insulating materials (λ refers to the thermal conductivity of thermo insulating material):

(I1) foam PIR, λ = 0.028 W/mK (density 30 kg/m^3);
(I2) mineral wool, λ = 0.035 W/mK (density 90 kg/m^3);
(I3) polystyrene foam, λ = 0.040 W/mK (density about 15 kg/m^3);
(I4) ecofibre [5], λ = 0.041 W/mK (density 60 kg/m^3);
(I5) thermo insulating plaster Thermopor [6], λ = 0.054 W/mK (density 334 kg/m^3).

Needed data was obtained from [7].

In table 1 and in figure 1 the results of LCA analysis for examined thermo insulating materials were presented, with the division into three damage categories.

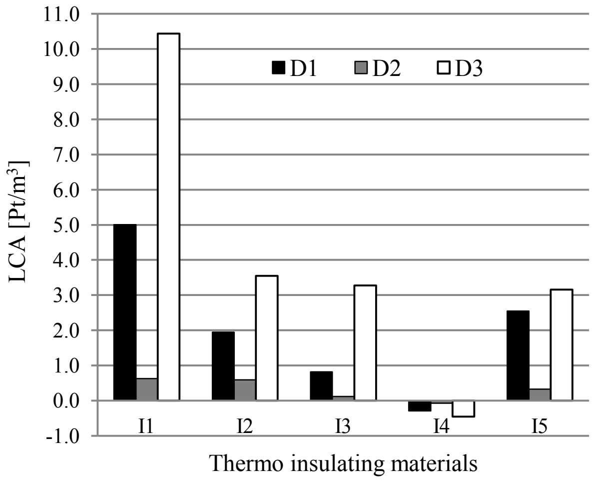

Fig. 1. The results of LCA analysis for thermo insulating materials divided into three damage categories [own elaboration based on SimaPro programme]

The greatest environment load in each category was obtained for foam PIR (I1). Except for ecofibre, the greatest environmental impact was obtained for all insulating materials in category of raw materials (D3). For ecofibre, in each category a negative value was obtained, which means the reduction of the environment load due to the production of this material.

LCA analysis for heat sources in buildings

The environment load generated as a result of heating the building depends to a great extent on the building demand for heating, but also on the heat and fuel source used. The analysis includes four kinds of heat sources:

(S1) hard coal boiler (boiler efficiency 80%, fuel calorific value 29 MJ/kg);

Table 1. The results of LCA analysis of thermo insulating materials divided into three damage categories (in Pt/m^3) [own elaboration based on SimaPro programme]

Damage category	Thermo insulating materials				
	I1	I2	I3	I4	I5
(D1) Human health	5.00106	1.94538	0.81526	–0.29287	2.55110
(D2) Ecosystem quality	0.62455	0.58584	0.11709	–0.07781	0.32993
(D3) Raw materials	10.43603	3.54963	3.27320	–0.46179	3.15410
Total:	16.06164	6.08085	4.20555	–0.83247	6.03513

(S2) natural gas boiler (boiler efficiency 90%, fuel calorific value 31 MJ/m^3);
(S3) electric energy boiler (boiler efficiency 99%);
(S4) heat pump (seasonal coefficient of pump performance SCOP = 3).

The number of Sd = 3605 degree days was taken (several years' average in Poland for the years 1980–2004 [8]). The number of degree days of heating season is a quantitative indicator defining heating energy demand of houses and public utility buildings, it is defined on the grounds of the climate data for a particular town. It is calculated when the whole day external air temperature is lower than the assumed base temperature.

In table 2 and in figure 2 the results of LCA analysis for considered heat sources were included for the assumed functional unit of 1 kWh. The environment load was assigned separately in each damage category.

Table 2. The results of LCA analysis for heat sources divided into three damage categories (in Pt/kWh) [own elaboration based on SimaPro programme]

Damage category	Heat source			
	S1	S2	S3	S4
(D1) Human health	0.007413	0.001414	0.016374	0.001298
(D2) Ecosystem quality	0.002900	0.000147	0.002475	0.000172
(D3) Raw materials	0.008994	0.010714	0.029657	0.009652
Total:	0.019307	0.012275	0.048506	0.011122

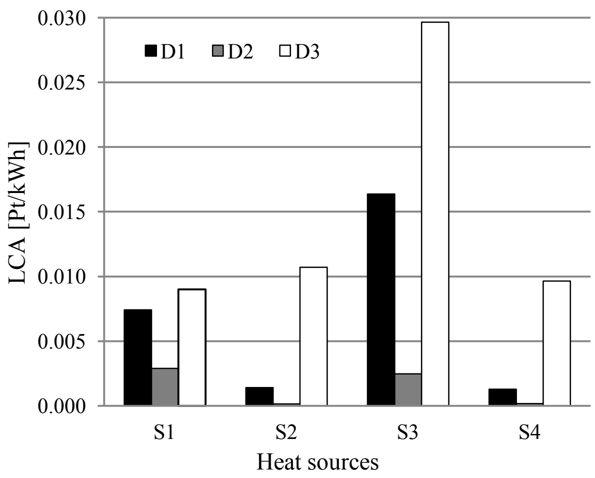

Fig. 2. The results of LCA analysis for heat sources divided into three damage categories [own elaboration based on SimaPro programme]

The greatest environment load as a result of producing 1 kWh was obtained with the use of electric energy boiler (S3) as a heat source, and the smallest one for natural gas boiler (S2) and heat pump (S4). For each heat source the biggest load emerges in category of raw materials (D3).

Environmental benefits resulting from thermo insulation of external building walls

Due to thermo insulation of external walls in the building the heating demand of the building is reduced. The reduction depends substantially on the wall parameters without thermo insulation.

Three different kinds of construction materials used to build external walls were taken into account:

(P1) cellular concrete blocks (density 400 kg/m^3): the thickness of 24 cm, thermal conductivity of 0.10 W/mK, (R_o = 2.40 m^2K/W, U_o = 0.39 W/m^2K);
(P2) ceramic hollow blocks MAX: the thickness of 29 cm, thermal conductivity of 0.21 W/mK, (R_o = 1.38 m^2K/W, U_o = 0.65 W/m^2K);
(P3) sand-lime blocks (silikat): the thickness of 24 cm, thermal conductivity of 0.46 W/mK, (R_o = 0.52 m^2K/W, U_o = 1.45 W/m^2K).

According to norm PN-EN ISO 6946 inside air film thermal resistance R_{si} = 0.13 m^2K/W and outside air film thermal resistance R_{se} = 0.04 m^2K/W were taken.

The analysis concerned a house with a garage having the usable floor area of 156.1 m^2 and the area of external walls of p = 158.7 m^2 (building cubature 390 m^3).

The next stage of the analysis was to verify the thermal phase of the building use. The values of a building demand for heat to realize central heating in a heating season were determined, for walls with different heat transfer coefficients, applying Herz OZC version 3.0 computer programme. The external building walls have to have a heat transfer coefficient not bigger than U_N = 0.30 W/m^2K, according to a proper Regulation of Infrastructure Minister [9]. The results were presented in table 3.

Table 3. Building heating demand for central heating purposes (in kWh/year) [own elaboration]

Type of wall	Heating demand
(P1) The wall U_o = 0.39 W/m^2K	19,192
(P2) The wall U_o = 0.65 W/m^2K	22,664
(P3) The wall U_o = 1.45 W/m^2K	33,448
The wall U_N = 0.30 W/m^2K	17,997

Using the results from table 2 and 3 it was possible to determine the environmental impact of one year thermal phase of building usage, depending on the kind of heat source and heat transfer coefficient of external walls. The results were presented in table 4.

Table 4. The result of LCA analysis of one year thermal phase of building usage (in Pt/year) [own elaboration]

Type of wall	Damage category	Heat source			
		S1	S2	S3	S4
(P1) The wall $U_o = 0.39$ W/m^{2}K	D1	142.270	27.137	314.250	24.911
	D2	55.657	2.821	47.500	3.301
	D3	172.613	205.623	569.177	185.241
	Total:	370.540	235.581	930.927	213.453
(P2) The wall $U_o = 0.65$ W/m^{2}K	D1	168.008	32.047	371.100	29.418
	D2	65.726	3.332	56.093	3.898
	D3	203.840	242.822	672.146	218.753
	Total:	437.574	278.201	1099.339	252.069
(P3) The wall $U_o = 1.45$ W/m^{2}K	D1	247.950	47.295	547.678	43.416
	D2	96.999	4.917	82.784	5.753
	D3	300.831	358.362	991.967	322.840
	Total:	645.780	410.574	1622.429	372.009
The wall $U_N = 0.30$ W/m^{2}K	D1	133.412	25.448	294.683	23.360
	D2	52.191	2.646	44.543	3.095
	D3	161.865	192.820	533.737	173.707
	Total:	347.468	220.914	872.963	200.162

The greatest environment loads were obtained in case of using S3 source. These are simple consequences of results from table 2. It is obvious, however, that the worse (bigger) coefficient the wall has, the bigger demand for heat becomes, and as a consequence, the environment load due to heating the building.

Let us assume that the thickness of thermo insulation is selected in such a way that the wall after thermo insulation has the heat transfer coefficient $U_N = 0.30$ W/m^{2}K. Therefore, thickness d of thermo insulation should be [10]:

$$d = \lambda \left(\frac{1}{U_N} - \frac{1}{U_o} \right) \quad [\text{m}] \qquad (1)$$

where:

- λ – thermo insulating material thermal conductivity coefficient [W/mK];
- $U_N = 0.30$ – coefficient of heat transfer of a wall with thermo insulation layer [W/m^{2}K];
- $U_o = 1/(R_o+R_{si}+R_{se})$ – coefficient of heat transfer of a wall without thermo insulation [W/m^{2}K].

In table 5 the thicknesses of thermo insulation assigned from the formula (1) were included. Thermopor plaster can have thickness not more than 8 cm, therefore, in case of P2 and P3 walls it cannot be used independently to heat up the building (obtained thicknesses are bigger than 8 cm). It is obvious that for a particular wall the obtained thicknesses are the bigger the worse (greater) coefficient of heat conductivity for a particular insulation material is.

Table 5. Thicknesses of thermo insulation (in m) [own elaboration]

Type of wall	Thermo insulating material				
	I1	I2	I3	I4	I5
P1	0.022	0.027	0.031	0.032	0.042
P2	0.050	0.063	0.072	0.074	0.097
P3	0.074	0.093	0.106	0.108	0.143

In order to determine environmental benefits resulting from thermo insulation of building external walls, it is necessary to take into consideration: environment load connected with the production of thermo insulating material, annual reduction of environment load in the thermal phase of the building usage and the number of years of thermo insulation usage. The environmental benefits K for 1 m^2 of the wall area can be assigned from the formula:

$$K = -I + N\,\frac{E_O - E_N}{p} \quad [\text{Pt/m}^2] \qquad (2)$$

where:

- I – environment load connected with production of thermo insulating material for 1 m^2 of wall area [Pt/m^2] ($I = L_I \cdot d$, L_I – results of LCA analysis for 1 m^3 of thermo insulating material [Pt/m^3] from table 1, d – thicknesses of thermo insulation [m] from table 5);
- N – number of years of thermo insulation usage;
- E_O – results of LCA analysis of one year thermal phase of building usage, for coefficient of heat transfer U_o [Pt/year] (from table 4);
- E_N – results of LCA analysis of one year thermal phase of building usage, for coefficient of heat transfer U_N [Pt/year] (from table 4);
- p – area of building external walls [m^2].

For calculating, the period of thermo insulation usage was taken as $N = 25$ years. In table 6 benefits for wall type P1 were determined (from the formula (2)) depending on heat source and thermo insulating material used. The calculations were carried out separately in each damage category.

For each variant of heat source and thermo insulation material, the environmental benefits were obtained bigger than 0 in each damage category. For a particular heat source, the biggest benefits are obtained with use of ecofibre (I4). Due to heat source, the biggest benefits appear with use of S3 boiler, for which the greatest environment load was obtained with production of 1 kWh of heating energy.

Table 6. Environmental benefits for wall P1 (in Pt/m^2) [own elaboration]

Heat source	Damage category	Thermo insulating material				
		I1	I2	I3	I4	I5
S1	D1	1.285	1.342	1.370	1.404	1.288
	D2	0.532	0.530	0.542	0.548	0.532
	D3	1.463	1.597	1.592	1.708	1.561
	Total:	3.281	3.470	3.505	3.661	3.382
S2	D1	0.156	0.213	0.241	0.275	0.159
	D2	0.014	0.012	0.024	0.030	0.014
	D3	1.787	1.921	1.916	2.032	1.885
	Total:	1.956	2.145	2.180	2.336	2.057
S3	D1	2.972	3.029	3.057	3.091	2.975
	D2	0.452	0.450	0.462	0.468	0.452
	D3	5.353	5.487	5.482	5.598	5.451
	Total:	8.777	8.966	9.001	9.157	8.878
S4	D1	0.134	0.191	0.219	0.253	0.137
	D2	0.018	0.016	0.028	0.034	0.018
	D3	1.587	1.721	1.716	1.832	1.685
	Total:	1.740	1.929	1.964	2.120	1.841

In table 7 the environmental benefits were obtained for P3 wall. The column for I5 was omitted as it is not possible to produce thermo insulation from this material with the thickness allowing to fulfil the conditions of a particular regulation [RMI]. As for P2 wall coefficient of heat transfer has the value between values for P1 and P3, the environmental benefits and ecological payback periods have average values between P1 and P3 as well.

Table 7. Environmental benefits for P3 wall (in Pt/m^2) [own elaboration]

Heat source	Damage category	Thermo insulating material			
		I1	I2	I3	I4
S1	D1	17.673	17.862	17.957	18.075
	D2	7.013	7.005	7.047	7.067
	D3	21.119	21.561	21.544	21.941
	Total:	45.805	46.428	46.548	47.083
S2	D1	3.072	3.261	3.356	3.474
	D2	0.312	0.304	0.346	0.366
	D3	25.306	25.748	25.731	26.128
	Total:	28.689	29.312	29.432	29.967
S3	D1	39.484	39.673	39.768	39.886
	D2	5.978	5.970	6.012	6.032
	D3	71.413	71.855	71.838	72.235
	Total:	116.875	117.498	117.618	118.153
S4	D1	2.789	2.978	3.073	3.191
	D2	0.373	0.365	0.407	0.427
	D3	22.721	23.163	23.146	23.543
	Total:	25.883	26.506	26.626	27.161

For P3 wall we obtain similar conclusions as for P1 wall. However, the values of benefits are several times bigger in each case, because P3 wall has a worse (bigger) coefficient of heat transfer without thermo insulation.

Additionally, the ecological payback period was assigned (in years), that is the smallest time N after which the environmental benefits K (assigned from the formula (2)) are no longer negative (see [11]). The results for P1 and P3 walls are presented in table 8.

Table 8. Ecological payback periods for P1 / P3 walls (in years) [own elaboration]

Heat source	Damage category	Thermo insulating material				
		I1	I2	I3	I4	I5
S1	D1	2 / 1	1 / 1	1 / 1	0 / 0	2 / –
	D2	1 / 1	1 / 1	1 / 1	0 / 0	1 / –
	D3	4 / 1	2 / 1	2 / 1	0 / 0	2 / –
	Total:	3 / 1	2 / 1	2 / 1	0 / 0	2 / –
S2	D1	11 / 3	5 / 2	3 / 1	0 / 0	11 / –
	D2	13 / 4	15 / 4	4 / 1	0 / 0	13 / –
	D3	3 / 1	2 / 1	2 / 1	0 / 0	2 / –
	Total:	4 / 1	2 / 1	2 / 1	0 / 0	3 / –
S3	D1	1 / 1	1 / 1	1 / 1	0 / 0	1 / –
	D2	1 / 1	1 / 1	1 / 1	0 / 0	1 / –
	D3	2 / 1	1 / 1	1 / 1	0 / 0	1 / –
	Total:	1 / 1	1 / 1	1 / 1	0 / 0	1 / –
S4	D1	12 / 3	6 / 2	3 / 1	0 / 0	11 / –
	D2	11 / 3	12 / 4	3 / 1	0 / 0	11 / –
	D3	4 / 1	2 / 1	2 / 1	0 / 0	2 / –
	Total:	5 / 2	2 / 1	2 / 1	0 / 0	4 / –

For ecofibre (I4) the ecological payback periods reached 0, because the production itself of this material causes the reduction of the environment load in each damage category (see table 1). For P1 wall the payback of total environment load appears within 0 – 5 years, while for P3 wall within 0 – 2 years. Considering particular damage categories, the shortest payback periods emerge in category D3 (raw materials), for P1 0 – 4 years and for P3 0 – 1 year. In category D3 itself there was the biggest environment load out of all three categories (see tables 6 and 7) for each combination: heat source and thermo insulating material. The latest payback appears in category D2 (ecosystem quality) for variant P1/S2/I2, after 15 years, but it is still much earlier than the assumed time of thermo insulation usage – 25 years.

Conclusions

Thermo insulation of building external walls causes the reduction of energy demand for heating. It leads to the economic consequences related to the reduction of heating cost. While assessing this type of investments, the environmental aspect is usually omitted. The article examines, with use of LCA technique, what is the impact of the analyzed investment on the environment. It turns out that for the studied variants, which are dependent on the construction material of the wall, the kind of heat source and thermo insulating material, thermo insulation brings substantial environmental benefits. These benefits are the most dependent on the heat source used for a particular wall, whereas to the smaller extent on the type of thermo insulating material. Although the production of thermo insulating materials causes the increase of the environment load (apart from ecofibre), the environment load in the thermal phase of the building usage is reduced in a much greater degree. In case when walls before thermo insulation have the coefficient of heat transfer much different from the required U_N = 0.30 W/m^{2}K, the ecological payback period takes place already after 2 years at the latest. Even for the wall with a good coefficient of heat transfer before thermo insulation U_O = 0.39 W/m^{2}K the payback takes place after 5 years at the latest.

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