Calculation of cost-optimal combination of building materials and technical systems for nZEB single-family house using global cost calculation method

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Abstract. As a rule, during the design stage of a single-family house, only initial costs are taken into account and optimised. Long-term financial calculations are usually not even made. At the same time, total costs to design, build and operate the building show a real difference in expenses while living in this house. In the case of nearly zero energy buildings (nZEBs), this global cost approach becomes especially useful because of the strict requirements of heating and primary energy, as well as the compulsory use of renewable energy sources, requiring more detailed and comprehensive calculations of a cost-optimal set of solutions. In this study, a nZEB single-family house is analysed in detail using a comparative global cost calculation methodology. Different insulation materials and construction types, as well as two types of windows and various heating systems, are combined to obtain the same calculated annual energy consumption. The economic calculations of each combination are carried out for the calculation period of 30 years, taking into account expected energy price increase, discount rate, etc. These calculations show the cost-optimal variants, allowing the prediction of a more advantageous selection of materials and system use in a nZEB in terms of the real operation costs.

1 Introduction

The building and construction sectors are responsible for 36% of global final energy use and 39% of energy-related CO₂ emissions [1]. The EU directive on energy performance of buildings (EPDB) [2] requires member states to set minimum requirements for energy performance of buildings and elements, including new and existing buildings. This directive demands the calculation of the cost-optimal balance between the primary energy and the total cost during the lifetime of a building through the use of a comparative methodology [3]. According to this directive, all the member states have to update and revise the national requirements every five years [4, 5]. The same methodology can also be successfully used for purposes that are more practical, such as, for example, helping to choose the most cost-effective construction option for a building.

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Almost always, only the initial construction costs are taken into account during the design stage of a single-family house. These are also discussed and optimised with the customer with the aim of reducing them. At the same time, not only design and build costs, but also the building's operating and maintenance costs show a real difference in total expenses while living in the house in estimations of the so-called 'cost of ownership' [6, 7]. Practically speaking, the cheapest building rarely results in the lowest operation costs; in fact, it is generally the other way around. In the case of nZEB buildings (mandatory requirements in Latvia from 2021), this global cost approach becomes especially useful because of the strict requirements in terms of heating and primary energy, as well as the compulsory use of renewable energy sources, which requires more detailed and more comprehensive calculations of a cost-optimal set of solutions.

In this study, a newly built nZEB single-family house (Fig. 1) is analysed in detail through using a comparative global cost calculation methodology. Different insulation materials and construction types, as well as two types of windows and various heating systems, are combined to obtain the same calculated annual energy consumption. The economic calculations of each combination are carried out for the lifetime period of 30 years, taking into account expected energy price increase, discount rate, etc. These calculations show the differences in the total cost of ownership, which allows for choosing more advantageous materials and systems during the planning phase, thus eliminating unexpected expenses later.

Fig. 1. Cross-section of an analysed building (left) and a photo after the construction (right).

2 Assumptions and methods

It is assumed that total cost of ownership consists of an initial investment (generally construction costs) and the follow-on costs (e.g. energy, utilities, cleaning, maintenance, replacement costs, etc.). The costing process includes two calculation types – energy and economic – which are described in detail below.

Thermal transmittance (U -value) for building structures, as well as the information related to the ventilation system with heat recovery, provides information about heat losses during the heating season, which is dominant in Latvia due to its climate. With taking into account the climatic data together with the internal and solar heat gains, it is possible to calculate the total heating consumption of a whole building based on the EN ISO 52016-1 standard [8]. The simplified monthly calculation principle is applied for this methodology, while it also includes a calculation of the primary energy and CO₂ emissions according to Latvian legislation [9]. The thickness of the used insulation materials for different constructions is slightly altered to obtain the same U -value, meaning this does not change the annual energy consumption. The planned U -values for the boundary structures are very low (see Table 2), meaning that in the case of masonry walls, a rendered facade cannot be used due to the limitation of the insulation material thickness (maximum 20 cm) – thus only hinged ventilated facades are considered. Parallel to the constructions, the heating systems

with different energy sources and efficiency are also varied, which is easy to do in the case of a new building. General building parameters are presented in Table 1, while a summary of the analysed building constructions and the different heating systems are presented in tables 2 and 3.

The second and largest calculation part consists of financial calculations (macro-economic calculations may be made as well, taking into account CO₂ costs, no taxes, modest price forecast changes, etc.) and a combination of variants (Table 4). These calculations have been made according to the chosen methodology [3], taking into account the variables summarised in Table 5. The differences in cost-optimal energy efficiency packages (combinations of measures) may vary significantly in macro-economic and financial calculations (without any improvements) since macro-economic calculations show more positive values (meaning more cost-effective investments) than with the financial calculation approach.

Several expenses were not included in the calculation, including plumbing, floor finish, inner doors, etc., because they are not directly related to energy efficiency, while inner wall, ceiling and floor base expenses were taken into account, because they are directly related to the building's main structure of masonry (clay/concrete blocks) or wooden frame.

Table 1. General nZEB building parameters.

Floor area	Volume	Outer walls	Ground/ roof	Energies, kWh/m ²				
				Heating	Cooling	Ventilation	Hot water	Lighting
154 m ²	384 m ³	214 m ²	101 m ²	20,9	0,6	2,1	3,6	2,7

Table 2. Summary of analysed building constructions.

Element	U-value (W/m ² /K)	Main construction	Insulation material	Designation
Outer wall	0.10	Wooden frame	Mineral wool, 30 cm	O0mw
		Wooden frame	Loose-fill cellulose, 45 cm	O1cel
		Expanded clay blocks	Hinged ventilated facade, mineral wool, 35 cm	O2mw
			Hinged ventilated facade, EPS, 30 cm	O2eps
		Perforated concrete blocks	Hinged ventilated facade, mineral wool, 34 cm	O3mw
			Hinged ventilated facade, EPS, 28 cm	O3eps
		Aerated concrete blocks	mineral wool, 30 cm	O4mw
EPS, 24 cm	O4eps			
Floor construction	0.13	Slab-on-ground foundation	XPS, 28 cm	F0xps
		Slab-on-ground foundation	mineral wool, 28 cm	F1mw
		Slab-on-ground foundation	EPS, 27 cm	F2eps
		Strip foundation	XPS, 20 cm	F3xps
Roof construction	0.06	Flat roof	glass wool, 65 cm	R0gw
		Flat roof	loose-fill cellulose 65 cm	R1cel
		Flat roof	mineral wool, 60 cm	R2mw
Windows	0.77	Triple glazed, wood frame		W0w
		Triple glazed, PVC frame		W1pvc

Table 3. Summary of analysed heating systems.

Type	Designation	SCoP (for heating only) / efficiency	Primary energy factor [9]	CO ₂ factor (kg/MWh) [9]
Heat pump (borehole-water)	H0hpV	3.9 (5.5)	1.5	109
Heat pump (earth-water)	H1hpH	4.1 (5.8)	1.5	109
Heat pump (air-water)	H2hpA	3.7 (3.9)	1.5	109
Natural gas boiler	H3gas	0.95	1.1	202
Pellet boiler	H4pel	0.9	0.2	0
Electric heaters	H5ele	1	1.5	109

Table 4. Combination of construction and systems analysed (designations see in Tables 2, 3).

Combination (changes are <u>underlined</u>)	Short description	Initial investment (€/m ²)	Global costs (€/m ²)
O0mw.W0w. R0gw.F0xps.H0hpV	Original '0' variant as built (Fig. 1, right)	1 030	1 768
Ocel.W0w. R0gw.F0xps.H0hpV	Changed wall and floor constructions	1 027	1 766
Omw.W0w. R0gw.F3xps.H0hpV	Changed wall and floor constructions	1 345	2 061
O2eps.W0w. R0gw.F3xps.H0hpV	Changed wall and floor constructions	1 314	2 030
O3mw.W0w. R0gw.F3xps.H0hpV	Changed wall and floor constructions	1 349	2 066
O3eps.W0w. R0gw.F3xps.H0hpV	Changed wall and floor constructions	1 306	2 023
O4mw.W0w. R0gw.F3xps.H0hpV	Changed wall and floor constructions	1 342	2 062
O4eps.W0w. R0gw.F3xps.H0hpV	Changed wall and floor constructions	1 311	2 031
O0mw.W1pvc.R0gw.F0xps.H0hpV	Changed windows	998	1 720
O0mw.W0w. R1cel.F0xps.H0hpV	Changed roof construction	1 030	1 772
O0mw.W0w. R2mw.F0xps.H0hpV	Changed roof construction	1 060	1 806
O0mw.W0w. R0gw.F1mw.H0hpV	Changed floor construction	1 034	1 773
O0mw.W0w. R0gw.F2eps.H0hpV	Changed floor construction	1 029	1 767
O0mw.W0w. R0gw.F0xps.H1hpH	Different heating system	1 046	1 856
O0mw.W0w. R0gw.F0xps.H2hpA	Different heating system	1 060	1 932
O0mw.W0w. R0gw.F0xps.H3gas	Different heating system	1 053	1 649
O0mw.W0w. R0gw.F0xps.H4pel	Different heating system	1 042	1 702
O0mw.W0w. R0gw.F0xps.H5ele	Different heating system	976	1 462
O0mw.W0w. R2mw.F1mw.H0hpV	Mineral wool as insulation	1 064	1 811
O2mw.W0w. R2mw.F3xps.H0hpV	Mineral wool as insulation (exc. floor)	1 376	2 099
O3mw.W0w. R2mw.F3xps.H0hpV	Mineral wool as insulation (exc. floor)	1 380	2 104
O4mw.W0w. R2mw.F3xps.H0hpV	Mineral wool as insulation (exc. floor)	1 373	2 100
O0mw.W1pvc.R2mw.F1mw.H0hpV	Mineral wool as + PVC windows	1 033	1 763
O2mw.W1pvc.R2mw.F3xps.H0hpV	Mineral wool as insulation (exc. floor) + PVC windows	1 344	2 051
O3mw.W1pvc.R2mw.F3xps.H0hpV	Mineral wool as insulation (exc. floor) + PVC windows	1 348	2 056
O4mw.W1pvc.R2mw.F3xps.H0hpV	Mineral wool as insulation (exc. floor) + PVC windows	1 341	2 052
O1cel.W0w. R1cel.F0xps.H0hpV	Loose-fill cellulose as insulation	1 030	1 772
O1cel.W1pvc.R1cel.F0xps.H0hpV	Loose-fill cellulose as insulation + PVC windows	996	1 722
O2eps.W0w. R0gw.F3xps.H0hpV	EPS/XPS as insulation for walls, floor	1 314	2 030
O3eps.W0w. R0gw.F3xps.H0hpV	EPS/XPS as insulation for walls, floor	1 306	2 023
O4eps.W0w. R0gw.F3xps.H0hpV	EPS/XPS as insulation for walls, floor	1 311	2 031
O2eps.W1pvc.R0gw.F3xps.H0hpV	EPS/XPS as insulation for walls, floor + PVC windows	1 282	1 982
O3eps.W1pvc.R0gw.F3xps.H0hpV	EPS/XPS as insulation for walls, floor + PVC windows	1 275	1 975
O4eps.W1pvc.R0gw.F3xps.H0hpV	EPS/XPS as insulation for walls, floor + PVC windows	1 279	1 983

Table 5. Parameters used in economic calculations.

Parameter	Value	Estimated lifetime, years
Discount rate, %	5%	
Changes in commodity prices, % annum	1%	
Changes in maintenance and operating costs, % annum	1%	
Changes in energy prices, % annum	1%	
Price of energy - electricity , euro/MWh	€ 150	
Price of energy - natural gas , euro/MWh	€ 41	
Price of energy - wood pellets , euro/MWh	€ 35	
Maintenance cost - windows/doors , % annum	2%	20
Maintenance cost - hinged ventilated facade , % annum	1%	30
Maintenance cost - roof insulation , % annum	2%	30
Maintenance cost - slab insulation , % annum	4%	25
Maintenance cost - heat pump , % annum	7%	15
Maintenance cost - natural gas boiler , % annum	3%	15
Maintenance cost - pellet boiler , % annum	5%	15
Maintenance cost - electric heaters , % annum	3%	30
Maintenance cost - recuperation system , % annum	8%	15
Maintenance cost - wooden frame construction		40
Maintenance cost - masonry construction		50

3 Results

As the heating energy demand (MWh) for all the considered combinations is the same, only initial and global costs (€) are variable and they can be analysed according to different aspects. A summary of the initial and global costs for all the combinations excluding changes in heating system is presented in Table 4 and is visually shown in Fig. 2 (where the combinations are arranged from smallest to highest initial costs). A comparison of both costs over a 30-year period clearly shows that buildings with lower construction costs also have lower global costs, while for cases with variable heating consumption, this correlation would not be so strong. The two combinations with the lowest costs are the original variant with altered PVC windows only and the combination with loose-fill cellulose used as insulation for the walls and roof construction and with PVC windows. The reason for the choice of more expensive wooden windows is generally linked to psychological and ecological aspects. The original variant is the fifth cheapest, while the difference between it and the third variant is negligible.

A comparison of the sum of initial costs and the calculated heating costs for a 30-year period for the five most popular heating systems (Table 3) is shown in Fig. 3. Here, it is clear that the most cost-effective system is the geothermal heat pump with a borehole heat exchanger. However, it is important to note that the calculations of thermal energy produced by heat pumps is highly dependent on their assumed seasonal coefficient of performance, which varies for different soil types and groundwater levels. The very low initial costs of electric heaters are not optimal in the long run due to high electricity prices, but this type of heating is economically justifiable in the shorter run.

Fig. 2. Comparison of initial and global costs (see Table 5).

Fig. 3. Total initial and energy costs for heating system in 30 years.

4 Conclusions

In the case of a nearly zero energy building, due to its low energy consumption and higher building costs, long-term economic calculations using the global cost methodology are very useful to justifying the choice of materials, construction types and systems based on the real, long-term operation costs.

The most critical assumptions used in the calculation methodology, which can have a significant impact on the reliability of the results, are the forecast of future energy prices and operating and maintaining costs as well as the highly fluctuating construction costs. The choice of heating systems for the building is limited by the availability of resources and

the possible restrictions from the local municipalities (e.g. whether it is possible to join the district heating systems; there may be ban on making an independent system).

In cases with the same heating energy consumption, initially cheaper buildings equate to lower global costs during the analysed 30-year operating period, while here, other non energy-related factors influence the customer's choice of materials and construction. In addition to the analysed ventilated facades, there is another very popular type of wall – rendered facades. However, due to their limitation in terms of thermal insulation material thickness (and, therefore, lower U -values) this construction type is not included in the reviewed solutions. In future studies, rendered facades should be included for more objective and comprehensive market studies.

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