Calculation of initial and long-term heating costs for a nearly zero energy single-family building over 30 years

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Abstract. In practice, during the design stage of a building, only the initial costs are taken into account. These costs are also discussed with the customer and optimised with the aim of reducing them. It is the global costs over a longer period that show the real difference in the total expenses of living in a particular house, however. In this study, one newly built, nearly zero energy single-family building was studied in detail using a comparative global cost calculation methodology. The most popular insulation materials, construction types, types of windows, and types of floor construction in Latvia are included in the calculation of the costs. The results demonstrate that initially cheaper building means lower global costs during the analysed 30-year operating period due to initial costs are significantly higher than all other costs including energy costs, meaning that changes in construction type and building materials affect the initial cost more than the long-term energy costs. In parallel, different modern heating systems (including heat pumps) were included in the analysis to calculate and compare heating expenses. The results show that almost all the heating systems have the same energy costs regardless of fuel type for the 30-year period, however, the initial costs of these systems vary due to the different used technologies. Therefore, only the sum of the initial and long-term energy costs provides objective information about heating systems that are optimal in the long-term.

1. Introduction

The EU directive on the energy performance of buildings (EPDB) [1] defines the minimum requirements for the energy performance of buildings and their elements and requires that all new buildings must be nearly zero energy buildings (nZEBs) as of 31 December 2020. The low amount of energy that nZEBs require should come mostly from renewable energy sources. 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 [2, 3]. The same methodology can also be used for practical purposes, such as choosing the initial building construction or analysing the heating systems over a longer period.

Normally, only the initial construction costs are taken into account during the design stage of a single-family house and these are usually reduced after consultation with the customer. At the same time, the building’s operating and maintenance costs lead to a real difference in the total costs during a long operation period (so-called ‘cost of ownership’). In the case of nZEBs, this global cost approach becomes especially useful because of the strict requirements in terms of heating and primary energy and the compulsory use of renewable energy sources, which requires more detailed and more comprehensive calculations of a cost-optimal set of solutions.
In this paper, a newly built nZEB single-family house (Fig. 1) with a heated floor area of 154 m² is analysed in detail using this global cost calculation methodology. The most popular types of insulation materials in Latvia (loose cellulose wool, mineral wool, EPS/XPS) combined with two external wall types (wooden frame construction, masonry construction), two floor types (slab-on-ground, strip foundation), and windows with wooden and PVC frames, as well as various heating systems are included. The economic calculations of each combination are carried out for a period of 30 years, taking into account the expected energy price increase, discount rate, etc. These calculations show the differences in the total costs and the influence of separate investment (initial, energy, replacement, maintenance, etc.) parts in total balance.

Comparing the initial and long-term energy costs for different heating systems allows the optimal system to be chosen during the planning phase, thus eliminating unexpected expenses later on.

As the cold season lasts for a long time in Latvia (around seven months with an average temperature between 0 and 2°C), the highest calculated annual energy consumption in the analysed building is for space heating: 21 kWh/m². Energy consumption for other purposes is significantly lower (1 kWh/m² for cooling, 4 kWh/m² for domestic hot water, 2 kWh/m² for mechanical ventilation).

Figure 1. A photo (left) and a cross-section (right) of an analysed nZEB.

2. Methods
The total heating consumption of a whole building is calculated in accordance with Latvian legislation, which is based on the ISO 52016-1 standard [4]. The simplified monthly calculation principle with Latvia’s climate data is applied for this methodology, including calculation of the primary energy and CO₂ emissions. The main target of this research is to compare different popular building materials and construction types with the purpose of analysing global and initial costs and to investigate the long-term usage of typical modern heating systems in terms of total costs based on existing building (Figure 1).

Two types of wall constructions (a timber frame filled with insulating material and solid masonry with an external insulation layer) are included in the calculations combined with loose cellulose wool, mineral wool, and EPS insulation materials. Slab-on-ground and strip foundation types are used for the floor construction. A flat roof construction with timber firrings and different insulation materials is viewed. Triple-glazed windows are chosen with either PVC or a more expensive wooden frame. The area of outer walls is 215 m², basement/roof area is 101 m² and the windows area is 46 m². Basic information about the main used materials is given in Table 1. Building is equipped with modern recuperative ventilation system with efficiency 90%

The combinations of all the materials and construction types used are summarised in Table 2. Combination #1 corresponds to the existing building. The analysed heating systems varied according to energy source and efficiency and included natural gas and wood pellet boilers, four types of heat pumps, and electric heaters.
The next calculation step consisted of financial calculations according to the methodology [2] and defined the total cost of ownership, which consisted of an initial investment (construction costs) and the follow-on costs (energy, maintenance, replacement costs, etc.). The residual value was also taken into account to compare variations with different lifetimes. Initial energy prices corresponding to 2019 in Latvia with a 1% annual increase were assumed as follows: 150 €/MWh for electricity, 41 €/MWh for natural gas, and 35 €/MWh for wood pellets. Other parameters used for the calculation are summarised in Table 3. The most difficult to predict (even for a couple of years) were future energy prices and maintenance costs.

| Table 1. Basic parameters of used materials. |
|---------------------------------------------|
| Construction | Material          | Thermal conductivity $\lambda$ (W/m/K) | Thickness, cm |
|---------------|-------------------|----------------------------------------|---------------|
| Wooden frame  | 0.2               | 5*+20*                                 |
| Expanded clay | 0.245             | 30                                     |
| Perforated ceramic | 0.175          | 25                                     |
| Aerated concrete | 0.11            | 30                                     |
| Mineral wool  | 0.35              | 34/24                                  |
| Cellulose wool | 0.042             | 24                                     |
| EPS           | 0.038             | 10/15                                  |
| Concrete      | 2.0               | 15                                     |
| XPS           | 0.038             | 15                                     |
| EPS           | 0.037             | 25                                     |
| Plasterboard  | 0.25              | 1                                      |
| Mineral wool  | 0.043             | 65/53                                  |
| Cellulose wool | 0.042             | 35                                     |
| EPS           | 0.039             | 30                                     |

| Table 2. Summary of analysed combinations for the nZEB. |
|---------------------------------------------------------|
| Floor | Walls | Roof |
|-------|-------|------|
| #     | Type          | Insulation | Base       | Insulation material | Insulation, cm | Insulation material | Insulation, cm | Window frame |
| 1     | Slab-on-ground XPS Wooden frame | Mineral wool | 34 | Mineral wool | 65 | Wood |
| 2     | Slab-on-ground EPS Wooden frame | Mineral wool | 24 | Mineral wool | 35 | Wood |
| 3     | Slab-on-ground EPS Wooden frame | Cellulose wool | 24 | Mineral wool | 35 | Wood |
| 4     | Slab-on-ground XPS Wooden frame | Cellulose wool | 24 | Cellulose wool | 35 | Wood |
| 5     | Strip footings EPS Expanded clay | Mineral wool | 15 | Mineral wool | 35 | Wood |
| 6     | Strip footings EPS Perforated ceramic | Mineral wool | 15 | Mineral wool | 35 | Wood |
| 7     | Strip footings EPS Aerated concrete | Mineral wool | 10 | Mineral wool | 35 | Wood |
| 8     | Strip footings EPS Aerated concrete | Mineral wool | 15 | Mineral wool | 35 | Wood |
| 9     | Strip footings EPS Aerated concrete | EPS | 10 | Mineral wool | 35 | Wood |
| 10    | Strip footings EPS Aerated concrete | EPS | 15 | Mineral wool | 35 | Wood |
| 11    | Strip footings EPS Aerated concrete | EPS | 10 | EPS | 30 | Wood |
| 12    | Strip footings EPS Aerated concrete | EPS | 15 | EPS | 30 | Wood |
| 13    | Slab-on-ground XPS Wooden frame | Mineral wool | 34 | Mineral wool | 65 | PVC |
| 14    | Slab-on-ground EPS Wooden frame | Mineral wool | 24 | Mineral wool | 35 | PVC |
| 15    | Slab-on-ground EPS Wooden frame | Cellulose wool | 24 | Mineral wool | 35 | PVC |
| 16    | Slab-on-ground XPS Wooden frame | Cellulose wool | 24 | Cellulose wool | 35 | PVC |
| 17    | Strip footings EPS Expanded clay | Mineral wool | 15 | Mineral wool | 35 | PVC |
| 18    | Strip footings EPS Perforated ceramic | Mineral wool | 15 | Mineral wool | 35 | PVC |
| 19    | Strip footings EPS Aerated concrete | Mineral wool | 10 | Mineral wool | 35 | PVC |
| 20    | Strip footings EPS Aerated concrete | Mineral wool | 15 | Mineral wool | 35 | PVC |
| 21    | Strip footings EPS Aerated concrete | EPS | 10 | Mineral wool | 35 | PVC |
| 22    | Strip footings EPS Aerated concrete | EPS | 15 | Mineral wool | 35 | PVC |
| 23    | Strip footings EPS Aerated concrete | EPS | 10 | EPS | 30 | PVC |
| 24    | Strip footings EPS Aerated concrete | EPS | 15 | EPS | 30 | PVC |
Table 3. Main parameters used in the economic calculations.

| Parameter                  | Value | Estimated lifetime, years |
|----------------------------|-------|---------------------------|
| Discount rate, %           | 5%    |                          |
| 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                        |

3. Results

3.1. Calculation of global and initial costs

The changing the constructions and insulation materials with different thicknesses affects not only the construction costs, but also the U-value (see Table 4) and, therefore, total building’s heating energy need, which is calculated for each combination. For the windows the weighted average U-value is used. Results of the calculated annual heating consumption, as well as all other costs from global cost calculation approach for all the combinations is presented in Table 5. The most important are global and initial costs, as well as energy (mainly heating) costs.

By analysing the obtained results, it can be concluded that the key component in the global cost is the initial costs (including design, purchase of building elements and systems, installation and commissioning costs) the resulting that the lowest construction costs also means the smallest global costs. This can be explained by the fact, that the initial costs are higher than all other costs (Figure 2), leading to significantly less impact of other components. This finding means that significant changes in calculated heating energy consumption (from 21 up to 38 kWh/m²) due to different construction types and insulation materials does not affect the global costs as much as they might seem to initially. It is important to note that this statement applies only to the 30-year calculation period and to low energy consumption buildings and that for longer time periods and buildings with higher energy consumption the impact of heating costs will increase (assuming that energy prices do not decrease). Figure 3 shows a characteristic distribution of the construction costs for the analysed building (in the case of combination #1).

Comparative analysis of the economic calculation results (Table 5) with a view to find the optimal combination for a single-family nZEB shows that there are two options with the lowest initial (and therefore global) costs: #14 and #15. Both consist of a slab-on-ground foundation with 15 cm EPS insulation, a flat roof construction with 35 cm mineral wool insulation, wooden frame outer walls, and windows with PVC frames. The only difference between these combinations is the insulation material in the walls: mineral wool (#14) or loose-fill cellulose (#15), resulting in an ~3% difference in initial and global costs.

Table 4. U-values (W/m²K) for analysed constructions (see Table 2).

| Combination | Floor | Walls | Roof | Windows* |
|-------------|-------|-------|------|----------|
| 1 (13)      | 0.12  | 0.10  | 0.06 | 0.77 with wooden frame |
| 2 (14)      | 0.19  | 0.15  | 0.12 |          |
| 3 (15)      | 0.19  | 0.15  | 0.12 |          |
| 4 (16)      | 0.12  | 0.15  | 0.08 |          |
| 5 (17)      | 0.18  | 0.19  | 0.12 |          |
| 6 (18)      | 0.18  | 0.18  | 0.12 |          |
| 7 (19)      | 0.18  | 0.18  | 0.12 | 0.80 with PVC frame |
| 8 (20)      | 0.18  | 0.15  | 0.12 |          |
| 9 (21)      | 0.18  | 0.18  | 0.12 |          |
| 10 (22)     | 0.18  | 0.15  | 0.12 |          |
| 11 (23)     | 0.18  | 0.18  | 0.12 |          |
| 12 (24)     | 0.18  | 0.15  | 0.12 |          |

Figure 3
Table 5. Summary of main economic calculation for all analysed combinations.

| Combination | Annual heating need, kWh/m² | Global costs, €/m² | Initial costs, k€ | Maintenance costs, k€ | Energy costs, k€ | Residual value, k€ | Replacement costs, k€ |
|-------------|-----------------------------|-------------------|------------------|-----------------------|----------------|-------------------|----------------------|
| 1           | 21.1                        | 907.55            | 121.52           | 5.49                  | 6.01           | 18.61             | 25.07                |
| 2           | 34.3                        | 875.09            | 115.01           | 5.49                  | 8.16           | 17.22             | 23.06                |
| 3           | 34.3                        | 898.32            | 118.58           | 5.49                  | 8.16           | 17.22             | 23.06                |
| 4           | 28.0                        | 909.30            | 120.05           | 5.49                  | 7.12           | 17.42             | 24.52                |
| 5           | 35.7                        | 1,032.73          | 144.76           | 6.94                  | 8.26           | 44.43             | 43.21                |
| 6           | 34.5                        | 1,026.71          | 143.81           | 6.94                  | 8.05           | 44.21             | 43.21                |
| 7           | 34.5                        | 1,042.55          | 145.57           | 6.94                  | 8.05           | 43.36             | 43.04                |
| 8           | 30.7                        | 1,039.26          | 145.66           | 6.94                  | 7.44           | 43.41             | 43.10                |
| 9           | 34.5                        | 1,027.25          | 143.69           | 6.94                  | 8.05           | 42.33             | 41.54                |
| 10          | 30.7                        | 1,032.53          | 144.83           | 6.94                  | 7.44           | 42.96             | 42.45                |
| 11          | 34.5                        | 1,026.15          | 144.11           | 6.94                  | 8.05           | 41.01             | 39.62                |
| 12          | 30.7                        | 1,031.42          | 145.25           | 6.94                  | 7.44           | 41.63             | 40.53                |
| 13          | 22.8                        | 859.19            | 116.66           | 5.49                  | 6.16           | 16.99             | 20.72                |
| 14          | 36.3                        | 827.17            | 110.15           | 5.49                  | 8.38           | 15.60             | 18.71                |
| 15          | 36.3                        | 850.40            | 113.72           | 5.49                  | 8.38           | 15.60             | 18.71                |
| 16          | 29.9                        | 861.20            | 115.19           | 5.49                  | 7.32           | 15.80             | 20.17                |
| 17          | 37.9                        | 985.13            | 139.90           | 6.94                  | 8.54           | 42.82             | 38.86                |
| 18          | 36.7                        | 979.07            | 138.95           | 6.94                  | 8.32           | 42.59             | 38.86                |
| 19          | 36.7                        | 994.91            | 140.71           | 6.94                  | 8.32           | 41.74             | 38.68                |
| 20          | 32.9                        | 991.52            | 140.80           | 6.94                  | 7.69           | 41.79             | 38.75                |
| 21          | 36.7                        | 979.62            | 138.83           | 6.94                  | 8.32           | 40.71             | 37.19                |
| 22          | 32.9                        | 984.79            | 139.97           | 6.94                  | 7.69           | 41.34             | 38.10                |
| 23          | 36.7                        | 978.51            | 139.25           | 6.94                  | 8.32           | 39.39             | 35.27                |
| 24          | 32.9                        | 983.68            | 140.39           | 6.94                  | 7.69           | 40.01             | 36.18                |

Figure 2. Composition of the global costs for the analysed combinations (see Tables 2 and 5).
3.2. Calculation of heating costs

The calculation methodology [2] is also very useful for the calculation of heating costs according to the type of heating system and the installation costs. To exclude the influence of any other parameters, the heating systems were varied for the existing building (combination #1) with a calculated annual heating need of 3.2 MWh. The seven most popular and modern heating systems (Table 6) were chosen for the comparative analysis. One half of the analysed heating systems consisted of four heat pumps with two different energy sources: ground (with vertical/borehole or horizontal collectors) or air, and two heat transfer mediums: water and air. Another two heating systems were classical boilers (natural gas and wood pellet) with a required chimney installation and the last one was simple electric heaters connected directly to the power outlet.

| Type                                      | Designation | Seasonal efficiency (-) | Initial costs, k€ | Heating costs over 30 years, € |
|-------------------------------------------|-------------|-------------------------|-------------------|-------------------------------|
| Heat pump (borehole/vertical-water)*      | HP-V/W      | 3.7                     | 11.5              | 3,118                         |
| Heat pump (earth/horizontal-water)*       | HP-H/W      | 4.1                     | 9.5               | 2,814                         |
| Heat pump (air-water)                     | HP-A/W      | 3.5                     | 10.7              | 3,296                         |
| Heat pump (air-air)                       | HP-A/A      | 4.1                     | 7.7               | 2,814                         |
| Natural gas boiler                        | GAS         | 0.97                    | 8.1               | 3,250                         |
| Pellet boiler                             | PEL         | 0.9                     | 10.0              | 2,991                         |
| Electric heaters                          | ELE         | 1                       | 1.9               | 11,536                        |

* including ground heat exchanger

As the heat pumps produce more thermal energy than the consumed electricity, they are typically characterised by their seasonal efficiency (or seasonal coefficient of performance: SCOP), which describes the average ratio between these energies during a heating season. The difference between these energies comes from the renewable source (ground or air) produced onsite, which is a mandatory requirement for nZEBs. The use of boilers or electric heaters does not satisfy this requirement; therefore, additional renewable energy sources are needed to meet these requirements (e.g. solar energy). It is important to emphasise that the heat pumps included in this research were selected from the top lines of the best manufacturers and have excellent efficiency. In the case of the air-air heat pump, a multi-split system with one outdoor unit and five indoor units was used.

The comparison of the initial (installation) costs and the costs of providing heating energy over 30 years for different heating systems (Figure 4) shows that five heating systems were very close in terms of energy cost regardless of fuel type. The corresponding initial costs varied, however, due to the use of different technologies with specific nuances (borehole drilling, chimney construction, etc.). The electric heaters were significantly different and had low initial costs but high long-term energy costs.

A combination of both initial and long-term energy costs provides objective information about the running costs of different heating systems over a longer period. Analysis of this combination for heating systems (Figure 5) shows that the most cost-effective systems for the calculation period of 30 years were
those with lower initial costs (except electrical heaters), i.e. the air-air heat pump and the natural gas heating system. The main reason for this is the very small heating energy consumption of nZEBs, which means that even for a period of 30 years, the energy costs are smaller than the initial costs of the heating systems.

It is important to note that the calculations of the thermal energy produced by the heat pumps are highly dependent on their SCOP, which varies for different soil types, groundwater levels, and outdoor temperatures [5, 6]. A very important factor influencing the heat pump’s SCOP is water temperature in the indoor coil as a lower temperature means a smaller temperature difference, which is the most important factor for heat exchange efficiency [7]. As the underfloor heating is designed for heat pumps with water inside coil, the designed SCOP is relatively high; for the radiator heating system efficiency and SCOP will be significantly lower.

The very low initial costs of electric heaters are not optimal in the long run due to high electricity prices, however, this type of heating is economically justifiable in the short term. The choice of initially expensive heating systems is not justifiable from an economic point of view and there should be other reasons, e.g. free summer cooling (use of only the heat exchanger and brine pump) in the case of ground source heat pumps.

**Figure 4.** Initial and long-term heating costs for different heating systems (see Table 6).

**Figure 5.** Total running costs over 30 years for different heating systems (see Table 6).
Conclusions
Due to the low energy consumption and relatively high building costs of nZEBs, long-term economic calculations using the global cost methodology are very useful when it comes to choosing materials, construction type, and systems based on long-term operation costs. The most critical assumption used in the calculation methodology that plays a key role in the reliability of the calculated results is the forecast of future energy prices and hard-to-predict maintenance costs.
Long-term calculations show that because constructions costs are significantly higher than all other costs, different construction types and insulation materials affect the initial costs more than the long-term energy costs. It follows that initially cheaper buildings mean lower global costs during the analysed 30-year operating period. At this point, it should be noted that this statement applies only to this time period and to low energy consumption buildings. For longer periods and buildings with higher energy consumption the impact of heating costs will increase (assuming that energy prices do not decrease).
Economic analysis of widely used and modern heating systems (excluding electric heaters) showed that their long-term energy costs were very similar regardless of fuel type, but that their corresponding initial costs varied due to the different costs of the technologies used. The initial costs of electric heaters are very low, but they have high long-term energy costs. An objective indicator of the choice of heating systems is the sum of initial and energy costs, providing information about total costs in the long term.
The most cost-effective systems for the selected building were the air-air heat pump with multiple indoor units or the natural gas heating system. The reason for this is the very small heating energy consumption of the building, which means that even for a period of 30 years the energy costs for such systems are several times smaller than the installation costs. The use of electric heaters is economically justifiable for a shorter period or in case when price difference between electricity and other fuels will increase.

Acknowledgments
This work was supported by the European Regional Development Fund project, “Development, optimization and sustainability evaluation of smart solutions for nearly zero energy buildings in real climate conditions” [1.1.1.1/16/A/192].

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