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# Cost optimal and nearly zero energy performance requirements for buildings in Estonia

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**Abstract.** Estonian cost optimal and nearly zero energy building (nZEB) energy performance levels were determined for the reference detached house, apartment and office building. Cost optimal energy performance levels, i.e. the energy performance leading to the lowest life cycle cost according to defined methodology, are implemented into new Estonian energy performance regulation as minimum requirements for new buildings. The regulation that came into force since 9 January 2013 includes requirements for nZEB buildings, but they are not mandatory. Compared to previous requirements, cost optimal requirements improve energy performance by 20%–40% depending on the building type and energy sources used. The results of the reference office and apartment building are reported. The results of the reference detached house, being previously reported, have been recalculated with new energy carrier factor for electricity, which was one major change in the regulation in addition to new requirements. When the detached house showed global cost curves with well-established cost optimal points, global cost curves were much more flat for the apartment and office building. This indicates that the results are sensitive to input data and relatively small changes in input data can significantly shift the cost optimal points. As uncertainties related to nZEB performance level and cost calculation are generally much higher due to high performance technical solutions not commonly used and costs not well established, it is recommended to repeat nZEB calculations with possibly refined input data before setting mandatory nZEB requirements.

**Key words:** nearly zero energy buildings, nZEB, REHVA nZEB technical definition, cost optimal, global cost, EPBD recast, energy performance.

## 1. INTRODUCTION

Directive 2010/31/EU, EPBD recast [1] stipulates that Member States (MS) shall ensure that minimum energy performance requirements of buildings are set with a view of achieving cost optimal levels for buildings, building units and building elements using a comparative methodology framework established by the Commission, completed with relevant national parameters. Cost optimal performance level means in this context the energy performance in terms of primary energy leading to minimum life cycle cost. After some delays in the preparation, the comparative methodology, called "delegated Regulation supplementing Directive 2010/31/EU", was published on 21.3.2012 [2,3] and MS had to provide cost optimal calculations to evaluate the cost optimality of current minimum requirements until 21 March 2013. The results were to be reported to the Commission and if not on cost optimal level, it is expected that national requirements will be adjusted within reasonable time frame.

Cost optimal policy, launched by EPBD recast, will instruct MS for the first time on how to set minimum requirements and shift those away from only upfront investment cost in order to find optimal solutions for the full life cycle. The regulation [2] provides guidance on cost optimal methodology and reflects accepted principles for the cost calculations to be done with relevant national parameters. In addition to cost optimal policy, EPBD recast established the political target of nearly zero energy buildings for all new buildings by 1 January 2021 according to Article 9. However, not directly linked to the cost optimality assessment of the minimum requirements, the cost optimality analysis needed to include best available technical solutions and therefore enable the assessment of nZEB performance levels and cost implications with very little extra effort. It is expected that cost optimal energy performance levels by 2013 will tighten requirements in most of MS and therefore the cost optimal energy performance can be seen as a first step towards the nZEB target laid down in the EPBD recast.

To be able to perform energy calculations for high performance buildings with on-site renewable energy production that has to be included in the assessment according to cost optimal regulation, relevant system boundary definitions and energy calculation framework are needed. There is large variety of ways how technical details of energy calculation methodology are addressed in national regulations as concluded in the ASIEPI project [4]. In the nZEB definitions and calculation methodologies review [5] it is concluded that consistent definition and a commonly agreed energy calculation methodology is needed for nZEB implementation. In the directive 'nearly zero-energy building' means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Based on the principles, given in the directive and regulation, REHVA has developed nZEB technical definition [6] followed by a set of system boundaries for delivered and exported energy and primary energy indicator calculation as required by the directive and regulation. REHVA definition has been revised in 2013 [7] in cooperation with European standardization organization CEN especially with complementary specification for nearby renewable energy production and renewable energy contribution calculation principles, but without changes in general energy calculation principles. CEN is working with 2nd generation EPBD standards in order to include system boundaries and calculation principles capable for the calculation of buildings with on-site and nearby renewable energy production. The draft, overarching EPBD standard prEN 15603:2013, is currently available [8] and will replace existing standard. Energy calculations conducted in this study follow the system boundary definitions of [6,7].

In this study, the results of Estonian cost optimal calculations, conducted as financial calculations, are reported. These results are implemented with some safety margins in new Estonian energy performance minimum requirements that came into force on 9 January 2013 [9]. The results of energy and cost analyses of the Estonian reference office and apartment buildings are reported. These include energy simulation results for various construction concepts, building technical systems and renewable energy production solutions, which are used as input data to conduct economic calculations, resulting in cost optimal energy performance levels for studied building types. The results of the reference detached house are previously reported in [10], but they are recalculated in this study with a new energy carrier factor for electricity, which was changed from 1.5 to 2.0, as one major change in the new regulation [9]. The safety margins, used for regulatory values, and some limitations in energy calculation input data for office and apartment buildings are discussed, both indicating further cost effective energy performance improvement potential in future. The results reported provide a scientific documentation for new cost optimal and nZEB energy performance requirements for new buildings, implemented in the new Estonian regulation [9].

## 2. METHODS

### 2.1. Calculation procedure

Systematic and robust scientific seven step procedure was followed to determine cost optimal and nZEB energy performance levels including the following steps:

1) selection of the reference buildings;
2) definition of construction concepts, based on building envelope optimization for fixed four specific heat loss levels (from business as usual construction to highly insulated building envelope);
3) specification of building technical systems;
4) energy simulations for specified construction concepts;
5) post-processing of the simulation results to calculate delivered, exported and primary energy;
6) economic calculations for construction cost and net present value calculations;
7) sensitivity analyses for interest rate, escalation of energy prices and other parameters.

The procedure is tested and reported in detail in [10], concluding that all these steps can be treated as independent and they did not lead to iterative approach because of the use of stepwise specification for building envelope, done in four steps in this study. To use four insulation levels for the building envelope is a robust description but will limit the number of possible combinations so that all combinations can be calculated. This allowed to conduct cost optimal calculation just by straightforward calculation of steps 2 to 6 for all specified cases (according to steps 2 and 3). The case, obtaining the minimum net present value (NPV), is by the definition the cost optimal, or the closest to cost optimal because of stepwise robust approach used. It is possible that specified cases will not show the minimum of the NPV. In such a situation, additional cases are to be specified to obtain the minimum.

The use of locked stepwise discrete values is justified because of the cost calculations and discrete nature of the building elements or technical system components. As insulation thickness can be added typically by 5 or 10 cm, it is not needed to treat this as a continuous variable, but to calculate with 5 or 10 cm step from typical insulation thickness up to very thick insulation not any more cost efficient. Construction cost calculation, based on the unit material, and labor costs require also the use of fixed building envelope and technical system solutions.

All calculated cases were equipped with mechanical supply and exhaust ventilation with effective heat recovery, and were calculated with almost all possible heating systems with appropriate sizing (all together seven technical systems with sizing/capacity for four construction concepts, described in Chapter 2.4). The same distribution and emission system was used for all cases to simplify cost calculations and to ensure equal comfort level in all cases. Cost optimal primary energy use is determined by the solutions, leading to minimum NPV of 30 years period for residential buildings and 20 years period for non-residential buildings, according to regulation [2].

## 2.2. The reference buildings

Calculations were conducted for the Estonian reference detached house, apartment building and office building. The reference buildings were selected by the architects as typical representative buildings of new construction. The reference detached house is reported in [10]; apartment and office buildings are shown in Figs 1 and 2.

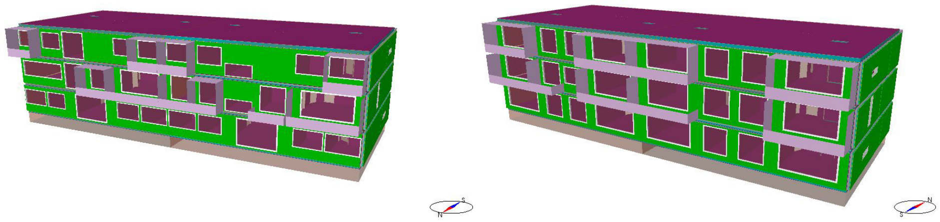

**Fig. 1.** IDA-ICE simulation model of the reference apartment building with heated net floor area of 1796 m$^2$, consisting of 22 apartments and designed for 62 persons.

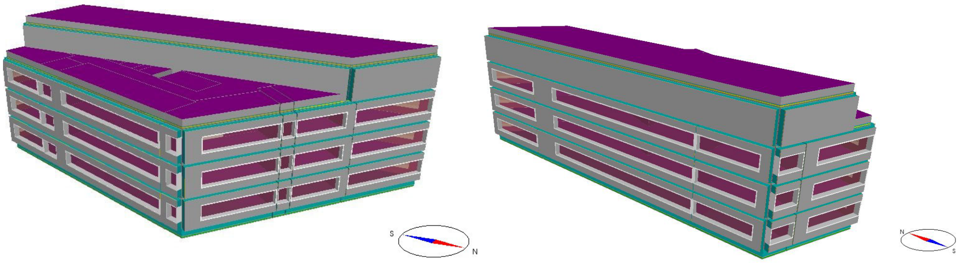

**Fig. 2.** IDA-ICE simulation model of the reference four storey office building with modelled heated net floor area of 2750 m$^2$.

### 2.3. Construction concepts

Energy simulations were conducted for four construction concepts, representing building envelopes from business as usual construction to highly insulated building envelope (Tables 1 and 2). Four construction concepts were enough to change insulation thickness mainly with 5 cm step and with 10 cm step for thicker insulations. These construction concepts were described by the specific heat loss coefficient that includes transmission and infiltration losses through the building envelope and is calculated per heated net floor area as

$$\frac{H}{A_{\mathrm{floor}}} = \frac{\Sigma U_i A_i + \Sigma \Psi_j l_j + \Sigma \chi_p n_p + \rho_a c_a \dot{V}_i}{A_{\mathrm{floor}}}, \tag{1}$$

where:

| | |
|---|---|
| $H$ | heat loss coefficient, W/K; |
| $A_{\mathrm{floor}}$ | heated net floor area, m$^2$; |
| $U_i$ | thermal transmittance of envelope part $j$, W/m$^2$ K; |
| $A_i$ | area of envelope part $i$, m$^2$; |
| $\Psi_j$ | thermal conductance of linear thermal bridge $j$, W/m K; |
| $l_j$ | length of linear thermal bridge $j$, m; |
| $\chi_p$ | thermal conductance of point thermal bridge $p$, W/K; |
| $n_p$ | number of point thermal bridge $p$; |
| $\rho_a$ | density of air, kg/m$^3$; |
| $c_a$ | specific heat capacity of air, J/kg K; |
| $\dot{V}_i$ | infiltration rate, m$^3$/s. |

**Table 1.** Construction concepts for the reference apartment building of 1796 m$^2$. Construction concepts are marked according to specific heat loss coefficient (AB 0.23 means the apartment building with specific heat loss of 0.23 W/K m$^2$)

| | AB 0.23<br>“Nearly zero” | AB 0.32<br>“Low” | AB 0.43 | AB 0.52<br>“BAU“ |
|---|---|---|---|---|
| Specific heat loss coefficient $H/A$, W/K m$^2$ | 0.231 | 0.315 | 0.431 | 0.521 |
| External wall, 591 m$^2$ | 20 cm LWA block + 35 cm EPS insulation | 20 cm LWA block + 25 cm EPS insulation | 20 cm LWA block + 20 cm EPS insulation | 20 cm LWA block + 15 cm EPS insulation |
| $U$, W/m$^2$ K | 0.1 | 0.14 | 0.17 | 0.23 |
| Roof, 449 m$^2$ | 80 cm mineral wool + concrete slab | 50 cm mineral wool + concrete slab | 32 cm mineral wool + concrete slab | 25 cm mineral wool + concrete slab |
| $U$, W/m$^2$ K | 0.06 | 0.09 | 0.14 | 0.18 |
| Floor, 449 m$^2$ | Slab on ground + 70 cm EPS insulation | Slab on ground + 45 cm EPS insulation | Slab on ground + 25 cm EPS insulation | Slab on ground + 18 cm EPS insulation |
| $U$, W/m$^2$ K | 0.06 | 0.09 | 0.14 | 0.18 |
| $q_{50}$, m$^3$/h m$^2$ | 0.6 | 1.0 | 2.0 | 3.0 |
| Windows, 433 m$^2$ glazing/frame/ total | 4 mm-16 mmAr-SN4 mm-16 mmAr-SN4 mm<br>Insulated frame | 4 mm-16 mmAr-4 mm-16 mmAr-SN4 mm<br>Insulated frame | 4 mm-16 mm-4 mm-16 mmAr-SN4mm | 4 mm-16 mmAr-SN4 mm<br>Common frame |
| $U$, W/m$^2$ K | 0.6/0.7/0.7 | 0.8/0.8/0.8 | 1.0/1.3/1.1 | 1.1/1.4/1.2 |
| Solar factor, g | 0.46 | 0.5 | 0.55 | 0.63 |
| Ventilation, m$^3$/s | 1.11 | 1.11 | 1.11 | 1.11 |
| SFP*, kW/m$^3$/s | 1.5 | 1.7 | 2.0 | 2.0 |
| AHU** HR***, % | 85 | 80 | 80 | 70 |
| Heating capacity, kW ($t_e$ –21 °C) | 46 | 52 | 59 | 65 |
| Cooling capacity, kW | 48 | 50 | 51 | 70 |
| Energy need kWh/m$^2$ a | | | | |
| Space heating | 7.1 | 13.0 | 21.9 | 28.4 |
| Supply air heating | 4.7 | 6.6 | 6.9 | 7.0 |
| Domestic hot water | 35.6 | 35.6 | 35.6 | 35.6 |
| Cooling | 11.3 | 9.9 | 8.6 | 14.5 |
| Fans and pumps | 8.9 | 9.9 | 11.6 | 11.6 |
| Lighting | 7.0 | 7.0 | 7.0 | 7.0 |
| Appliances | 22.3 | 22.3 | 22.3 | 22.3 |
| Total energy need | 96.9 | 104.3 | 113.9 | 126.4 |

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* SFP – specific fan power; ; ** AHU – air handling unit; *** HR – heat recovery efficiences.

**Table 2.** Construction concepts for the reference office building of 2750 m$^2$. The building envelope components with the same properties as shown in Table 1 were used. Surface areas for external walls, roof, floor and windows were 1098, 621, 606 and 715 m$^2$, respectively

| | OB 0.25 "Nearly zero" | OB 0.33 "Low" | OB 0.45 | OB 0.55 "BAU" |
|---|---|---|---|---|
| Specific heat loss coefficient $H/A$, W/K m$^2$ | 0.245 | 0.334 | 0.454 | 0.548 |
| Ventilation, m$^3$/s | 4.6 | 4.6 | 4.6 | 4.6 |
| SFP, kW/m$^3$/s | 1.5 | 1.7 | 2.0 | 2.0 |
| AHU HR, % | 80 | 75 | 75 | 75 |
| Heating capacity, kW ($t_e$ –21 °C) | 151 | 160 | 172 | 181 |
| Cooling capacity, kW | 155 | 156 | 160 | 193 |
| Energy need kWh/m$^2$ a | | | | |
| Space heating | 5.8 | 11.4 | 21.9 | 29.0 |
| Supply air heating | 2.8 | 4.1 | 6.2 | 6.4 |
| Domestic hot water | 7.4 | 7.4 | 7.4 | 7.4 |
| Cooling | 32.9 | 30.9 | 28.9 | 37.8 |
| Fans and pumps | 7.3 | 7.9 | 10.9 | 10.9 |
| Lighting | 18.9 | 18.9 | 18.9 | 18.9 |
| Appliances | 23.7 | 23.7 | 23.7 | 23.7 |
| Total energy need | 98.8 | 104.3 | 117.9 | 134.1 |

Infiltration rate was calculated according to Estonian energy calculation methodology [11] using factors determined in [12]:

$$\dot{V}_i = \frac{q_{50} A_{\mathrm{env}}}{3600x}, \tag{2}$$

where:

$q_{50}$ air leakage rate of building envelope, m$^3$/(h m$^2$);
$A_{\mathrm{env}}$ area of building envelope (including the bottom floor), m$^2$;
$x$ factor, taking into account the height of the building: 35 for single-storey buildings, 24 for 2-storey buildings, 20 for buildings with 3–4-storeys and 15 for 5 or more storeys.

The construction concept with the lowest $H/A$ value represents the best available technology of highly insulated building envelope which may be associated with nearly zero energy buildings. In the construction concepts, the building envelope was optimized for each specific heat loss value, so that the most cost effective combination of insulation levels for windows, external walls, slab on ground and roof were used to achieve the given specific heat loss value. With this optimization, the insulation levels resulting in the lowest construction cost for each specific heat loss value were selected.

## 2.4. Energy simulations, delivered and primary energy calculations

Energy simulations were conducted with dynamic simulation tool IDA-ICE [13] for specified four construction concepts. This software is carefully validated [14] and with advanced features [15]. Simulated energy needs are shown in Tables 1 and 2.

Delivered energy was calculated with post-processing from simulated energy needs. Energy needs were divided with relevant system efficiencies. System efficiency values (combined efficiency of the generation, distribution and emission) are shown in Table 3. To calculate the combined efficiency, under floor heating distribution was considered with average distribution and emission efficiency of 0.9 according to Estonian regulation [11]. This distribution and emission efficiency is included in the combined efficiency values in Table 3.

**Table 3.** System efficiencies for delivered energy calculation

| Heat source (under floor heating) | Generation and distribution combined efficiency | |
|---|---|---|
| | Space heating/cooling | Domestic hot water |
| Gas/oil condensing boiler | 0.86 | 0.83 |
| Pellet boiler | 0.77 | 0.77 |
| Air to water heat pump (electricity) | 1.98 | 1.62 |
| Electrical heating | 0.90 | 0.90 |
| Ground source heat pump (electricity) | 3.15 | 2.43 |
| District heating | 0.90 | 0.90 |
| Cooling (electricity) | 3.0 | |

To calculate primary energy, exported energy was deleted from delivered energy. Primary energy (ETA-values in Estonian regulation) were calculated with Estonian primary energy factors which are:

- 1.0 for fossil fuels
- 2.0 for electricity
- 0.9 for district heating
- 0.75 for renewable fuels

## 2.5. Economic calculations

Economic calculations included construction cost calculations and discounted energy cost calculation for 30 years (20 years in the office building). Construction cost was calculated not as total construction costs, but only construction works and components related to energy performance were included in the cost (energy performance related construction cost included in the calculations). Such construction works and components were:

- thermal insulation (with cost implications to other structures)
- windows
- air handling units (without ductwork)
- heat supply solutions (boilers, heat pumps etc.)

In all calculated cases an under floor heating system and a hot water boiler were considered, and these were not included in the energy performance related construction cost. The effect of maintenance, replacement and disposal costs were studied with sensitivity analyses and because of minor differences between calculated cases, these costs were not included in the energy performance related construction cost to keep calculations as transparent as possible. Labour costs, material costs, overheads, the share of project management and design costs, and VAT were included in the energy performance related construction cost.

Global cost (= life cycle cost, the term of EN 15459) and NPV calculation followed EN 15459 [16]. Global energy performance related cost was calculated as a sum of the energy performance related construction cost and discounted energy costs for 30 years (20 years in the office building), including all electrical and heating energy use. Because the basic construction cost was not included, the absolute value of the global energy performance related cost is small. For that reason the global incremental energy performance related cost was calculated. This was calculated relative to the reference building, representing business as usual (BAU) construction with gas boiler heating:

$$C_\mathrm{g} = \frac{C_I + C_\mathrm{a} f_\mathrm{pv}(n)}{A_\mathrm{floor}} - \frac{C_\mathrm{g}^\mathrm{ref}}{A_\mathrm{floor}}, \tag{3}$$

where:

$C_\mathrm{g}$ global incremental energy performance related cost, NPV, €/m$^2$;
$C_I$ energy performance related construction cost included in the calculations, €;
$C_\mathrm{a}$ annual energy cost during starting year, €;
$f_\mathrm{pv}(n)$ present value factor for the calculation period of $n$ years;
$C_\mathrm{g}^\mathrm{ref}$ global energy performance related cost incl. in the calculations of BAU reference building, NPV, €;
$A_\mathrm{floor}$ heated net floor area, m$^2$.

To calculate the present value factor $f_\mathrm{pv}(n)$, real interest rate $R_\mathrm{R}$ depending on the market interest rate $R$ and on the inflation rate $R_\mathrm{i}$ (all in per cents) is to be calculated as [16]

$$R_\mathrm{R} = \frac{R - R_\mathrm{i}}{1 + R_\mathrm{i}/100}. \tag{4}$$

The present value factor $f_\mathrm{pv}(n)$ for the calculation period of $n$ years is calculated as [16]:

$$f_\mathrm{pv}(n) = \frac{1 - \left(1 + (R_\mathrm{R} - e)/100\right)^{-n}}{(R_\mathrm{R} - e)/100} \tag{5}$$

where:

$R_R$ the real interest rate, %;
$e$ escalation of the energy prices, % (inflation reduced from actual price increase);
$n$ the number of years considered, i.e. the length of the calculation period.

Global energy performance related costs were calculated in the basic case with the real interest rate of 3% and escalation of energy prices of 2%, according to the guidance of the cost optimal regulation [2], allowing to conclude that the escalation of main energy carriers has been 2%–3% per year in history. The discounting interest rate ($R_R$-$e$), used in the discounting of energy costs, is therefore the difference between the real interest rate and the escalation of the energy price, i.e. in the basic case 1%. For example, the discounting interest rate of 1.5% may correspond to real interest rate of 3% and escalation of 1.5%, or real interest rate of 2% and escalation of 0.5%. Some calculations were also conducted with escalation of 3%. These escalation rates of 2%–3%, can be seen in Estonian conditions as somewhat conservative values, which were intentionally used, in order not to overestimate energy prices in life cycle calculations in any case.

For energy prices, the Estonian price levels during the preparation of the regulation in 2011 were used as follows:

- Electricity 0.0983 €/kWh + VAT (20%)
- Natural gas 0.0395 €/kWh + VAT (20%) (consumption over 750 m$^3$/year)
- Pellet 0.033 €/kWh + VAT (20%)
- Heating oil 0.0717 €/kWh + VAT (20%)
- District heating 0.0569 €/kWh + VAT (20%) (Tallinn, natural gas boiler)

The only exception was the electricity price used, which was significantly higher compared to 2011 price level. The electricity price was the estimate of the free electricity market price by the ministry, which was used because in 2012 Estonia joined the Nordic Countries' stock exchange Nord Pool Spot which made a remarkable correction in electricity prices, being well in line with the ministry estimate used in this study. Connection fees for electricity and heating were taken into account as follows:

- Electricity 111.85 € + VAT (20%) per 1 A of main fuse
- Gas 2046 € + VAT (20%)
- District heating 2500 € + VAT (20%)

## 3. RESULTS

### 3.1. The reference apartment building

Global incremental energy performance related costs included in the calculations (explained in Chapter 2.5) are shown in Fig. 3 for discounting interest rate of 1% that corresponds to real interest rate of 3% and escalation of 2%. The global incremental cost is therefore presented as relative to the business as usual construction concept AB 0.52 with gas boiler, that is very close to the previous minimum requirement of 150 kWh/m$^2$ a primary energy of 2008 regulation.

The cost optimal performance level was achieved with gas boiler and AB 0.32 construction concept at 145 kWh/m$^2$ a primary energy use. Negative NPV values compared to BAU show that the better construction standard can save some global cost. The global cost curves, shown in Fig. 3, are very flat and all cases except oil and electric heating are within relatively narrow global cost range. The flat curves mean that energy performance investments are just paid back by energy savings.

It is important to notice that the global incremental cost is less than the investment cost, because of reduced cost of energy use. The breakdown of the global cost components is shown in Fig. 4. It can be seen that an additional investment cost from AB 0.32 to DH 0.23 construction concept is 30 242 € for improved thermal insulation and 4072 € for air handling unit. This investment corresponds to 8698 € increase in NPV. The sensitivity to the interest rate is shown in Fig. 5. The 1% lower interest rate will shift the cost optimal to lower primary energy use, however the differences in the global cost are marginal.

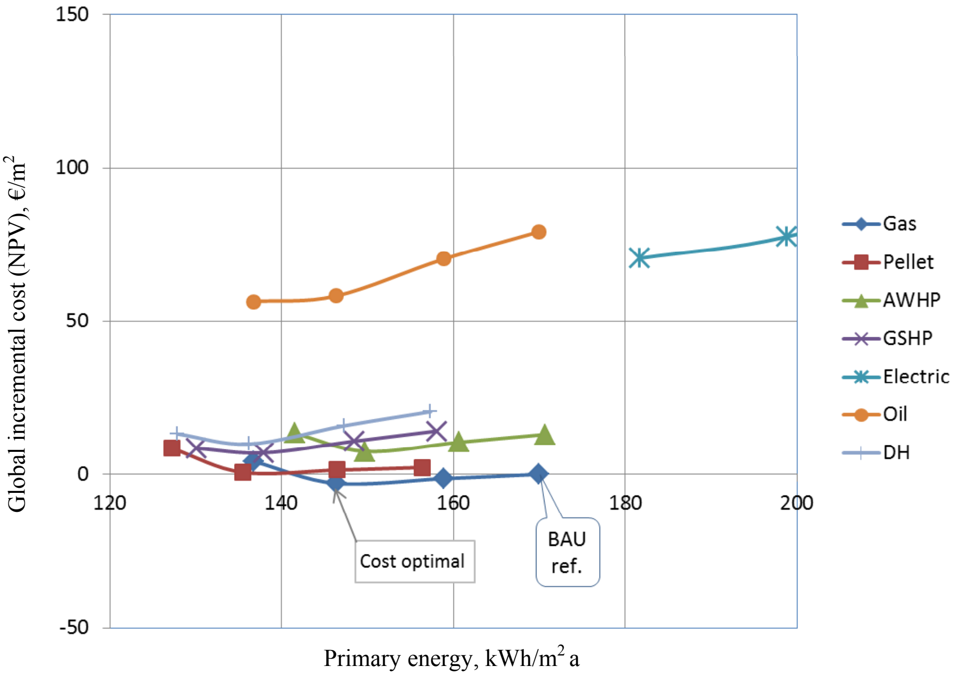

**Fig. 3.** Global energy performance related costs in the reference apartment building, calculated with discounting interest rate of 1% (the real interest rate of 3% and the escalation 2%) and 30 years calculation period; AWHP – air to water heat pump; GSHP – ground source heat pump; DH – district heating. For each heating system, from left to right the cases AB 0.23, 0.32, 0.43 and 0.52 are shown.

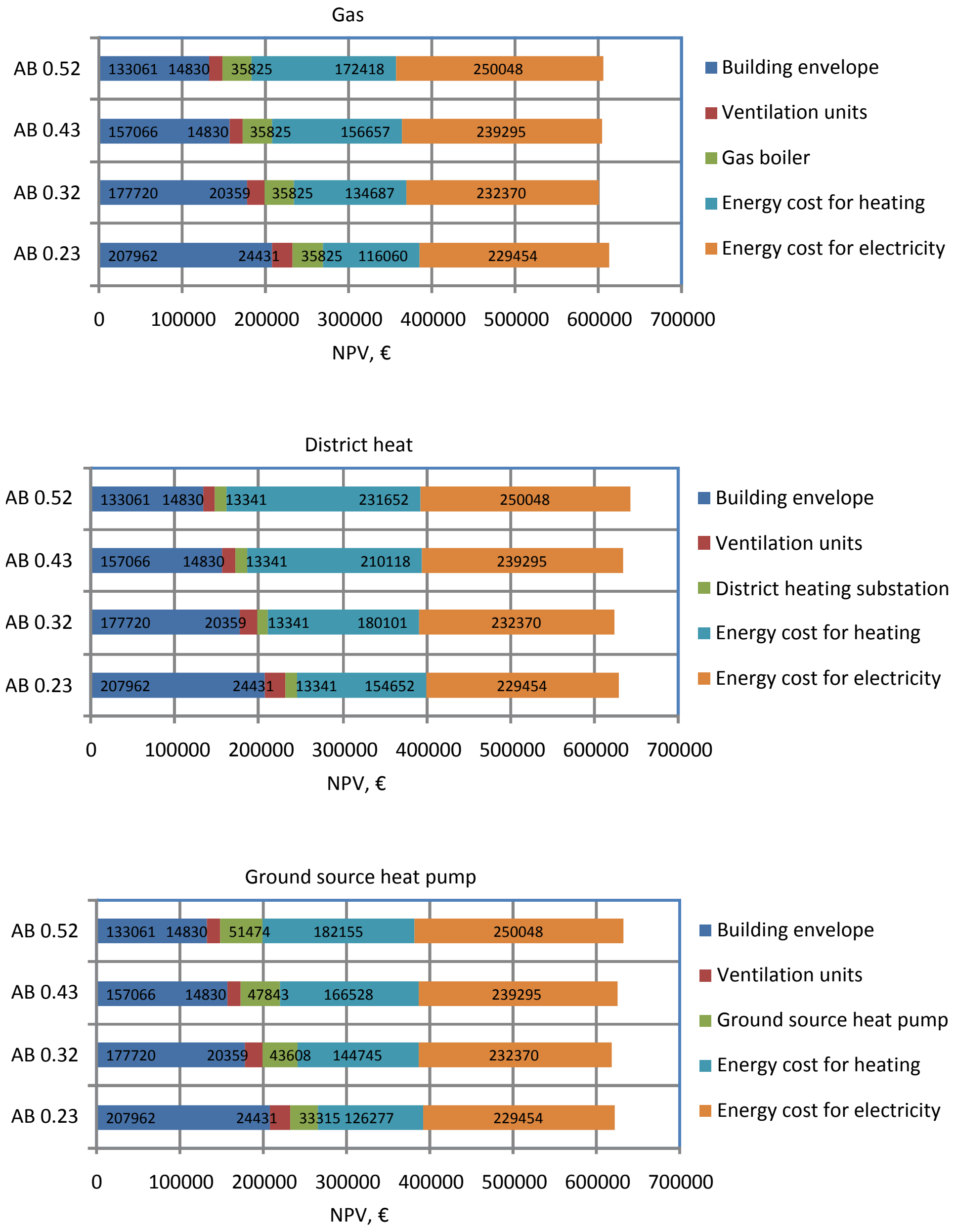

**Fig. 4.** Breakdown of the global energy performance related costs for three heating systems. Discounting interest rate of 1% (the real interest rate of 3% and escalation 2%) and 30 years calculation period. First three categories from left are construction cost components and two last categories NPV of energy costs.

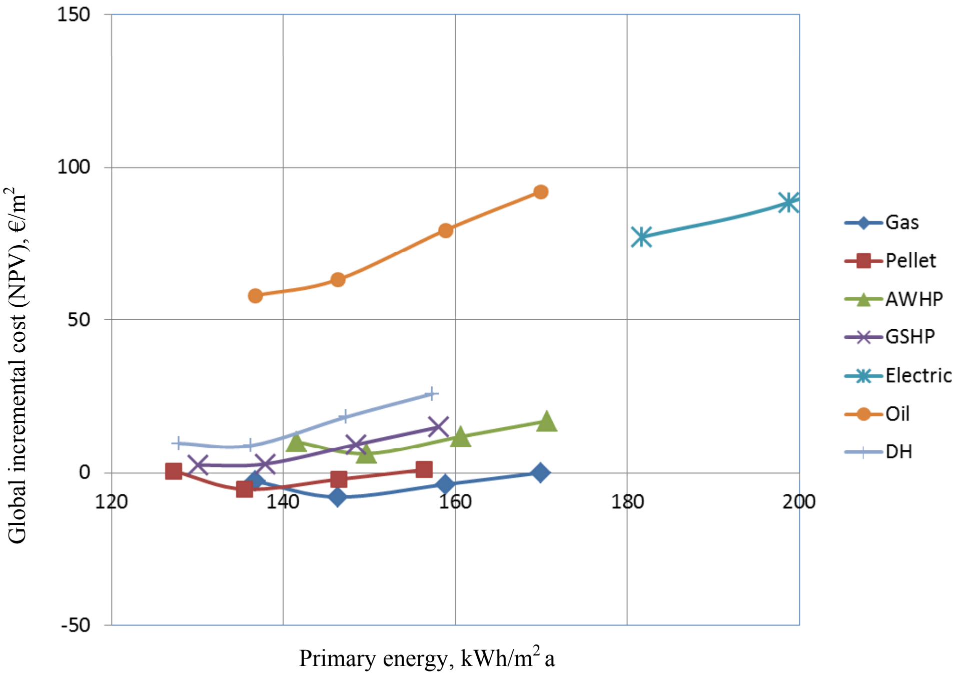

**Fig. 5.** The same results as in Fig. 3, but with the discounting interest rate of 0% (the real interest rate of 3% and escalation of 3%).

For nZEB performance level, on-site renewable energy production has to be added for cases with highest energy performance. The results calculated without solar thermal and PV show that primary energy of about 130 kWh/m$^2$ a is achievable with most of technical solutions studied. Solar thermal producing 50% of domestic hot water will reduce this value to about 110 kWh/m$^2$ a. For solar PV, at least 10 kWh/m$^2$ a primary energy can be accounted, leading to nZEB performance level of 100 kWh/m$^2$ a primary energy. Additional investment cost for nZEB will be the cost difference from AB 0.32 to AB 0.23 construction concept 19.1 €/m$^2$ plus the cost of solar thermal and PV installation, not estimated in this study.

### 3.2. The reference office building

Cost optimal results, shown in Fig. 6 for discounting interest rate of 1% (real interest rate of 3% and escalation of 2%) suggest that OB 0.33 construction concept has led to cost optimal solution with district heating at around 140 kWh/m$^2$ a primary energy. Global cost differences are relatively small, especially between district, gas and air to water heat pump heating. Ground source heat pump shows the highest global cost, mainly because of high investment cost of boreholes. The breakdown of global cost components is shown in Fig. 7.

For nZEB performance level, on-site renewable energy production has to be added for cases with highest energy performance. The results, calculated without solar PV, show that primary energy of about 135 kWh/m$^2$ a is achievable with most technical solutions studied. As solar PV can produce in office buildings at least 20 kWh/m$^2$ a primary energy, nZEB performance level of about 115 kWh/m$^2$ a primary energy is achievable. Additional investment cost for nZEB will be the cost difference from OB 0.33 to OB 0.25 construction concept 18.6 €/m$^2$ plus the cost of solar PV installation.

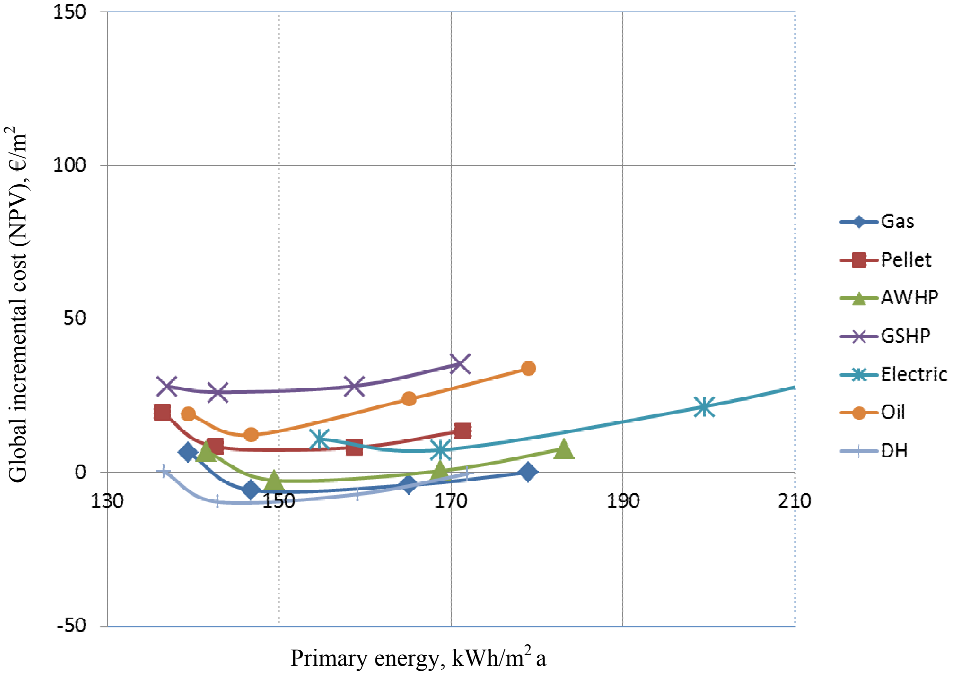

**Fig. 6.** Global energy performance related costs in the reference office building calculated with discounting interest rate of 1% (the real interest rate of 3% and the escalation 2%) and 20 years calculation period; AWHP – air to water heat pump; GSHP – ground source heat pump; DH – district heating. For each technical system, from left to right the cases OB 0.25, 0.33, 0.45 and 0.55 are shown.

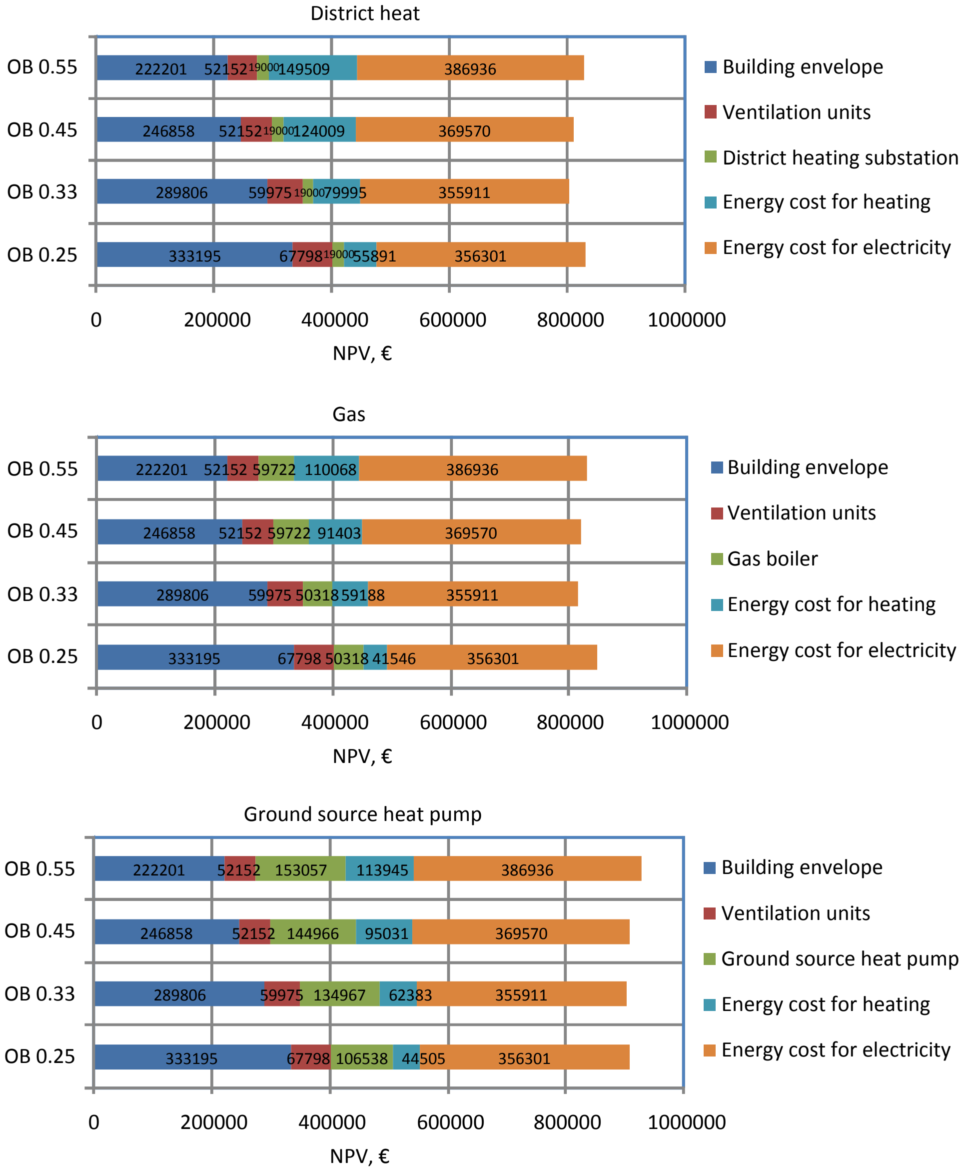

**Fig. 7.** Breakdown of the global energy performance related costs for selected technical systems. Discounting interest rate of 1% (the real interest rate of 3% and escalation 2%) and 30 years calculation period. First four categories from left are construction cost components and two last categories NPV of energy costs.

### 3.3. The reference detached house

The results reported in [10] were recalculated with new primary energy factor of 2.0 for electricity (in [10] 1.5 is used). This changed the primary energy values, all other data remained the same as reported in [10]. Recalculated results are shown in Fig. 8. Three almost equal cost optimal points were found with marginal difference less than 2 €/m$^2$ in NPV, provided by DH 0.76 and DH 0.58 with gas boiler and DH 0.76 with ground source heat pump, all without solar collectors (the results reported in [10] with and without solar collectors showed that cost optimal solution was achieved without solar collectors). Within these cost optimal points, the lowest primary energy of about 140 kWh/m$^2$ a was achieved with DH 0.76 with ground source heat pump and about 160 kWh/m$^2$ a with DH 0.58 with gas boiler.

The nZEB performance level was calculated from 120 kWh/m$^2$ a primary energy, which was achievable with most of heating solutions studied and solar collectors. The 6 kW solar photovoltaic installation with about 5400 kWh/a electricity generation (about 32 kWh/m$^2$ a), corresponding to 2 × 32 = 64 kWh/m$^2$ a primary energy reduction, resulted in 56 kWh/m$^2$ a primary energy. Additional investment cost for nZEB will be the cost difference from DH 0.58 to DH 0.42 construction concept 63.5 €/m$^2$ plus the cost of solar PV installation.

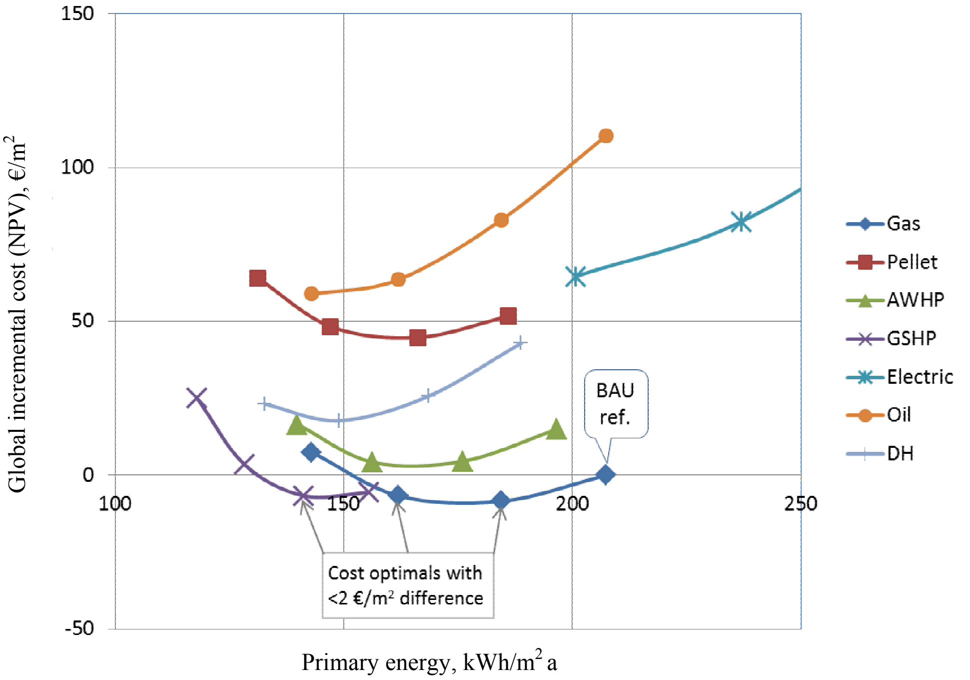

**Fig. 8.** Global incremental energy performance related costs in the reference detached house, calculated with discounting interest rate of 1% (the real interest rate of 3% and the escalation 2%) and 30 years calculation period; AWHP – air to water heat pump; GSHP – ground source heat pump; DH – district heating. For each heating system curve, the dots from left to right represent DH 0.42, 0.58, 0.76 and 0.96 construction concepts.

## 4. DISCUSSION

Cost optimal analyses resulted in cost optimal energy performance of 140–160, 145 and 140 kWh/m$^2$ a primary energy in the detached house, apartment building and office building, respectively, as reported in Chapter 3. Based on these results, new cost optimal minimum energy performance requirements have been prepared and implemented into regulation as shown in Table 4. Cost optimal requirements of new buildings correspond to category C of energy performance certificate and category D is for major renovation. These cost optimal requirements are mandatory. Requirements for nZEB and low energy buildings are not mandatory, but shall be followed, if nZEB or low energy building (corresponding to A or B class of energy performance certificate) is constructed.

It can be seen that in the implementation some safety margins have been used. As the size and form of detached houses and office buildings can vary remarkably, about 15% safety margin has been used for these buildings to allow some architectural freedom in the design. Apartment buildings can be considered as more homogeneous and because of very flat global cost curves, the safety margin is smaller. For nZEB performance levels, safety margins have not been used, because these requirements are not mandatory and likely even more effective technical solutions than those used in the analyses could be found or developed in near future. For office buildings nZEB requirement even slightly more strict value was used than calculated. This is because of adjustments in energy calculation input data regarding appliances and hot water in office building having reduced values with impact of about 10 kWh/m$^2$ a in primary energy. Additionally, it was taken into account that cooling need in the office building was excessively high, for the cases with lower specific heat loss much higher than heating need, as can be seen in Table 2. This shows that overheating issue has been underestimated and the solutions used have not been optimal for solar shading, indicating the potential for energy performance improvement. Some overheating problems can be seen also in the apartment building (Table 1).

The use of safety margins is also justified because of reference buildings were used as stand-alone buildings in the field. In dense city environment neighbouring buildings may reduce on-site energy production and there are additional limitations for high rise buildings. How much and when it will become a problem

**Table 4.** Estonian primary energy requirements [9], which came into force on 9.1.2013. The requirements and corresponding energy certificate classes are shown for three building types out of nine. The nZEB and low energy requirements are not mandatory

| | nZEB<br>A<br>kWh/m$^2$ a | Low energy<br>B<br>kWh/m$^2$ a | Min.req. new<br>C (cost opt.)<br>kWh/m$^2$ a | Min.req. maj.ren.<br>D (cost opt.)<br>kWh/m$^2$ a |
|---|---|---|---|---|
| Detached houses | 50 | 120 | 160 | 210 |
| Apartment buildings | 100 | 120 | 150 | 180 |
| Office buildings | 100 | 130 | 160 | 210 |

will be the research question for future studies. For such situations EPBD has a nearby renewable energy production option, but this is not yet implemented neither in Estonian nor in any other regulation.

## 5. CONCLUSIONS

Estonian cost optimal and nZEB energy performance level analyses were determined for the reference detached house, apartment and office building. Cost optimal energy performance levels are implemented into new Estonian energy performance regulation as minimum requirements for new buildings that came into force since 9 January 2013. In the implementation, safety margins up to 15% were applied to cost optimal minimum requirements to consider the variation of size and form of buildings and to allow reasonable architectural freedom in design. Compared to previous requirements, cost optimal requirements improve energy performance by 20%–40% depending on the building type and energy sources used. Safety margins were not applied for nZEB requirements, because they are not mandatory and evidently technical progress will enable to achieve in near future even better performance.

The detached house showed global cost curves with well-established cost optimal points. However, two cost optimal points at 140 and 160 kWh/m$^2$ a primary energy with marginal difference less than 2 €/m$^2$ in the net present value were found with ground source heat pump and gas boiler, respectively. These cost optimal points were achieved with two steps less insulated building envelope than the best level studied in the case of ground source heat pump, and one step less insulated in the case of a gas boiler.

For the apartment and office building the global cost curves were much more flat, indicating that energy performance improvements were in balance with achieved energy savings. Cost optimal energy performance was achieved with the building envelope insulated one step less than the best level studied. In the office building, district heating and gas boiler were most cost effective, but in the apartment building with more dominating heating energy use, more expensive solutions as pellet boiler, air to water heat pump and ground source heat pump showed also good cost effectiveness.

Flat global cost curves of the apartment and office building also mean that the results are sensitive to input data and relatively small changes in input data can significantly shift cost optimal points. This applies in addition to energy prices and interest rates also to optimality of technical solutions used and accuracy of the cost calculation. Elevated cooling needs especially in the office building but also in the apartment building indicates that overheating issue has been underestimated and the solutions used have not provided enough good solar shading. If improved glazing properties or solar shading solutions would be applied, somewhat better energy performance can be expected.

The nZEB performance was achieved with additional investment compared to cost optimal level of 64 €/m$^2$ in the detached house and 19 €/m$^2$ in the apartment and office building, showing that insulating is relatively more expensive in houses, because of larger building envelope surface area per floor square meter. These costs do not include solar photovoltaic in all buildings and also solar thermal in the apartment building, which were not estimated. Uncertainties related to nZEB performance level and cost calculation are generally much higher, because of high performance technical solutions not commonly used and with costs not well established. Therefore, it could be useful to repeat nZEB calculations with possibly refined input data before setting mandatory nZEB requirements.

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## Kuluoptimaalsed ja liginullenergiahoonete energiatõhususe nõuded Eestis

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On tehtud Eesti tüüpväikeelamu, -korterelamu ja -büroohoone kuluoptimaalse ning liginullenergiahoone energiatõhususe tasemete analüüs. Primaarenergiana väljendatud kuluoptimaalsed energiatõhususe nõuded, mis vastava metoodika järgi arvutades tagavad hoonete elutsükli minimaalse maksumuse, on tulemuste põhjal sisse viidud Eesti uuendatud energiatõhususe miinimumnõuete määrusesse. Määruses, mis jõustus 9. jaanuaril 2013, on toodud ka liginullenergiahoonete nõuded, kuid need ei ole kohustuslikud. Eelnevate miinimumnõuetega võrreldes parendavad kuluoptimaalsed nõuded energiatõhusust 20–40% sõltuvalt hoone tüübist ja energiaallikatest. Tüüpbüroohoone ja -korterelamu tulemused on esitatud täies ulatuses. Tüüpväikeelamu tulemused, mis on varem avaldatud, on ümber arvutatud uue elektri primaarenergiateguriga, mis oli lisaks uutele nõuetele üks määruse suuremaid muudatusi. Väikeelamu elutsükli kulugraafikutel on kuluoptimaalsed punktid hästi näha, kuid büroohoones ja korterelamus olid kulugraafikud tunduvalt lamedamad. See näitab, et nende hoonete puhul on arvutustulemused tundlikud lähteandmete väikestelegi muudatustele, mis võivad oluliselt nihutada kuluoptimaalseid punkte. Liginullenergiahoonete energiatõhususe taseme ja maksumusega seonduvate suhteliselt suurte määramatuste tõttu, mis tulenevad tavakasutusest oluliselt kõrgematasemelistest tehnilistest lahendustest ning nende maksumuse väljakujunematusest, on enne kohustuslike nõuete kehtestamist soovitatav korrata liginullenergiahoonete arvutusi täpsustatud lähteandmetega.