NERO – Cost reduction of new Nearly-Zero Energy Wooden buildings in Northern Climate Conditions

D3.4 Report on nZEB cost calculation and analysis

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ABSTRACT:

This report is connected to WP3 Task 3.3 nZEB cost calculation and analysis. Based on the data collected in WP2 (Task 2.1), the costs changes (for all demo-buildings) caused by the implementation of the nZEB solutions are calculated.

Depending on the data available from the demonstration projects, an analysis of either:

1) Detailed energy performance related costs of the actual solution components compared with the reference solution (minimum requirements, BAU solutions) or
2) Detailed energy performance related costs for the actual solution components compared with the statistic national reference of studied building category.

If the necessary data is available, both calculations are carried out. Cost due to operational energy use and renewable energy harvesting are calculated for different future energy price scenarios.

A systematic evaluation of the impact is conducted for all demonstration buildings. An evaluation matrix based on the correlation between the lifecycle cost and lifecycle emissions will define a matrix of assessment of the different solutions. The results of the calculations for each of the demonstration buildings are put together into the report: D4.1 Report on cost reduction's technical elements.

Norway:

1) Energy performance related costs for ZEB Lab (built as ZEB COM) compared to reference solutions as for the national building code.
2) Energy performance related costs for ZEB Lab compared to national statistic reference from the Norwegian price book (Norsk Prisbok).

Cost due to operational energy use and renewable energy harvesting are calculated for different future energy price scenarios.

ZEB Lab is built with energy performance as ZEB-COM definition net energy need

with zero emissions from construction, operation and materials. This is more ambitious than the national building code for Norway (TEK17). To find the cost effective nZEB level, different scenarios are investigated, starting with TEK17. The requirement for the energy performance according to TEK17 is a net energy need of 115 kWh/m2. …

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Deliverable Leader[4]			

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2 R = Report; R+O = Report plus Other. Note: all “O” deliverables must be accompanied by a deliverable report.
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1 Method

WP3 Task 3.3 (report D3.4) nZEB cost calculation and analysis. Based on the data collected in WP2 (Task 2.1), the costs changes (for all demo-buildings) caused by the implementation of the nZEB solutions are calculated.

Depending on the data available from the demonstrations, an analysis of either:

1. Detailed energy performance related costs of the actual solution components compared with the reference solution (minimum requirements, BAU solutions) or
2. Detailed energy performance related costs for the actual solution components compared with the statistic national reference of studied building category

If the necessary data is available, both calculations are carried out. Cost due to operational energy use and renewable energy harvesting are calculated for different future energy price scenarios.

A systematic evaluation of the impact is conducted for all demonstration buildings. An evaluation matrix based on the correlation between the lifecycle cost and lifecycle emissions will define a matrix of assessment of the different solutions. The results of the calculations for each of the demonstration buildings are put together into this report.

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2 ZEB Laboratory, Norway

2.1 Introduction and method

This section contains energy and cost calculations for the Norwegian demonstration building, ZEB Laboratory, hereafter referred to as ZEB Lab. Explicitly, the following analyses are performed:

- Energy performance related costs for ZEB Lab (built according to ZEB COM definition) is compared to three different sets of solutions that meet the requirement of the national building code (TEK17).
- Energy performance related costs for ZEB Lab is also compared to national statistic reference from a Norwegian publication on updated cost data for buildings (Norsk Prisbok 2019).
- Costs due to operational energy use are calculated for different future energy price scenarios.

The goal for energy performance of ZEB Lab is ZEB-COM (zero emissions from construction, operation and materials over the building's lifetime). This is significantly more ambitious than the national building code for Norway (TEK17). To investigate the cost effective nZEB level, the as-built design of ZEB Lab is compared to three different variants satisfying the requirement of TEK17. The requirement for the energy performance according to TEK17 is that the net energy need should be maximum 115 kWh/(m^2·year), in addition to certain minimum requirements for the energy efficiency of the building envelope. The as-built design and three different TEK17-variants with higher U-values are specified and simulated in SIMIEN (v6.012) [1] to find the difference in energy performance. Furthermore, the cost difference of the building components of the TEK17-variants compared to the ZEB Lab design are found using Norsk Prisbok [2]. The difference in calculated net energy need, delivered energy [7] and cost difference are then used to assess the profitability of the TEK17-variants compared to the ZEB Lab design.

ZEB Lab (https://zeblab.no/) is located in Trondheim, Norway, and consists of four floors as can be seen in Figure 1. ZEB Lab will be an office/education building in regular use for staff members from SINTEF and NTNU, as well as students at NTNU. The ZEB Lab is built according to ZEB definitions developed by the research centre FME ZEB [3]. The ZEB definition has several ambition levels and ZEB Lab is classified at the second highest level, ZEB-COM, i.e. with zero emissions for the building including emissions from construction, operation and production of materials. Zero emission over the building lifetime is achieved through compensation for greenhouse gas emission through renewable energy produced on the building. ZEB Lab will thus produce more energy than it uses during operation, to also cover the emissions from construction and production of materials. 524 m^2 PV panels on a southfacing roof with 30º slope, significant amounts of PV on the facades and a heat pump with both outdoor air and excess heat from the inverter room as heat sources enables the renewable energy production. In addition, the ventilation system is designed to be extremely energy efficient and the heating system include an innovative phase-change-material (PCM) storage.

[7] Net energy need is the building's energy need without considering the energy systems efficiency or losses in the energy chain (used in TEK17-evaluation). Delivered energy (to the building) includes the system efficiency of the energy system (production efficiency, distribution losses).

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Figure 1 Illustration of the ZEB Lab. Illustration: LINK Arkitektur

In addition to be a highly ambitious project satisfying ZEB-COM, ZEB Lab will be an arena where new and innovative materials and solutions are developed, investigated, tested and demonstrated in mutual interaction with people [4]. The building is designed to be flexible, so that materials and technical installations can be easily replaced for research purposes. In addition, the building and infrastructure is climate adapted to for instance handle increasing rainwater. The ambition level and flexibility aspect should be kept in mind when evaluating the cost of the building compared to other conventional building projects.

The gross internal area (GIA) is 1742 m^2, while the gross total area (GTA, including external walls) is 2001 m^2. Due to two inclined walls, the first floor is 440 m^2 as seen in Figure 2, the second and the third floor is 448 and 453 m^2, while the fourth floor is 414 m^2. Figure 3 and Figure 4 shows the facades of the building.

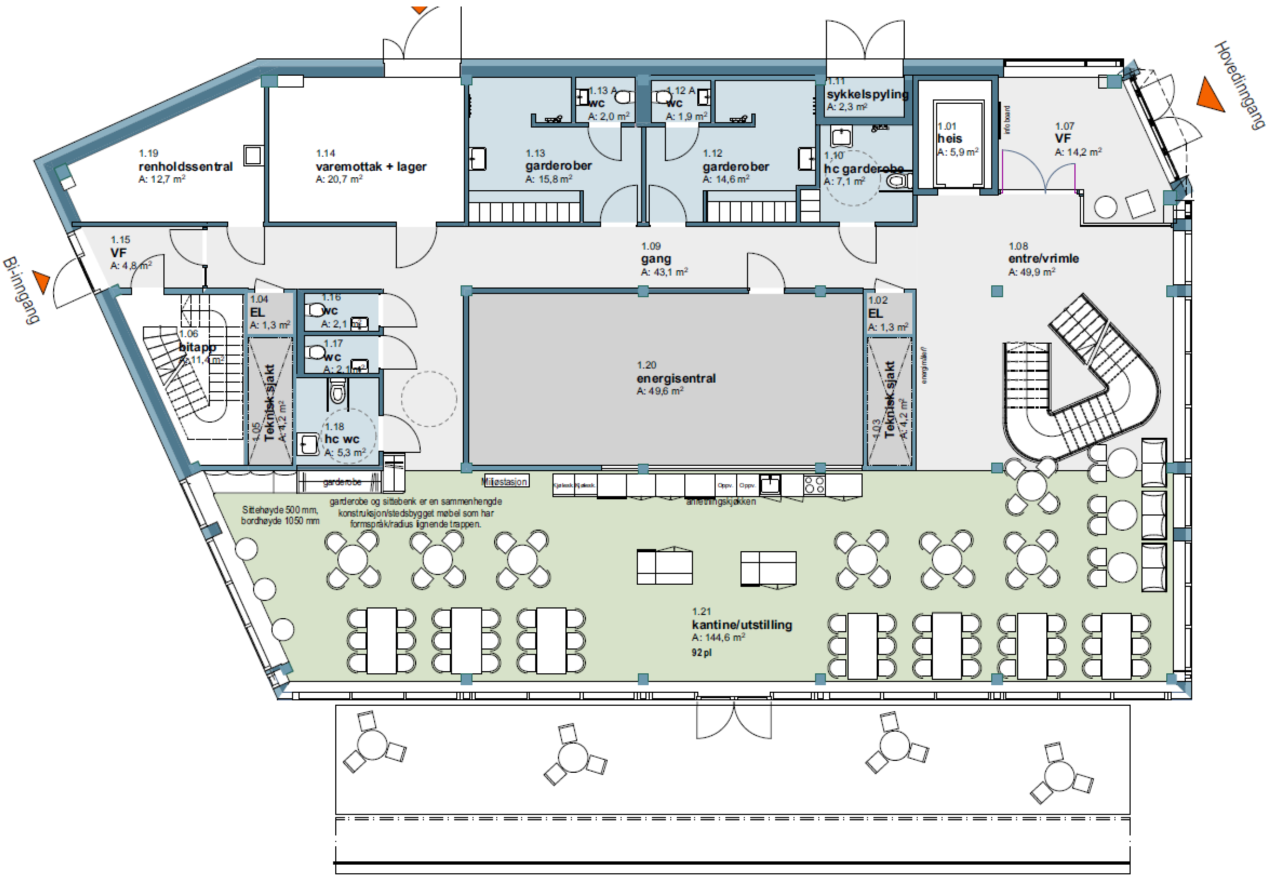

Figure 2 Layout of the first floor of the ZEB Lab. Illustration: LINK Arkitektur

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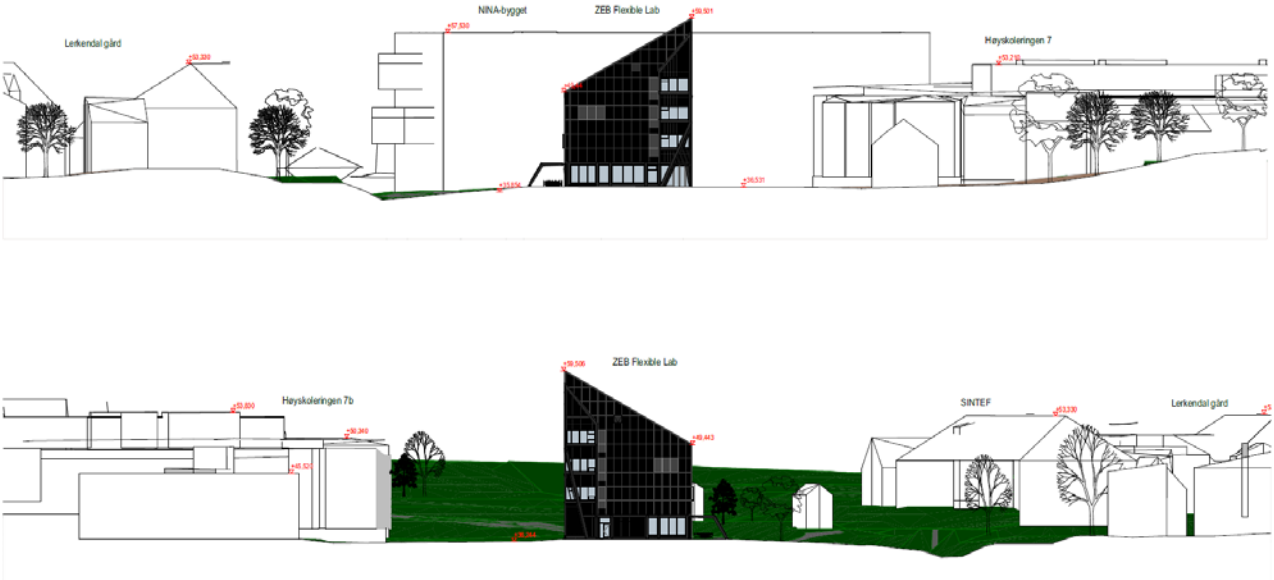

Figure 3 Top picture shows the east facade while the bottom picture shows the west facade of the ZEB Lab. Illustration: LINK Arkitektur

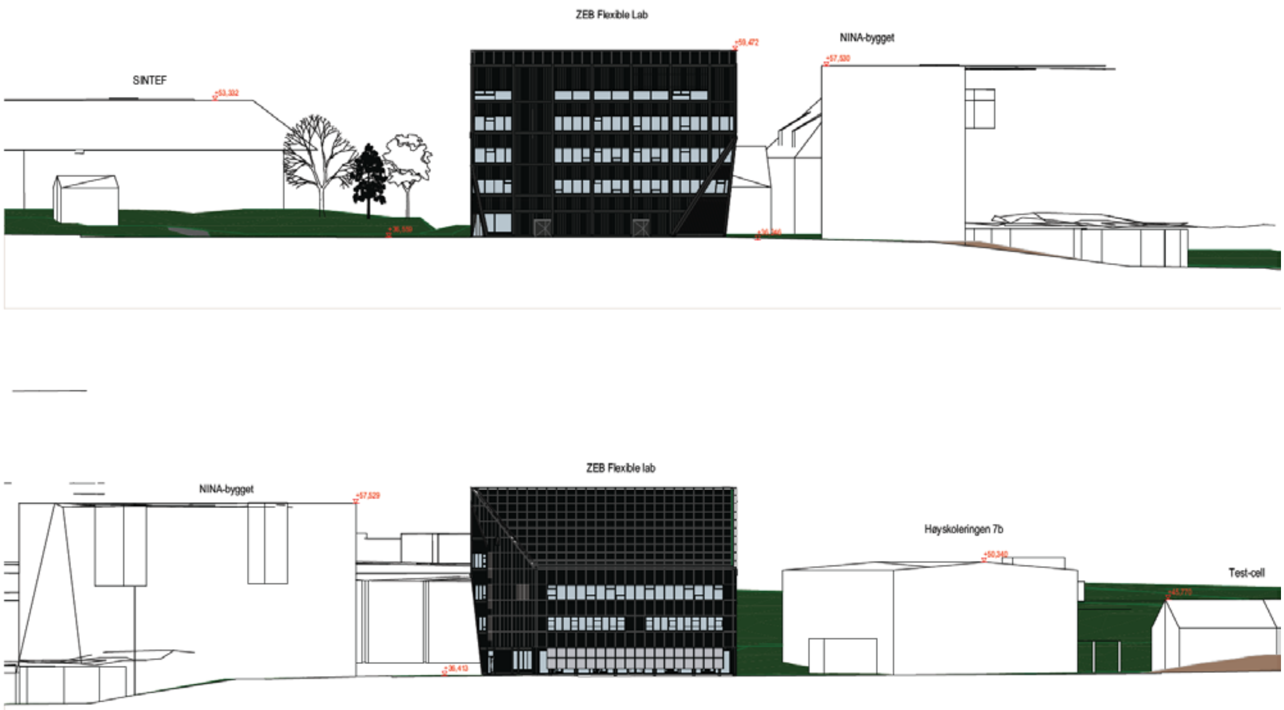

Figure 4 Top picture shows the north facade while the bottom picture shows the south facade of the ZEB Lab. The south facing roof has a 30º slope and is covered with 524 m² photovoltaic cells. Illustration: LINK Arkitektur

The stairwells and "suspended floors" consist of cross-laminated timber (CLT), while columns and beams are glue laminated timber. The columns span several floors. The facades are made of timber framing and some of the interior walls are made of CLT. The staircase, elevator and ventilation shafts consist of vertical solid wood. The roof is built as a sloping ventilated roof (30°) with light elements. Almost the entire roof will be covered with photovoltaics alongside most of the south, east and west facades. Some pictures from the construction process can be seen in Figure 5 and Figure 6.

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Figure 5 Pictures from the construction site. Photos: Øystein Rønneseth

Figure 6 Webcam photos of ZEB Lab under construction, 26.08.2019 [5].

2.2 Energy simulations

As previously mentioned, energy simulations of the ZEB Lab are performed with as-built design and three different TEK17-variants. TEK17 has a maximum requirement of 115 kWh/(m²·year) for the total *net energy need* for office buildings. In order to fulfil the TEK17 requirements, both the energy requirement for the building category and minimum requirements for energy performance of the building envelope must be fulfilled. Chosen design values for ZEB Lab and minimum requirement for components specified in TEK17 are presented in Table 1.

Table 1: Design values for the building envelope and minimum requirement for components from TEK17 §14-3 [6].

	Windows and doors (W/m²·K)	Roof (W/m²·K)	Facades (W/m²·K)	Floor (W/m²·K)	Building leakage at 50 Pa (ACH)*
Design values ZEB Lab	0.8	0.09	0.15	0.10	0.30
TEK17 minimum requirement	< 1.2	< 0.18	< 0.22	< 0.18	< 1.50

*ACH = Air changes per hour (h^{-1}).

The net energy need of the building is calculated using the simulation tool SIMIEN (v6.012) [1], a software commonly used in Norway. Firstly, simulations are performed according to the evaluation against Norwegian building regulations, TEK17, with standard input data from NS 3031:2014 [7] to confirm that the proposed TEK17-variants are within the requirements. This includes relatively high values for especially lighting and technical equipment compared to what the ZEB Lab is designed for, as can be seen in Table 2. Internal loads in the TEK17 evaluation (64 kWh/(m²·year)) actually make up over half of the total energy requirement

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of maximum 115 kWh/(m²·year). To reach the ambition of ZEB-COM, it is necessary to use the most energy efficient products on the market. The validation procedure for TEK17 also requires simulations to be performed with Oslo-climate, even though the building is located in Trondheim. The simulation with Oslo-climate and internal loads for the TEK17 evaluation are only used here for validation and specifying the three TEK17-variants. In further calculations and analysis of the TEK17-variants, local climate (Trondheim) and ZEB Lab design values for internal loads are used.

Table 2 Standard net energy need for lighting, technical equipment and DHW from NS 3031:2014 used for TEK 17 evaluation, compared to design values for ZEB Lab.

Net energy need per purpose	TEK17 evaluation	ZEB Lab design
Lighting (kWh/(m²·year))	25	9.4
Technical equipment (kWh/(m²·year))	34	10
Domestic hot water (kWh/(m²·year))	5	1.0
Sum (kWh/(m²·year))	64	20.4

Before defining the different TEK17-variants, a simulation was performed for the ZEB Lab to find the net energy need of the as-built version, to use as a basis for comparison. The net energy need was calculated to be 95.8 kWh/(m²·year), as shown in Table 3. Separate simulations were then performed to find the effect of different single measures, reducing the energy efficiency from design values to TEK17 minimum requirements for components and other typical values (leakage number 0.6 and 1.0 ACH). For the building components, increasing the U-value of the windows was found to have the largest effect, increasing the net energy need with 8.4 kWh/(m²·year). Increasing the infiltration number for the building envelope is found to have the largest effect overall, with 11 kWh/(m²·year) for the increase to 1.5 ACH.

Table 3 Overview of single measures and simulated difference in net energy need compared to the basis of ZEB Lab with TEK-evaluation.

Variants and different measures	Specific energy need (kWh/(m²·year))	Difference from basis (kWh/(m²·year))	Net energy need (kWh/year)
Basis: As-built ZEB Lab with input values for TEK-evaluation:	**95.8**	-	157 651
Single measures compared to the basis			**Difference from basis**
Windows, U=1.2 W/m²·K (basis is 0.8)	104.2	8.4	14 633
Doors, U=1.2 W/m²·K (basis is 0.8)	96.3	0.5	871
Roof, U= 0.18 W/m²·K (basis is 0.09)	98.3	2.5	4 355
Facades, U=0.22 W/m²·K (basis is 0.15)	99.9	4.1	7 142
External floor, U=0.18 W/m²·K (basis is 0.10)	97.1	1.3	2 265
Leakage number, 1.5 ACH (basis is 0.3)	106.8	11	19 162
Leakage number, 1.0 ACH (basis is 0.3)	102.1	6.3	10 975
Leakage number, 0.6 ACH (basis is 0.3)	98.5	2.7	4 703
TEK 17, all minimum requirements for components*	125.9	30.1	52 434

* The requirement for office buildings is max 115 kWh/(m²·year), so with all minimum requirements for components the requirement is not fulfilled.

The TEK17-variants are made by different combinations of measures for reducing the energy performance of the building envelope to the TEK17 minimum requirements for components, while still fulfilling the energy requirement for office buildings of 115 kWh/(m²·year). The U-values are either kept the same as for ZEB Lab Basis, or changed to the TEK17 minimum requirements. For the building leakage number, all four variants have the same value of 0.3 ACH. The leakage number is kept the same as it was not possible to quantify the cost difference for different leakage numbers. U-values for the ZEB Lab Basis and three TEK17-variants are

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presented in Table 4 alongside a description of the materials used in the building components. Common for all variants is a normalized thermal bridge value of 0.04 W/(K·m² floor area).

Table 4: Description of the actual ZEB Lab design (basis) and defined TEK17-variants.

		ZEB Lab Basis	TEK17-1 Variant 1	TEK17-2 Variant 2	TEK17-3 Variant 3
Facades	U-value (W/m²·K)	0.15	0.15	0.22	0.22
	Description	Timber frame of solid wood w/mineral wool 223 mm, 73 mm cladding w/mineral wool	Timber frame of solid wood w/mineral wool 223 mm, 73 mm cladding w/mineral wool	Timber frame of solid wood w/mineral wool 150 mm, 50 mm cladding w/mineral wool	Timber frame of solid wood w/mineral wool 150 mm, 50 mm cladding w/mineral wool
Roof	U-value (W/m²·K)	0.09	0.18	0.09	0.18
	Description	Rafter roof 48x400 mm I-studs, 200+200 mm Rockwool Flexi A-Plate	Rafter roof 48x400 mm I-studs, 200 mm Rockwool Flexi A-Plate	Rafter roof 48x400 mm I-studs, 200+200 mm Rockwool Flexi A-Plate	Rafter roof 48x400 mm I-studs, 200 mm Rockwool Flexi A-Plate
Floor	U-value (W/m²·K)	0.10	0.10	0.18	0.10
	Description	Floor on the foundation. Insulation 250 mm EPS	Floor on the foundation. Insulation 250 mm EPS	Floor on foundation. Insulation 100 mm EPS	Floor on the foundation. Insulation 250 mm EPS
Windows	U-value (W/m²·K)	0.8	1.2	0.8	1.2
Doors	U-value (W/m²·K)	0.8	1.2	0.8	1.2

Airflow rates and specific fan power (SFP) for the ventilation system is set to 7/2 $m^3/(h \cdot m^2)$ and 1/0.5 $kW/(m^3/s)$ respectively inside/outside operation hours. In reality, the ZEB Lab is designed with hybrid ventilation (motorized openable windows) and slightly lower ventilation airflow rates than TEK17 requirements (7/2 $m^3/(h \cdot m^2)$) used here. The design SFP-values are considered ambitious compared to conventional buildings, and are possible due to innovative displacement ventilation systems and by using the stairwells for extract air.The annual temperature efficiency of the heat recovery is modelled as 80 % for all variants, even though the ZEB Lab project team is using 85 % in their calculations. Research shows that due to longitudinal heat conduction effects, the *momentary temperature efficiency* of rotary heat recovery units is limited to 80 % [8]. The *annual temperature efficiency*, used for calculations will thus in practice be lower than 80 %. Reducing the heat recovery efficiency from 85 % to 80 % resulted in a 5 $kWh/(m^2 \cdot year)$ higher net energy need, but is considered more realistic.

Simulated net energy need for the ZEB Lab Basis model and three TEK17-variants are summarized in Table 5. One can see that all TEK17-variants fulfil the TEK17 energy requirement of maximum 115 kWh/(m²·year). In further calculations and analysis of the TEK17-variants, local climate (Trondheim) and ZEB Lab design values for internal loads are used, according to Table 7.

Table 5 Calculated net energy need for the basis and the three TEK17-variants used for validation against TEK17.

	ZEB Lab Basis	TEK17-1	TEK17-2	TEK17-3
Specific net energy need (kWh/(m²·year))	95.8	107.4	101.2	111.8

As shown in Table 3, the leakage rate has a high influence on the net energy need. It was not possible to quantify the costs of different leakage rates. As this was not included, a sensitivity analysis of different leakage rates (and abovementioned heat recovery) has been made with regards to net energy need instead, visualised in Figure 7. The chosen level is visualised with the yellow points (0.3 ACH / 80 %). For the

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simulations with the TEK17 minimum requirement of 1.5 ACH, TEK17-1 and TEK17-3 do not fulfil the TEK17 energy requirement of maximum 115 kWh/(m^2·year).

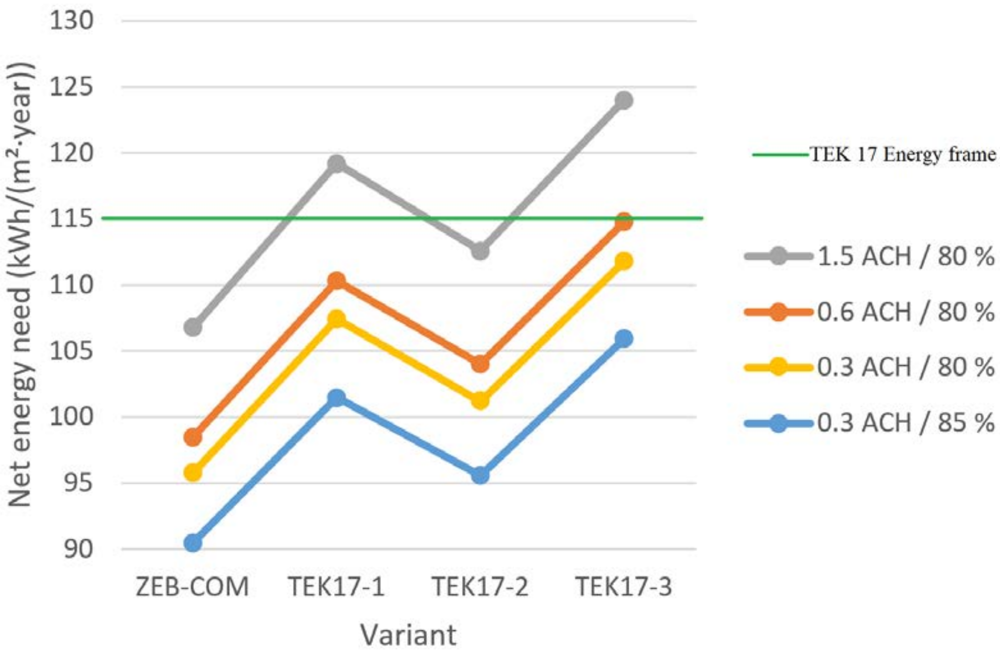

Figure 7 Sensitivity for changes in net energy need for different leakage numbers and heat recovery efficiencies.

Both net energy need and delivered energy is used to assess the energy costs for the different variants. The cost for energy from the heat pump is not included. The heating system is assumed identical for all variants with an annual system efficiency of 3.0. A heat pump system covers the base load of the heating demand, while electricity is used as top load, as illustrated by the energy coverage factors in Table 6. The energy calculations are simplified, and do not include the complexity of the heating system that involves a heat pump with both outdoor air and excess heat from the PV inverter room as heat sources, as well as a PCM (phase change material) energy storage system. The building is not designed to have a cooling system, except for in two identical rooms used for research purposes on the indoor environment.

Table 6 Energy coverage factors for the heating demand in ZEB Lab.

	Heat pump	Electricity
Space heating	100 %	0 %
Domestic hot water	70 %	30 %
Ventilation heating	100 %	0 %

For further calculations and analysis, the simulation results presented in Table 7 are used. The energy simulation with local climate and chosen design input data renders a total net energy need of 62.0 kWh/(m^2·year) for ZEB Lab Basis, 35 % lower than for the TEK17 evaluation with Oslo-climate and TEK17 internal loads of 95.8 kWh/(m^2·year). The table includes both net energy need and delivered energy for the ZEB Lab Basis and TEK17-variants, which are used to assess the costs of operational energy use.

Table 7 Simulated net energy need and delivered energy for Trondheim climate and design internal loads, used for further calculations and analysis.

	ZEB Lab Basis	TEK17-1	TEK17-2	TEK17-3
Specific net energy need (kWh/m²·year)	62.0	75.6	68.5	80.7
Total net energy need (kWh/year)	108 063	131 699	119379	140 510
Difference from basis (kWh/year)	-	23 636	11 316	32 447

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Specific delivered energy (kWh/m²·year)	38.4	43	40.6	44.7
Total delivered energy (kWh/year)	66 808	74 884	70 678	77 850
Difference from basis (kWh/year)	-	8 076	3 870	11 042

Table 8 shows renewable energy production for all variants. The renewable energy production from PV is not included in any calculations.

Table 8 Calculated renewable energy production from heat pump and PV system.

	ZEB Lab Basis	TEK17-1	TEK17-2	TEK17-3
Net energy need for heating purposes only (kWh/year)	62 513	85 853	73 682	94 441
Delivered electricity for heat pump (kWh/year)	20 663	28 443	24 386	31 366
Renewable energy production from heat pump (kWh/year)	41 850	57 410	49 296	63 075
Renewable energy production from PV (kWh/year) *	140 000	140 000	140 000	140 000
Total renewable energy production (kWh/year)	181 850	197 410	189 296	203 075

*Preliminary estimation by the PV supplier, Solcellespesialisten, by e-mail 05.09.2019.

2.3 Current and future electricity price

The energy price is crucial to find the profitability for the different TEK17-variants based on energy cost savings. As the building is modelled with a heat pump as base load and electricity as top load, electricity will be the only energy carrier. The total Norwegian electricity price consist of four parts: electricity fee, grid rent, electricity price and VAT (value added tax). The electricity fee (or consumption tax) is set by the government and may change slightly over time. Grid rent is paid to the local grid company and thus depends on the region the building is located in. The grid rent varies throughout the year and is more expensive during winter than summer due to higher peak demand. For non-residential buildings, such as ZEB Lab, the grid rent depends on the highest average hourly power consumption for certain months. As we do not have access to detailed modelling or measurement data of the power demand, a flat historical price for a reference building (40 kW and 160 000 kWh/year) have been used for grid rent, which is set to 0.03 €/kWh [9]. This price is Norway's average value of 2017 (as 2018 data was not yet available), which is close to identical to the grid rent in the Trøndelag region, where ZEB Lab is located. The electricity price is fluctuating throughout the year and the price given in Table 9 is the historic average electricity price in 2018 for Norway. Note that in 2018, Norway had a high electricity price during normally low-priced periods and the electricity price is expected to increase in the coming years. NVE see the high electricity prices last year in light of the increased gas and coal prices and a significantly higher price of CO_2-quotas in the EU [10]. For the sake of references, Table 9 also includes NOK/kWh, but €/kWh is used in the rest of the report.

Table 9: The different shares and total electricity price for Norway per 2018. A currency conversion rate of 9.93 NOK/EUR from 06.09.2019 was used [11].

Prices	NOK/kWh	EUR/kWh
Electricity fee [12]	0.1583	0.02
Grid rent [9]	0.274	0.03
Electricity price [13]	0.449	0.05
VAT (25 %)	0.220	0.02
Total	***1.10***	***0.11***

Future energy prices are very complex and almost impossible to estimate as they depend on numerous factors, such as renewable energy share in the EU, price of CO_2-quotas, political decisions, etc. To keep it simple but still include a sensitivity analysis regarding future energy prices, three scenarios with escalating energy price are used with 2 %, 4 % and 6 % increase per year. As ZEB Lab is a non-residential building, the calculation period for the profitability analysis is set to 20 years according to the Delegated Regulation (EU) No 244/2012 [14]. Figure 8 shows the future energy prices used in the calculations. Furthermore, the construction of ZEB

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Lab will be finished during the fall of 2020, so 2020 is set as year #1, thus including the increase in electricity price from 2018 to 2020.

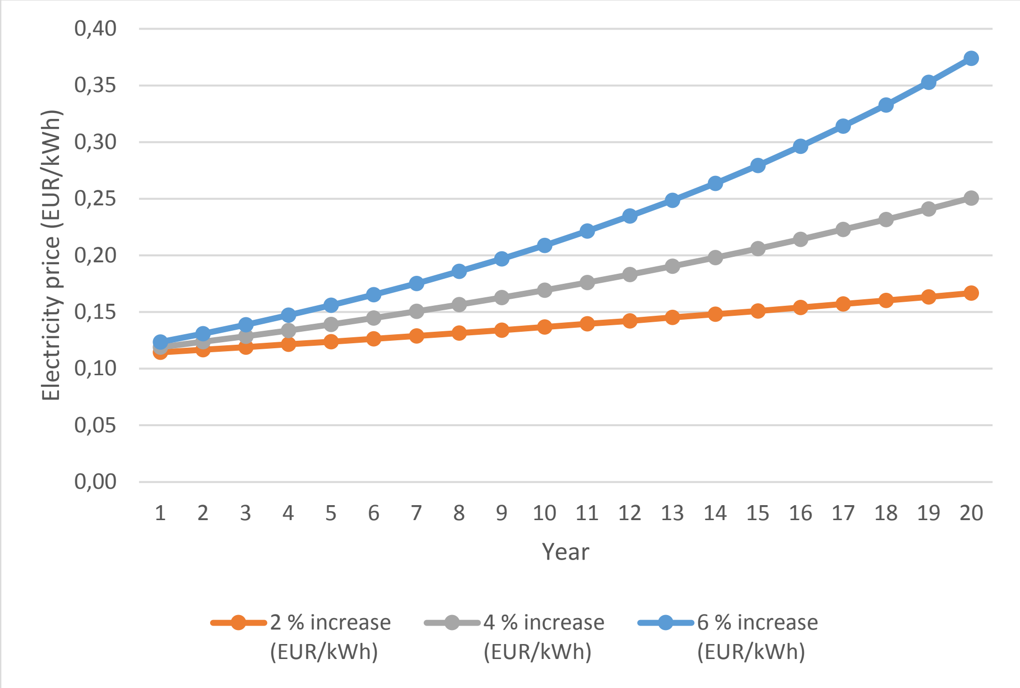

Figure 8 Future energy prices for the next 20 years (from 2020) with different rates of increase.

2.4 Costs for building components and different variants

Costs for the different building components have been found using Norsk Prisbok [2], including materials, work hours and subcontractors but not VAT. The costs are found for the whole component, as described in Table 4, with default extra materials (laths, plaster, vapor barrier, etc.) for a full component as defined in Norsk Prisbok's database. There might be small deviations in the chosen materials except for the wood/insulation layer, however, the interior and exterior materials are assumed to be identical for ZEB Lab Basis and the TEK17-variants, and thus the cost difference used in the analysis will be the same. The costs are limited to the building envelope affecting the energy performance, and so internal structures are not included.

Table 11 presents an overview of component area, lifetime, U-values and costs for the different building components for both ZEB Lab Basis and for TEK17 minimum requirements. Four different types of windows are specified, as some are fixed or openable and some have aluminium mantling or not. Some simplifications have been made that may slightly affect the total investment cost, however, the effect on the cost difference used in the profitability analysis is limited. ZEB Lab will in reality have both manual and motorized openable windows for the hybrid ventilation. Motorized windows are more expensive, but as the costs were not available in Norsk Prisbok, all are assumed to be manual. The building have four doors, whereas three are wood/glas doors with aluminum mantling, and one is a steel door. As steel doors with different U-values were not available in Norsk Prisbok (actually not with U-value listed at all) the steel door was assumed to be similar to the wood/glas doors with aluminum mantling in order to find the cost difference.

Table 10 Overview of costs for the building envelope with U-values according to both ZEB Lab Basis and minimum requirements of TEK17 found using Norsk Prisbok. VAT is not included.

			ZEB Lab Basis			TEK17 min. requirement		
Component	**Component area (m²)**	**Lifetime (years)**	**U-value (W/m²K)**	**Cost (€/m²)**	**Cost (€)**	**U-value (W/m²K)**	**Cost (€/m²)**	**Cost (€)**
Facades	1 130	60	0.15	179	201 976	0.22	140	158 781
Roof	535	60	0.09	183	98 188	0.18	154	82 290

Ground floor	440	60	0.10	106	46 826	0.18	82	36 270
Windows, fixed, wood	22	40	0.80	404	8 809	1.20	329	7 182
Windows, fixed, wood+alu.	207	60	0.80	472	97 511	1.20	422	87 085
Windows, openable, wood	3	40	0.80	544	1 656	1.20	477	1 452
Windows, openable, wood+alu.	197	60	0.80	577	113 700	1.20	515	101 509
Doors	4 pcs	60	0.80	1 308*	5 231	1.20	978*	3 912

*For doors, Norsk Prisbok listed the costs as cost per door, not cost per m^2 component as for the other components.

Typical values for lifetime of building components have been used. According to environmental product declarations (EPDs), windows and doors without/with aluminium cladding have an expected lifetime of 40/60 years [15-17]. Previously, 30 years have been commonly used in calculations, however, some studies show that existing windows and doors usually have a lifetime of around 30-50 years [18, 19]. It is reasonable to assume that newer products have longer lifetime, as suggested in the EPDs.

No studies are found quantifying the extra costs associated with different leakage numbers. Through discussions with experts in the field, the costs are associated with additional labour costs for craftsmen (carpenters, electricians, etc.), as well as extra air-tightening products, such as tape, sealing products for components (pipes, ducts, etc.) going through the membranes, fittings, joint-sealing compounds, etc. More control and documentation is needed, and in some cases external personnel must perform leakage tests, leading to an additional cost. Proper planning and design and early decisisons on the ambition level of airtighness was also considered important, as it requires additional focus during the entire project period. Due to stricter building regulations and more knowledge and experience among designers and craftsmen, Norwegian buildings have during recent years become more airtight.

The cost difference of each element in the building envelope from the ZEB Lab Basis to TEK17 minimum requirement is presented in Table 12. The periodic payment presents the extra investment cost per year for ZEB Lab Basis compared to TEK17 for the specified element, considering a calculation period of 20 years and an interest rate of 4 %. Although windows have the highest cost difference per component area, facades have the highest cost in the other categories, due to a larger component area, as given in Table 11.

Table 11 Cost difference for ZEB Lab Basis vs TEK17 minimum requirement for components and periodic payment for each building component considering a calculation period of 20 years and an interest rate of 4 %.

Component	**Cost difference ZEB Lab Basis vs TEK17 per component area (€/m^2)**	**Cost difference basis vs TEK17 (€)**	**Cost difference per floor area (€/m^2)**	**Periodic payment (€/year)**
Facades	38	43 195	25	3 178
Roof	30	15 897	9	1 170
Ground floor	24	10 556	6	777
Windows, fixed, wood	75	1 627	1	120
Windows, fixed, wood+alu.	50	10 426	6	767

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Windows, openable, wood	67	204	0	15
Windows, openable, wood+alu.	62	12 191	7	897
Windows total	**57**	**24 449**	**14**	**1 799**
Doors	330*	1 319	1	97

*For doors, Norsk Prisbok listed the costs as cost per door, not cost per m^2 component as for the other components.

The total costs of the different variants are summarized in Table 13, where the components in the TEK17-variants are either equal to ZEB Lab Basis or the TEK17 minimum requirement for components. TEK17-3 has the lowest cost of the variants, as this includes the most components built according to TEK17 minimum requirements for components. The investment cost for TEK17-3 is estimated to be 84 860 € lower than for ZEB Lab Basis.

Table 12 Total investment costs of the different variants, not including energy costs and savings.

	ZEB Lab Basis	TEK17-1	TEK17-2	TEK17-3
Facades (€)	201 976	201 976	158 781	158 781
Roof (€)	98 188	82 290	98 188	82 290
Ground floor (€)	46 826	46 826	36 270	46 826
Windows (€)	221 676	197 227	221 676	197 227
Doors (€)	5 231	3 912	5 231	3 912
Total cost (€)	**573 897**	**532 232**	**520 146**	**489 037**
Difference (saved cost) compared to basis (€)	-	41 665	53 751	84 860

In Table 14, periodic payment is calculated for upgrading the TEK17-variants to the ZEB Lab Basis level. The periodic payment for upgrading TEK17-3 is two times larger than for TEK17-1.

Table 13 Calculated periodic payments for upgrading the different TEK17-variants to ZEB Lab Basis.

	TEK17-1	TEK17-2	TEK17-3
Difference (saved cost) compared to ZEB Lab Basis (€)	41 665	53 751	84 860
Calculation period (years)	20	20	20
Interest rate (-)	0.04	0.04	0.04
Periodic payment for upgrading to ZEB Lab level (€/year)	3 066	3 955	6 244

2.5 Profitability analysis

The profitability analysis is based on the methodology described in Delegated Regulation (EU) No 244/2012 of the European Commission. The cost-effectiveness of different structural solutions was estimated using the net present value method:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \cdot R_d(i)\right) - V_{f,\tau}(j)\right] \quad (1)$$

where:

- τ means the calculation period;
- C_G (τ) means total cost (referred to starting year τ0) over the calculation period;

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- C_I means initial investment costs for measure or set of measures j;
- $C_{a,i}$ (j) means annual cost during year i for measure or set of measures j;
- $V_{f,\tau}$ (j) means residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year τ0)
- R_d (i) means discount factor for year i based on discount rate.

Calculations are performed based on the following input data:

- Calculation period 20 years (non-residential buildings), starting from year 2020 when ZEB Lab is completed.
- Discount rate of 4 %.
- Initial electricity price of 0.11 €/kWh and different future energy price scenarios, with electricity price increasing with 2 %, 4 % and 6 % per year.
- VAT is not included, nor costs for greenhouse gas emissions.

Common input data to calculate the profitability of the TEK17-variants compared to the ZEB Lab Basis are listed in Table 15. The calculations are performed both for *net energy need* (corresponding to electric heating) and for *delivered energy* (chosen heat pump with heating system efficiency of 3.0). Notice that the difference in net energy need for the TEK17-variants compared to the basis is close to 3 times higher than for delivered energy. The annual energy cost, $C_{a,i}$ (j), is found by multiplying the net energy need or delivered energy with the corresponding electricity price for each year.

Table 14 Common input data to calculate the profitability of the TEK17-variants compared to the ZEB Lab Basis.

Description	ZEB Lab Basis	TEK17-1	TEK17-2	TEK17-3
Calculation period (τ, years)	20	20	20	20
Total investment cost for building components (€)	573 897	532 232	520 146	489 037
Reduced investment cost for TEK17-variant (C_G (τ),€)	-	41 665	53 751	84 860
Extra net energy need for TEK17-variant, (kWh)	-	-23 636	-11 316	-32 447
Extra delivered energy for TEK17-variant, (kWh)	-	-8 076	-3 870	-11 042
Discount rate (R_d (i), %)	4	4	4	4
Extra residual value for ZEB Lab Basis discounted to the starting year ($V_{f,\tau}$ (j), €)	-	12 538	16 354	25 680

*The cost efficiency factor for the investments (investment costs divided by delivered energy saving) are 5.2, 13.9 and 7.7 €/kWh for TEK17-1, TEK17-2 and TEK17-3 respectively.

As a reminder, the TEK17-variants are identical to the ZEB Lab Basis, except for the following changes to the building envelope:

- TEK17-1: Windows, doors and roof are according to TEK 17 minimum requirement for components.
- TEK17-2: Facades and floor are according to TEK 17 minimum requirement for components.
- TEK17-3: Windows, doors, facades and roof are according to TEK 17 minimum requirement for components.

The building components will still have a residual value, $V_{f,\tau}$ (j), after the calculation period of 20 years, and this must be included in the profitability analysis. It is assumed that the residual value after the component lifetime (e.g. 60 years) is zero. The straight-line method is used to calculate the residual value of each component in the variants after the calculation period of 20 years, according to the equation below. As an example, the facades are considered to have a 60 year lifetime, and will thus have a remaining lifetime of 40 years after the calculation period of 20 years. Furthermore, the residual value is discounted to the starting year. Table 16 shows how the residual value is calculated. It is the "Reduced residual value TEK17-X vs basis" that is used as input in the net present value calculation. This value has been discounted to the starting year in Table 15.

$$Residual\ value = \frac{Investment\ cost}{Component\ lifetime} \times (component\ lifetime - calculation\ period)$$

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Table 15 Calculation of residual value and difference in residual value between ZEB Lab Basis and TEK17-variants used for profitability calculations.

	Facades	Roof	Ground floor	Windows,60	Windows,40	Doors	Total
ZEB Lab Basis investment cost (€)	201 976	98 188	46 826	211 211	10 465	5 231	573 897
TEK 17 investment cost (€)	158 782	82 290	36 270	188 594	8 634	3 912	478 481
Component lifetime (years)	60	60	60	60	40	60	-
Calculation period (years)	20	20	20	20	20	20	-
Residual value, ZEB Lab Basis components	134 651	65 459	31 217	140 807	5 232	3 487	380 854
Residual value, TEK17 components	105 854	54 860	24 180	125 729	4 317	2 608	317 548
Residual value TEK17-1 (€)	134 651	54 860	31 217	125 729	4 317	2 608	353 383
Residual value TEK17-2 (€)	105 854	65 459	24 180	140 807	5 232	3 487	345 020
Residual value TEK17-3 (€)	105 854	54 860	31 217	125 729	4 317	2 608	324 586
Reduced residual value TEK17-1 vs basis (€)	-	-	-	-	-	-	**27 471**
Reduced residual value TEK17-2 vs basis (€)	-	-	-	-	-	-	**35 834**
Reduced residual value TEK17-3 vs basis (€)	-	-	-	-	-	-	**56 268**

Table 17 shows an example of calculation of net present value (NPV) with 4 % increase of future electricity prices. The residual value is discounted to the starting year but inserted in year 20 of the calculations. Similar calculations are also performed with 2 % and 6 % increase of future electricity prices. Results for all three price scenarios are summarized in Table 18.

Table 16 Calculation of net present value (NPV) for net energy need and delivered energy with 4 % increase in electricity price per year.

	Net energy need			Delivered energy			
Year	**TEK17-1 (€/year)**	**TEK17-2 (€/year)**	**TEK17-3 (€/year)**	**TEK17-1 (€/year)**	**TEK17-2 (€/year)**	**TEK17-3 (€/year)**	**4 % el. price increase (€/kWh)**
1	-2 723	-1 304	-3 738	-930	-446	-1 272	0.12
2	-2 723	-1 304	-3 738	-930	-446	-1 272	0.12
3	-2 723	-1 304	-3 738	-930	-446	-1 272	0.12
4	-2 723	-1 304	-3 738	-930	-446	-1 272	0.13
5	-2 723	-1 304	-3 738	-930	-446	-1 272	0.14
6	-2 723	-1 304	-3 738	-930	-446	-1 272	0.14
7	-2 723	-1 304	-3 738	-930	-446	-1 272	0.15
8	-2 723	-1 304	-3 738	-930	-446	-1 272	0.15
9	-2 723	-1 304	-3 738	-930	-446	-1 272	0.16
10	-2 723	-1 304	-3 738	-930	-446	-1 272	0.16
11	-2 723	-1 304	-3 738	-930	-446	-1 272	0.17
12	-2 723	-1 304	-3 738	-930	-446	-1 272	0.18
13	-2 723	-1 304	-3 738	-930	-446	-1 272	0.18
14	-2 723	-1 304	-3 738	-930	-446	-1 272	0.19
15	-2 723	-1 304	-3 738	-930	-446	-1 272	0.20
16	-2 723	-1 304	-3 738	-930	-446	-1 272	0.21
17	-2 723	-1 304	-3 738	-930	-446	-1 272	0.22
18	-2 723	-1 304	-3 738	-930	-446	-1 272	0.23

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19	-2 723	-1 304	-3 738	-930	-446	-1 272	0.23
20	-15 261	-17 658	-29 418	-13 468	-16 800	-26 952	0.24
NPV (€)	**-25 333**	**11 324**	**-15 582**	**10 519**	**28 480**	**33 738**	-

Table 18 shows results from profitability calculations using net present value (NPV) for different scenarios of future electricity price increase (2, 4 and 6 % per year). A positive net present value means the TEK17-variant is profitable, while a negative value means the variant is unprofitable compared to ZEB Lab Basis. The profitability of the TEK17-variants decreases with increasing electricity price.

Table 17 Results from profitability calculations for the TEK17-variants using net present value (NPV) for different scenarios of future electricity price increase (2, 4 and 6 % per year).

	Net energy need			**Delivered energy**		
	TEK17-1	**TEK17-2**	**TEK17-3**	**TEK17-1**	**TEK17-2**	**TEK17-3**
NPV with 2 % el. price increase (€)	-14 707	16 411	-995	14 150	30 220	38 702
NPV with 4 % el. price increase (€)	-25 333	11 324	-15 582	10 519	28 480	33 738
NPV with 6 % el. price increase (€)	-39 080	4 742	-34 454	5 822	26 229	27 316

Based on net energy need, TEK17-1 and TEK17-3 are not profitable compared to ZEB Lab Basis, regardless of the three future electricity price scenarios. For TEK17-3, the scenario with 2 % increase in electricity price is barely unprofitable compared to ZEB Lab Basis, while the others are quite unprofitable. If the electricity price will increase with 6 % annually, TEK17-1 and TEK17-3 are very unprofitable without an energy efficient heating system. TEK17-2 is profitable compared to ZEB Lab Basis. While the unprofitability for TEK17-1 and TEK17-3 were relatively similar for net energy need and 6 % el. price increase, TEK17-3 is significantly more profitable than TEK17-1 for delivered energy in the same price scenario.

For delivered energy, all the TEK17-variants are profitable for all three scenarios of electricity price increase. The profitability gradually decreases with increasing electricity prices and TEK17-1 is the least profitable. The investment cost of improving the building envelope to ZEB Lab design values from TEK17 minimum requirement for components are too high compared to the energy cost savings when evaluating based on delivered energy. Note that the profitability is found for delivered energy with an energy efficient heating system (system efficiency of 3), and the profitability would be higher for a better building envelope with a lower system efficiency (e.g. electric heating, which is commonly used in Norway). In addition, the domestic hot water need is set very low (1 kWh/m^2·year, instead of typically used 5 kWh/m^2·year from NS 3031:2014) and the leakage number for the building envelope is very low (0.3 ACH). ZEB Lab is a compact building with an energy efficient building design. For this specific project, the profitability of improving a relatively good building envelope (TEK17 standard) to a very good standard (ZEB COM) is evaluated. The potential for improving the energy efficiency is limited, and thus the investment costs have lower return value.

2.6 Main table of costs – ZEB Lab and reference building

For ZEB Lab a cost limit as a target cost is set. This cost is representing the available budget. The building is financed by the Research counsel of Norway, SINTEF, NTNU and Enova. The costs for the ZEB Lab cannot be compared directly to conventional wooden buildings since the building is designed for experimental use and research. To meet the demand for flexibility, parts of the building envelope, technical systems and inner walls are designed for easy reorganisation or replacement. The building is classified as a ZEB-COM building, with zero emission for the building including emissions from construction, operation and production of materials. A significant area of PV-panels on the roof and facades will harvest the energy needed to balance the energy used for construction, operation and production of materials over the buildings lifetime of 60 years.

Costs are described in terms of both gross total area (GTA), including the area of external walls (Norwegian: bruttoareal, BTA), and gross internal area (GIA) excluding the external walls (Norwegian: oppvarmet

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bruksareal, BRA). Energy calculations are performed based on GIA according to Norwegian building regulations (TEK17) [6].

The total budget costs of the building are divided into several categories and are shown in Table 19 alongside the costs per GIA and GTA. The table also portrays how much each category is represented in the total cost. As in the previous chapters, an exchange rate of 9.93 NOK/EUR has been used.

Table 18: Cost summary table for ZEB Lab according to NS 3453:2016 [20].

Account level	Cost elements	Costs (€)	Costs per GIA (€/m^2)	% of total cost limit	Costs per GTA (€/m^2)
1	Common costs	1 145 095	712	9	572
2	Building	2 915 739	1 812	22.8	1 457
3	HVAC installations	761 582	473	6	381
4	El-installations	377 516	235	3	189
5	IT and automation	376 424	234	2.9	188
6	Other installations, PV	506 631	315	4	253
	Building costs (sum 01-06)	**6 082 986**	**3 780**	**47.6**	**3 040**
7	Outdoors (including unspecified)	499 320	310	3.9	250
	Contractors costs (sum 01-07)	**6 582 306**	**4 091**	**51.6**	**3 289**
8	General costs (external)	1 724 926	1 072	13.5	862
	General costs (NTNU + SINTEF)	1 162 582	722	9.1	581
	Construction costs (sum 01-08)	**9 469 814**	**5 885**	**74.2**	**4 732**
9	Special costs	0	0	0	0
10	Value added taxes (VAT 25 %) for 01- 09	1 183 727	736	9.3	592
	Base costs (sum 01-10)	**10 653 541**	**6 621**	**83.4**	**5 324**
11	Expected additional costs (including VAT)	433 031	269	3.4	216
	Project costs (sum 01-11)	**11 086 572**	**6 890**	**86.8**	**5 540**
12	Risk provisions (including VAT)	1 359 517	845	10.6	679
	Cost limit (sum 01-12)	**12 446 089**	**7 735**	**97.5**	**6 220**
13	Price regulation (including VAT)	322 256	200	2.5	161
	Cost limit including price regulation (sum 01-13)	**12 768 345**	**7 935**	**100**	**6 381**

The construction cost before VAT is 5 885 €/m^2 GIA and 4 732 €/m^2 GTA. The total cost per square meter is 7 935 €/m^2 GIA and 6 381 €/m^2 GTA, including 25% VAT, risk provisions and price regulation. In Table 20 the total costs for a 5 000 m^2 steel and concrete office building with passive house standard is presented. This is considered a national statistic reference. The construction cost before VAT is 2 763 €/m^2 GTA. The total cost for this conventional building from Prisbok 2019 is 3 868 €/m^2 GTA including 25% VAT. This is a difference of 71% before VAT is included. Notice the cost from Prisbok 2019 is in GTA while ZEB Lab includes both GIA and GTA.

Table 19: Costs of a passive house office building, reference solution. Source: Prisbok 2019 [2].

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Account level	Cost elements	% of total cost limit	Costs per GTA (€/m^2)
1	Common costs	8.0	310
2	Building	31.7	1 225
3	HVAC installations	10.0	388
4	El-installations	6.6	256
5	IT and automation	3.4	133
6	Other installations, PV	2.6	101
	Building costs (sum 01-06)	**62.4**	**2 413**
7	Outdoors (including unspecified)	0.0	0
	Contractors costs (sum 01-07)	**62.4**	**2 413**
8	General costs	9.0	350
	Construction costs (sum 01-08)	**71.4**	**2 763**
9	Special costs	0.0	0
10	Value added taxes (VAT 25 %) for 01- 09	17.9	691
	Base costs (sum 01-10)	**89.3**	**3 453**
11	Expected additional costs (including VAT)	6.2	242
	Project costs (sum 01-11)	**95.5**	**3 695**
12	Risk provisions (including VAT)	4.5	173
	Cost limit (sum 01-12)	**100.0**	**3 868**
13	Price regulation (including VAT)	0.0	0
	Cost limit including price regulation (sum 01-13)	**100.0**	**3 868**

ZEB Lab is more expensive than the steel and concrete building for several reasons. Common costs are 85% higher and general costs comprising design, projecting and administration are 146% higher. These differences is most likely due to the lack of experience on planning large wooden office buildings in Norway. Other installations including PV is 150% higher. The main focus for the NERO project is reducing costs for wooden buildings. The cost for the building construction alone is 1 457 €/m^2 GTA for ZEB Lab and 1 225 €/m^2 GTA for the steel and concrete building. This is a difference of 19%.

Table 21 summarizes costs per GTA and % of total cost limit for the two buildings, as well as a the deviation in cost for ZEB Lab compared to the reference building.

Table 20 Comparison of costs for ZEB Lab and reference passive house office building.

Description		**ZEB Lab**		**Reference bldg.**		**Comparison**	
Account level	**Cost elements**	**Costs per GTA (€/m^2)**	**% of total cost limit**	**Costs per GTA (€/m^2)**	**% of total cost limit**	**Deviation for ZEB Lab per GTA**	**Deviation for ZEB Lab, % of total cost limit**
1	Common costs	572	9	310	8	85 %	13 %

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2	Building	1 457	22.8	1 225	31.7	19 %	-28 %
3	HVAC installations	381	6	388	10	-2 %	-40 %
4	El-installations	189	3	256	6.6	-26 %	-55 %
5	IT and automation	188	2.9	133	3.4	41 %	-15 %
6	Other installations, PV	253	4	101	2.6	150 %	54 %
	Building costs (sum 01-06)	**3 040**	**47.6**	**2 413**	**62.4**	**26 %**	**-24 %**
7	Outdoors (including unspecified)	250	3.9	0	0	-	-
	Contractors costs (sum 01-07)	**3 289**	**51.6**	**2 413**	**62.4**	**36 %**	**-17 %**
8	General costs (external)	862	13.5	350	9	146 %	50 %
	General costs (NTNU + SINTEF)	581	9.1	-	-	-	-
	Construction costs (sum 01-08)	**4 732**	**74.2**	**2 763**	**71.4**	**71 %**	**4 %**
9	Special costs	0	0	0	0	-	-
10	Value added taxes (VAT 25 %) for 01- 09	592	9.3	691	17.9	-14 %	-48 %
	Base costs (sum 01-10)	**5 324**	**83.4**	**3 453**	**89.3**	**54 %**	**-7 %**
11	Expected additional costs (including VAT)	216	3.4	242	6.2	-11 %	-45 %
	Project costs (sum 01-11)	**5 540**	**86.8**	**3 695**	**95.5**	**50 %**	**-9 %**
12	Risk provisions (including VAT)	679	10.6	173	4.5	292 %	136 %
	Cost limit (sum 01-12)	**6 220**	**97.5**	**3 868**	**100**	**61 %**	**-3 %**
13	Price regulation (including VAT)	161	2.5	0	0	-	-
	Cost limit including price regulation (sum 01-13)	**6 381**	**100**	**3 868**	**100**	**65 %**	**-**

2.7 Conclusions

With regards to energy efficiency and reduction of greenhouse gas emissions, improving the building envelope from TEK17 requirements to ZEB Lab Basis level is a robust solution, reaching zero emissions after 60 years. Whether this is profitable or not on a 20-year perspective, is found to depend on the energy efficiency of the heating system. The profitability analysis based on delivered energy showed that with an energy efficient heating system, it was not profitable upgrading the TEK17-variants to the ZEB Lab level. However, the analysis based on net energy need (without an efficient heating system) showed that the ZEB Lab design was profitable for most cases.

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When comparing the additional investment cost of improving the TEK17-variants to ZEB Lab Basis (ca. 40 000-85 000 €), this only amounts to 0.3-0.6 % of the total investment costs of the building. In order to reduce the consequences of increased energy prices in the future, energy efficiency can be a good investment.

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