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1. Synopsis – Methodology

1.1 Introduction

Work presented in this technical report was developed as a port of Horizon 2020 EU project REFURB. The number of deep energy retrofits is falling behind the EU ambitious targets. The REFURB project aims at finding technical and nontechnical solutions that would match demand and supply side of the residential building renovation market. Due to the multiple significant differences at the national level, compelling offers were developed specifically for each country participant. This report elaborates only on Danish approach, as stated in [1], the Danish approach to create compelling offers for pre-selected homeowner target groups was based on (I) selection of dwelling segment with high impact and energy saving potential. (II)Sequenced approach in creating package solutions. (III)Compelling offer to be proposed with specific timing. This report focuses mainly on the second listed component, namely, development of renovation package solutions.

This report presents methodology to develop cost efficient renovation packages tailored for the single family housing sector. The work frame of the developed methodology presented in this report is based on the 5 main “Parts” included in the Table of content.

Firstly, general summary of the method is presented. Each “Part” and sub-activity in each “Part” is shortly described. Afterwards, method is applied on the case family house that was constructed in Denmark in 70’s. Firstly, theoretical energy saving calculations and initial renovation packages are developed. Secondly, technical solutions to renovate case house to NZEB are proposed and described. Thirdly, price calculations of the proposed solutions are performed for the case house example. For the fourth, cost efficiencies, including life time expectancy of each technology are calculated for different energy improvements of the case house. Finally, in the last part, as an example, 5 renovation packages are developed indicating what improvements are possible for the budget varying between 200.000 DKK and 1.000.000 DKK.

1.2 Part 1 – Theoretical energy saving calculation and initial renovation packages development

In the 1st Part of the report are performed theoretical energy saving calculations using Danish national compliance tool Be15. Single energy improvements are applied at first in order to indicate how total energy is sensitive to once at a time change. In the first place, components of the envelope are improved. Secondly, different improvements were proposed to ventilation and heating system. Consequently, improvements are collected in some initial renovation packages gradually increasing the depth of the renovation scope aiming towards nZEB.

1.2.1 Methodology

Energy saving results for developed renovation packages presented in this report are based on theoretical calculations performed in the national compliance tool. In Denmark this tool is called Be15. Other European countries have their own equivalent compliance tools that take into account local building regulations and demands.

1.2.2 Identification of the building types to be energy renovated

In this chapter are collected information about the topology of the building type to be renovated, construction specification, mechanical systems and their efficiencies.

1.2.3 Identification of energy improvement of building envelope

In this section are presented envelope elements, such as, walls, windows, floors and roof with respect to their insulation properties before and after energy improvement. The energy renovation goal of the building envelope elements corresponds to low energy building class 1 according to Danish BR15 which for Danish condition and renovation work could be considered as equivalent to nZEB definition.

1.2.4 Identification of the installation improvement possibilities

In this section are studied different energy improvements to the:

- Ventilation of the building
- Heating source in the building

1.2.5 Gradual development of initial renovation packages

Development of the combined initial renovation packages is split into 3 stages. Their complexity is developed gradually, starting with only envelope improvements, continuing with envelope and system improvements and finishing with the envelope and system improvements combined with on-site electricity production from solar cells.

- Initial renovation packages; envelope improvement
- Initial renovation packages; envelope and installation improvement
- Initial renovation packages; envelope, installation improvement and on site el. production

1.3 Part 2 – Technical solutions to renovate to nZEB

In the 2nd Part of the report are presented real technical solutions to energy renovate building type under consideration. Very often more than one solution is described. These solutions are:

- Technical solutions to envelope
- Technical solutions to installation
- Technical solution to renewable energy production

To better illustrate proposed technical solutions, drawings, pictures and schematics are included in the technical description.

1.4 Part 3 – Technical solution price calculation

In the 3rd Part technical solutions presented in the 2nd Part are given prices. Using national price database dedicated to renovation building works each activity and technical improvement has its price calculated. Additionally, price discount related to work quantity is performed. Presented prices are total netto prices that correspond to contractors bidding offers.

1.5 Part 4 – Cost efficiency

In the 4th Part, technical and price calculations prepared in Part 2 and 3 are supplemented with renovated element life time expectancy and possible national subsidies to execute work. The result is cost efficiency of each of the proposed energy saving measures. Cast efficiency is calculated as kWh of saved energy divided by year and m^2 of the heated floor area of the building.

1.6 Part 5 – Final renovation packages examples development

In the last 5th Part are developed final examples of renovation packages taking into account cost efficiency of the measures and cost priority of the activities included in the renovation package. Based on previous renovation project experiences, renovation packages, as an example, are ranging from 200.000 DKK for shallow energy renovation (30% energy saving) towards 1.000.000 DKK for deeper energy renovations (60-70% energy saving).

2. Part 1 - Theoretical energy saving calculation and initial renovation packages development

2.1 Introduction

Energy calculations, further described in this report, are performed on a single family detached house. The building has been part of renovation project – 'EnergiParcel - ny energi til dit hus', together with 3 other typical Danish single family houses. This house is chosen:

1) Due to being part of the afore mentioned project, many of the technical specifications of construction elements and systems before renovation of the house are known.

2) The house is constructed in the period of 1960-1976, which falls in a category of Danish houses with high possibility for improvement (typically energy class from G to C) as well as high number of houses build in the given period.

The reference house is a detached single family house with area of 136 m^2 (approximately 19 x 7,15m). The house is built in 1973 and consist of four rooms, living room, kitchen, entrance, bathroom, toilet, corridor and utility room. Room distribution and orientation of the house can be seen in Figure 1.

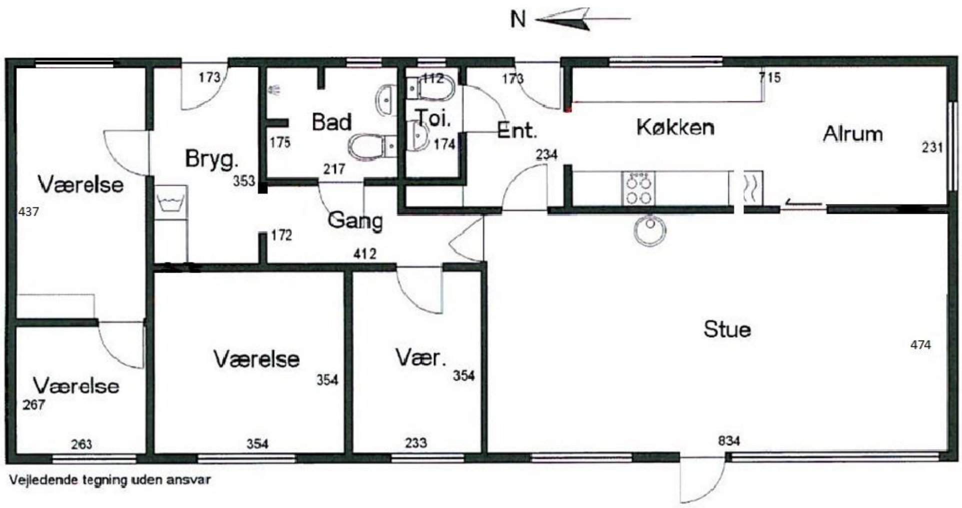

Figure 1. Floor plan and orientation of single family house at Langøvægnet 1.

Energy calculations for buildings in Denmark are performed with the calculation tool BE15. The tool takes into consideration the construction of the building envelope (construction elements, line losses), systems in the building (ventilation, lighting(not in residential buildings), mechanical cooling, heat distribution, domestic hot water, pumps and other electrical equipment) and energy supply (boilers, district heating, solar heating, heat pumps, PV cells, windmills and other room heating). When a building is defined, the calculation tool provides yearly and monthly information on the energy demand for the building.

In terms of energy requirement for domestic buildings, Building Regulations 2015 distinguishes between new and existing buildings in the following way:

- New residential buildings class 2015 - must not exceed 30 kWh/m^2 per year + 1000 kWh divided by the floor area.
- New residential buildings class 2020 - must not exceed 20 kWh/m^2 per year.
- Renovation class 2 – must not exceed 110 kWh/m^2 per year + 3200 kWh per year divided by heated floor area.
- Renovation class 1 – 52,5 kWh/m^2 per year plus 1650 kWh per year divided by heated floor area.

Included in those numbers is the energy needed for heating, cooling, ventilation and domestic hot water. For the purposes of this project renovation of existing building to nearly Zero Energy Building (nZEB) is considered building fulfilling Renovation Class 1.

2.2 Energy frame calculations

Starting point of the study is to investigate the energy saving potential of individual improvements of construction elements, installations and heat supply. This is done with aim to find out which of the building parts have the largest energy saving potential.

2.3 Construction improvements

Renovation of the construction elements is achieved by lowering the U-value of a given element to the minimum value stated in the Danish Building Regulations 2015 (BR15 – see last column in Table 1). In the initial study it is assumed that it is possible to reach the minimum U-value of the elements in reality, thus not taking into consideration any restrictions that may limit the possibility of renovating a given element to that extend. Overview of the investigated elements, their area and measured insulation values (before renovation) are shown in Table 2.

Table 1. General information of construction elements

Case Nr.	Construction element	Area [m^2]	Percent of envelope area [%]	Existing U-value* [$W/m^2.K$]	Minimum BR15 U-value requirement [$W/m^2.K$]*
1	External wall	87,5	22,97	0,42*	0,18*
	External wall – light	4	1	1,7*	
2	Roof	128	33,61	1,8*	0,12*
3	Ground floor	19,3	5,07	0,44*	0,10*
4	Crawl floor	103,2	27,10	0,38-1,8*	
5-7	Windows / Doors	29,7	7,8	2,8*	E_{ref} -17 [$kWh/m^2/year$]
8	Air tightness	-	-	0,32 [$l/s/m^2$]	0,24 [$l/s/m^2$]
9	Line loss around foundations	50,8 m	-	0,2 [W/m.K]	0,12 [W/m.K]

When calculating the possible achieved contribution to energy savings from changing all windows, 3 cases are investigated. The cases correspond to low-energy triple glazed windows (case 5), standard double glazed windows type I (case 6), and standard double glazed window type II (case 7). Overview of the three window types, used in the calculation are shown in Table 2.

Table 2. Windows properties that were used in the calculation tool BE15

Case Nr.	Window type	U_{window} [$W/m^2.K$]	Solar Transmittance g	Light Transmittance	Energy Gain - E_{ref} [$kWh/m^2/year$]
5	Low-Energy, 3-layers glass	0,79	0,53	0,74	32,71
6	Standard, 2-layers glass	1,29	0,64	0,82	9,13
7	Standard, 2 layers glass	1,32	0,63	0,80	4,46

Results, obtained by improving single construction element at a time are shown in Figure 2. The figure shows both the energy requirement of the reference case (prior renovation – case 0) and cases presented in Table 1 and Table 2. Right hand side of Figure 2 shows percent reduced energy for each case with respect to the reference case, which has energy demand of 222,8 kWh/m^2 per year. As it can be observed, more than 10 % reduction achieve the 3 cases with different windows, followed by cases where the crawl floor and external walls with a bit more than 8%.

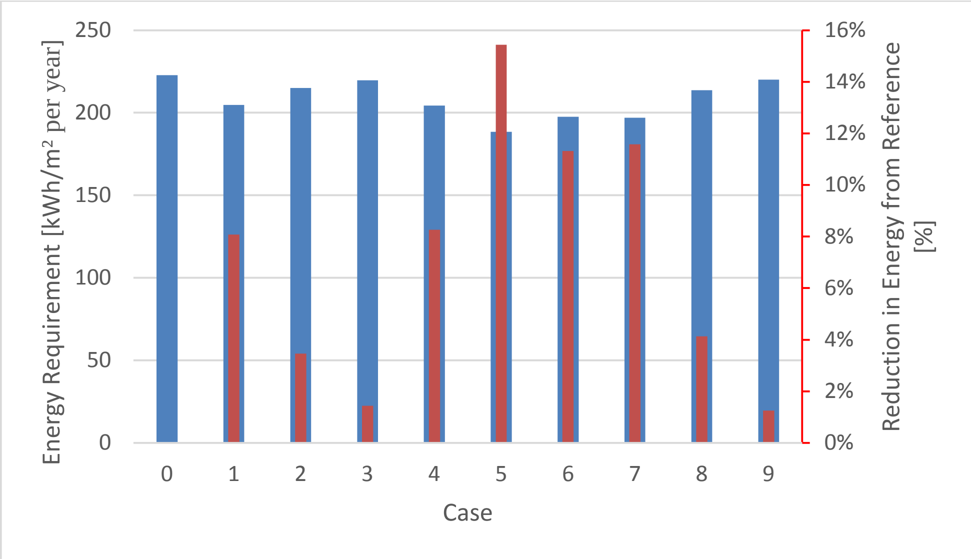

Figure 2. Energy requirement by renovation of single construction element. Case numbers on the x-axis correspond to Table 1

2.4 Installations improvements

Installation improvements include addition of mechanical ventilation to the building. As the energy saving potential with regards to mechanical ventilation is highly depended on the air tightness of the building and the ventilation strategy, the investigations are focused on 3 different levels of air tightness, for each of which, 3 ventilation strategies are applied. Overview of the applied infiltration levels and ventilation strategies are shown in Table 3.

Infiltration levels in cases 10-15 are set to 0,34 $l/s/m^2$ and 0,24 $l/s/m^2$, which are measured values before and after the actual renovation of the building respectively. The third infiltration level, (0,13 $l/s/m^2$) is standard minimum value, suggested in the operational manual of the program for calculation during operational hours of the building [2].

For each infiltration level, the following three cases of ventilation strategies are applied:

- Natural ventilation throughout the whole year.
- Natural ventilation throughout summer and mechanical ventilation during winter.
- Mechanical ventilation during both summer and winter time.

In cases where mechanical ventilation is applied, it is assumed that the ventilation unit can provide 85% heat recovery and specific fan power (SFP) is equal to 0,9 kJ/m^3. No additional heating plates for the mechanical ventilation unit have been specified in any of the investigated cases. Overview of the variated parameters in terms of infiltration, natural and mechanical ventilation are given in Table 3.

Table 3. Investigated cases of energy saving potential in case where mechanical ventilation is installed.

Case Nr.	Infiltration level [l/s/m^2]	Natural Ventilation [l/s/m^2]	Mechanical ventilation [l/s/m^2]
10	0,34	Summer = 1,2 / Winter = 0,3	Summer = 0 / Winter = 0
11		Summer = 1,2 / Winter = 0	Summer = 0 / Winter = 0,3

12		Summer = 0 / Winter = 0	Summer = 0,3 / Winter = 0,3
13	0,24	Summer = 1,2 / Winter = 0,3	Summer = 0 / Winter = 0
14		Summer = 1,2 / Winter = 0	Summer = 0 / Winter = 0,3
15		Summer = 0 / Winter = 0	Summer = 0,3 / Winter = 0,3
16	0,13	Summer = 1,2 / Winter = 0,3	Summer = 0 / Winter = 0
17		Summer = 1,2 / Winter = 0	Summer = 0 / Winter = 0,3
18		Summer = 0 / Winter = 0	Summer = 0,3 / Winter = 0,3

Figure 3 presents the results for cases presented in Table 3. The results show that improvement of energy use by different ventilation strategies occurs only for cases 14, 17 and 18. The improvement of energy use in case 14 is minimal (0,3% from reference case). The savings in this case are result of: 1) Mechanical ventilation running only in winter; 2) Lower infiltration value than the minimum ventilation requirement during winter; 3) Heat recovered by the mechanical ventilation during winter. The same reasoning is valid for cases 17 and 18, where the effect of lower infiltration becomes apparent, as the energy savings for the same ventilation strategies are 2-5 times better. Case 17 provides the greatest reduction of almost 6%, when compared to the reference case as the mechanical ventilation unit runs only during winter time.

Thus improvement in energy use by installing mechanical ventilation, prior any other energy saving measure (construction improvements for example) can be expected only if the infiltration of the building is low to begin with and natural ventilation is integrated during the summer months of the year.

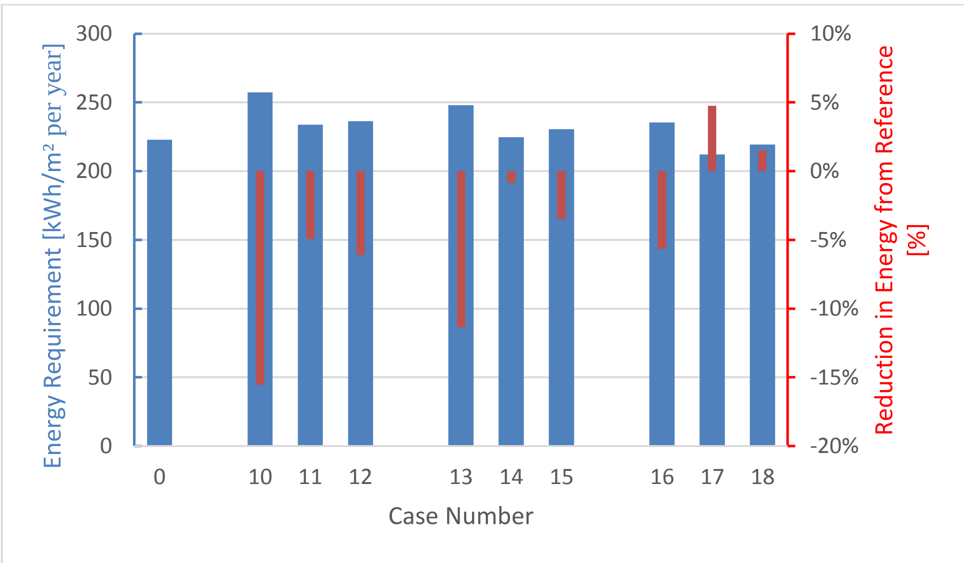

Figure 3. Energy requirement for cases with/without mechanical ventilation at different infiltration levels. Case numbers on the x-axis correspond to Table 3.

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2.5 Change of heat supply for the building

The heat source of the reference case is oil boiler with efficiency of 94%, which leads to the assumption that it has been changed prior renovation of the house. As this would not be the case in all of the houses from that period, the first step is to investigate what is the effect of changing old oil boiler to a new one. This is done by changing the efficiency of the boiler. Other types of heat supply compared to the reference case are district heating, gas boiler and three configurations of heat pump. All cases and general parameters describing each one are shown in Table 4.

Table 4. Investigated cases for heat supply

Case Nr.	Heat supply	Parameters
0	Relatively new oil boiler	Efficiency - 94%
19	Old oil boiler	Efficiency - 65%
20	District heating	Room heating only
21	Heat pump – room heating only	Air –Water Room heating COP 3.6
22	Heat pump – combined room and hot water heating	Air-Water Heat Pump Room heating COP – 4.2 DHW COP – 3.1
23	Heat pump – combined room and hot water heating integrated with solar heat	Air-Water Heat Pump Room heating COP – 4.2 DHW COP – 3.1 Solar Panels – 5 m^2
24	Gas Boiler – room and domestic hot water production	Efficiency – 98%

Results obtained by changing the heat supply from the reference model are presented in Figure 4. Comparison between the reference case and case 19 suggest that more than 30% of energy can be saved by replacing old, inefficient oil boiler with newer one.

If the location of the house allows connection to district heating, the results suggest that reduction of approximately 10% can be expected by changing the heat supply from new oil boiler to district heat.

When comparing the reference case and a case where heat pump for room heating is installed (case 21), Figure 5 shows increase in energy requirement with 11%. In that case domestic hot water is produced by electric boiler. The other two cases, where the heat pump is used for both room heating and production of domestic hot water (case 22), and further connected to supplementary heat from solar collectors (case 23), the energy demand of the house is reduced by 31% and 33% respectively. The savings can be associated with eliminating separate boiler for domestic hot water and higher COP's of the combined heat pump, both in terms of room heat and domestic hot water.

In the case of gas boiler heating (case 24), the observed savings of approximately 13% can be traced back to the higher efficiency of the gas boiler, compared to relatively new oil boiler as it is in the reference case.

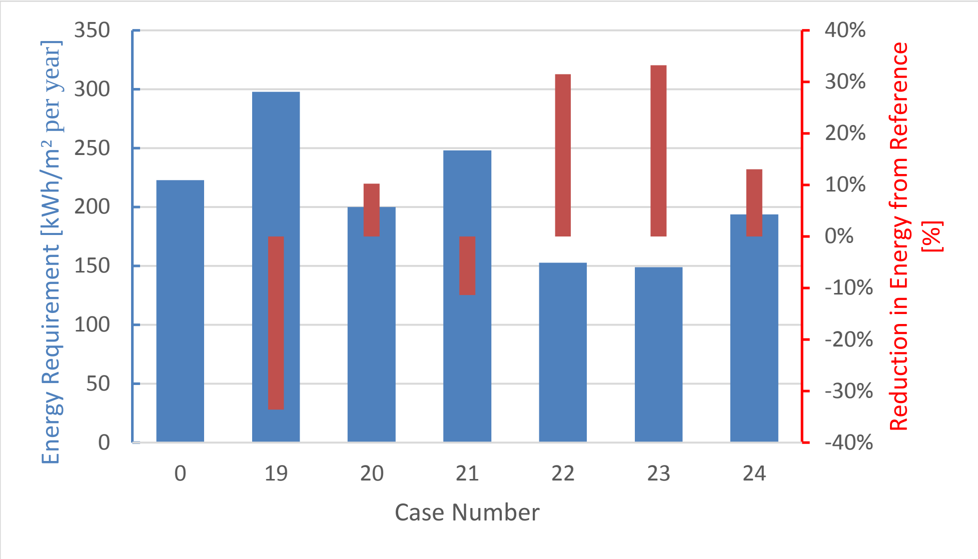


Figure 4. Energy requirement for different sources for heat supply. Case numbers on the x-axis correspond to Table 4.

2.6 Conclusive remarks for single element and installation improvements

All 24 presented cases so far consist of improvement of single element, installation or change of heat supply. As presented in Figure 3, some construction element improvements provide larger energy reduction than others. Never the less all cases do provide positive effect (lower energy demand of the building compared to the reference). Naturally, construction elements with larger share of the total envelope area (e.g. external wall - 23%, crawl floor - 27%) have big impact on the final energy demand of the building. Although the share of envelope is only one of the deciding factors in how much improvement of certain element would reduce the energy need. As described earlier in this report the U-value of an element is also of high importance. This is clearly illustrated by the cases investigating different windows. Despite windows being only approximately 8% of the envelope area those are the cases providing the most energy savings in the investigated cases. Furthermore, it could be very demanding or even not always possible, to improve construction element as external wall or floor to reach the desired U-value.

The results with regards to addition of mechanical ventilation, presented in Figure 3, show that in cases where infiltration trough the construction elements is high addition of mechanical ventilation results in higher energy use of the building. This is due to the extra energy for the fans in the ventilation unit. In cases where the building is air tight and appropriate ventilation strategy is in place energy savings of up to 6% can be achieved. This saving is obtained because of the fact that big amount of the already accumulated heat in the house is reused due to heat recovery of the ventilation unit.

All investigated cases regarding heat supply, that are presented in Figure 4, exhibit more than 10% difference in energy use compared to the reference case. Thus it can be concluded that having appropriate heat supply is crucial for a building to cover Be15 or nZEB demands. Results from Figure 4 suggest that newer, high efficiency (>90%) boilers and combined heat pumps for heating of rooms and domestic hot water (with or without supplementary solar heat) provide good energy saving opportunities. To secure choice of appropriate heating solution, selection and dimensioning of the heat supply equipment has to be planned carefully, considering possible renovations of the building. This could ensure that the system is not: 1) over-dimensioned, which could bring financial saving to the building owner; 2) under-dimensioned, which could bring discomfort.

2.7 Renovation packages

The following section describes investigation of package solutions consisting of combination of previously described single case solutions. The combination of different cases is performed in three main steps:

1. Combination of previously described construction elements into package solutions.
2. Five of the package solutions are further equipped with mechanical ventilation.
3. Keeping mechanical ventilation, 4 additional heat supply options are compared for each package.

Step 1

Table 5 shows overview of combinations of 'renovated' construction elements in step 1. Each construction element is improved to the same level as described earlier in this report. Dotted red lines in Table 5 indicate the five cases, which are further equipped with mechanical ventilation in step 2. The same five cases including mechanical ventilation are subjected to different heat supply options in step 3.

The five outlined cases in Table 5 are chosen to represent different levels of renovation, going from shallow renovation to deep, based on the representative area of the envelope. In increasing order, the chosen cases represent 23, 57, 64, 97 and 100% of the envelope, for cases 1, 6, 11, 14 and 15 respectively.

Table 5. Renovation package solutions

Package Number	External wall	Roof	Ground floor	Crawl floor	Windows	Air tightness	Line loss
1	✓					✓	✓
2	✓						✓
3	✓				✓		✓
4	✓	✓					✓
5	✓	✓			✓		
6	✓	✓				✓	✓
7		✓			✓		
8		✓		✓			
9	✓			✓			✓
10	✓	✓			✓		
11	✓	✓			✓	✓	✓
12			✓	✓			✓
13	✓	✓	✓	✓			✓
14	✓	✓	✓	✓	✓	✓	✓
15	Package 14 + 50% improvement of all other construction elements (13.5 m^2)						

Results obtained for all renovation packages described by Table 5 are shown in Figure 5. Case number on x axis corresponds to package number from Table 5. Figure 6 shows energy requirement for all investigated cases, the reference case, as well as reduction of energy in percent from the reference case.

In general, all cases including windows replacement achieve the highest energy savings. Excluding those cases energy savings increase with increase of the number of improved elements. It is clear that even if all of the building envelope is renovated so that each construction element fulfills BR15 requirements, it is still not enough to reach the energy frame set in the building regulations. Therefore, combination of renovation of construction elements and mechanical systems is necessary in order for a building to become nZEB. This is further investigated in the following two steps:

Figure 5. Energy requirement for different renovation packages. Case numbers on x-axis correspond to Table 5.

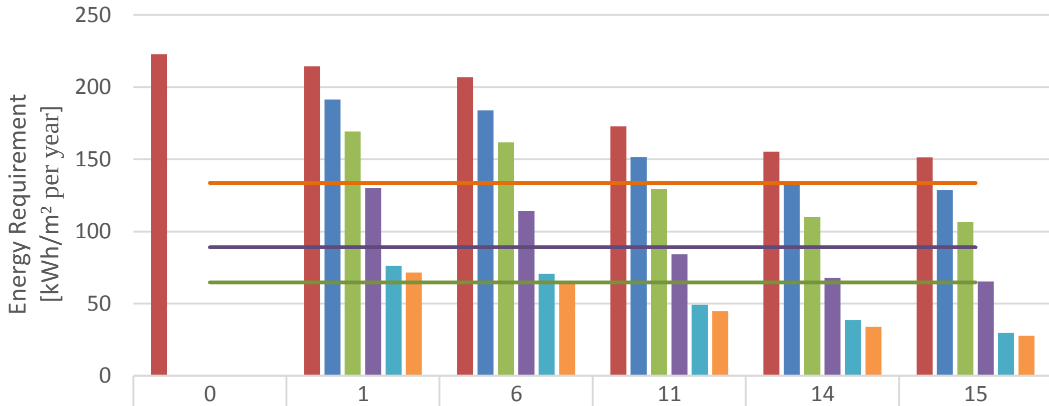
Step 2

In step 2 mechanical ventilation is added to 5 of the cases outlined by red dashed line in Table 5. The applied ventilation strategy is natural ventilation during the summer months and mechanical during the winter period. The ventilation rate in all cases is set to 0.3 $l/s/m^2$, which is the minimum required ventilation rate stated in the Danish Building Regulations. The infiltration rate is also set to the minimum value, as investigated in section 1.1.4 (Installation improvements). This assumption is made, based on the reasoning that cracks in walls and connections between construction elements are filled during improvement of the U-value of the external wall.

Step 3

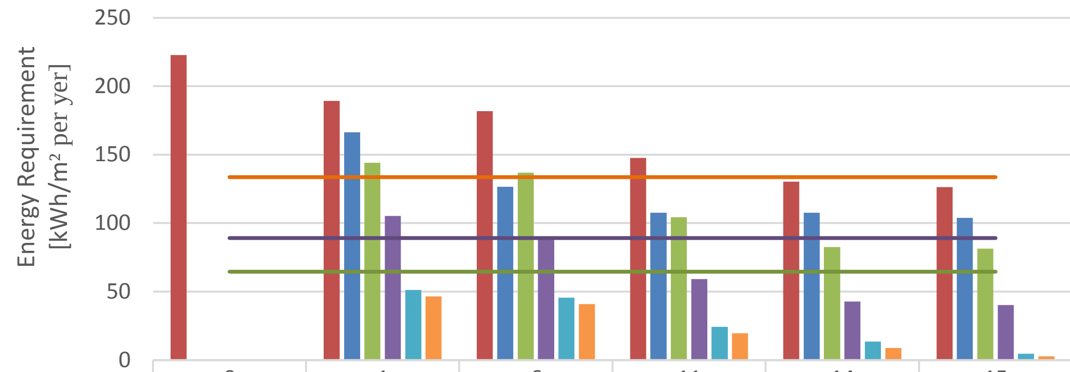
Starting point of step 3 are cases with mechanical ventilation that are also highlighted with red dashed line in Table 5. Key parameters of each applied heat source is previously introduced in Table 4. The investigation of each case is taken a step further by applying 11,25 m^2 of photovoltaic panels.

The results from the investigated cases are shown in Figure 7 and Figure 8, respectively for scenarios without and with photovoltaic panels. Packages achieving 40 and 60% energy reduction, with respect to the reference case are indicated by orange and purple color in the figures. Packages achieving nZEB, which in the investigated house corresponds to 71% energy reduction, are indicated with green color. As stated previously, nZEB definition is achieved when the energy demand of the building obtains values corresponding to renovation class 1. In Danish Building Regulation 2015, renovation class 1 is achieved when the total energy requirement of the renovated detached house for heating, cooling and domestic hot water does not exceed 52,5 kWh/m^2 per year plus 1650kWh per year divided by the heated floor area. As the heated floor area of the reference building is 136,2m^2, the requirement is met when the energy requirement is lower or equal to 64,61 kWh/m^2 per year.



Package Number	0	1	6	11	14	15
Without mechanical ventilation	222,80	214,40	206,80	172,70	155,40	151,30
With mechanical ventilation		191,30	183,80	151,50	132,50	128,80
District heat		169,20	161,80	129,40	110,20	106,60
Heat Pump - room heat		130,20	114,20	84,10	67,80	65,30
Heat pump - combined		76,30	70,60	49,30	38,50	29,70
Comb. Heat Pump + Solar Heat		71,50	65,80	44,70	33,90	27,80
40% Reduction	133,68	133,68	133,68	133,68	133,68	133,68
60% Reduction	89,12	89,12	89,12	89,12	89,12	89,12
nZEB (Renovation class 1)	64,61	64,61	64,61	64,61	64,61	64,61

Figure 6. Energy requirement for different renovation packages with/without mechanical ventilation and different heat source. Package number corresponds to Table 5.



	0	1	6	11	14	15
Without mechanical ventilation	222,80	189,40	181,80	147,70	130,40	126,30
With Mechanical Ventilation		166,30	126,50	107,50	107,50	103,80
District heat		144,20	136,80	104,40	82,50	81,40
Heat Pump - room heat		105,20	89,20	59,10	42,80	40,30
Heat pump - combined		51,30	45,60	24,30	13,50	4,70
Comb. Heat Pump + Solar Heat		46,50	40,80	19,70	8,90	2,80
40% Reduction	133,68	133,68	133,68	133,68	133,68	133,68
60% Reduction	89,12	89,12	89,12	89,12	89,12	89,12
nZEB (Renovation class 1)	64,61	64,61	64,61	64,61	64,61	64,61

Package Number

Figure 7. Energy requirement for different renovation packages with/without mechanical ventilation and different heat source including 11.25m² of photovoltaic panels. Package number corresponds to Table 5.

For cases excluding photovoltaic panels (Figure 6) the total number of packages achieving 40% energy reduction demand is 7. All of those cases include mechanical ventilation, where the two cases with 97 % and 100% of renovated envelope area (14 and 15) achieve 40% reduction with relatively new oil boiler. The same energy reduction can be achieved if district heating, mechanical ventilation and 64% or higher part of the envelope is renovated (Packages 11, 14 and 15 respectively). Mechanical ventilation and heat pump for room heating together, can also provide 40% energy reduction when combined with renovation of either 23 or 57% of the envelope area (package numbers 1 and 6).

Package 1 achieves 60% energy reduction when combined with heat pump for room heating and domestic hot water production, weather it is combined with solar heat collectors or not. For package number 6, where 57% of the envelope is improved, the combination of heat pump and solar collectors also provides enough energy reduction for the building to reach 60% energy reduction. Packages with higher percentage of renovated building envelope and combined heat pump (heat and DHW) provide enough reduction for classifying the building as nZEB, with and without solar collectors. The only case where heat pump for room heating obtains energy reduction to nZEB is when the envelope is fully renovated.

All packages, equipped with 11.25 m^2 photovoltaic panels (Figure 7) have energy requirement of 25kWh/m^2 per year lower than those without photovoltaic panels. This is also the maximum electricity production from renewable energy sources that can be taken into account in the compliance energy performance calculation for all types of buildings, regardless if the system can produce more electricity. A simple study in the compliance calculation tool Be15, showed that with the given area of photovoltaic panels, orientation and system efficiency does not affect the total energy frame of the building.

The reduction of energy demand due to on-site electricity production allows 13 of the investigated packages to reach nZEB requirement. For two of those cases it is possible to obtain nZEB classification by renovating the external walls only (in case the heat supply is combined heat pump - with and without solar heat collectors). Reduction of 60% in energy can be reached given that the heat supply is district heat and 97 or 100% of the envelope area is renovated to fit minimum insulation requirements set by building regulations 2015.

3 Part 2 - Technical solutions to renovate to nZEB

In the Danish condition it was concluded that one-family buildings, called "parcel houses", that were built in years 1960 to 1976 are the first one to start developing renovation packages for. The reasons for that are:

- they represent very large share of residential houses(approximately 30%).
- they are usually built in good locations.
- they are in the age when the first major renovation might be required and comparing to present building standards they perform rather poor with regards to energy use and indoor climate.

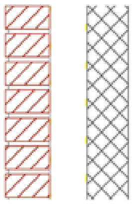
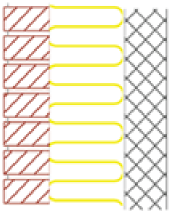
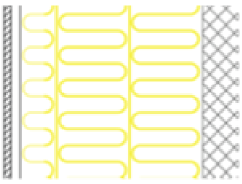
These houses would be very often owned by Empty Nesters (EN) or would be considered as potential house to buy as the first house for Young Families (YF).

3.1 Construction improvements

Constructions that are described in this chapter are: external wall, roof, floor on the ground, floor above crawl basement, windows, foundation and footing. Each considered in this chapter construction element has potential for energy improvement. The measure of thermal insulation property of construction element is given by its U-value. The lower the U – value is the better construction insulates from heat losses. To give an example of U-value range, a poorly insulated, good insulated and excellent insulated external wall is described, see

Table 6.

Table 6. Example of poorly, well and excellent insulated external wall.

		Material	Thickness	U value [W/m^2K]
Poorly insulated		Light concrete	10 cm	1,5
		Air cavity	8-10 cm	
		Masive brick	10 cm	
Good insulated		Light concrete	10 cm	0,16
		Insulation	20 cm	
		Masive brick	10 cm	
Excellent insulated		Light concrete	10 cm	0,08
		Insulation	50 cm	
		Facade solution	2 cm	

:

Houses constructed between 1960 and 1976 are the one that were constructed according to the first Building Regulation in Denmark. Thanks to that fact, generic expectation to the most of the construction elements can be assumed with very satisfactory approximation. In Table 7 are collected typical insulation properties of the construction element in the "parcel houses" from that period and they are compared with minimum demand for insulation for renovation according to the recent Building Regulation from 2015.

Table 7. Comparison of construction U values and line losses between 1960-76 period and BR15.

	1960-1976	BR 2015

Construction type	U value [W/m²K]	U value [W/m²K]
Heavy external wall	0,42	0,18
Light external wall	0,49	0,18
Roof	0,39	0,12
Basement wall against ground	0,3	0,18
Floor on the ground	0,3	0,1

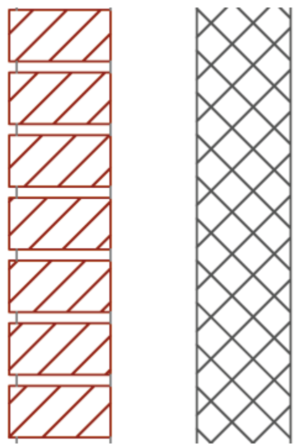
	1960-1976	**BR 2015**
Line losses	ψ	ψ
	[W/(mK)]	[W/(mK)]
Heavy walls and Foundation	0,66	0,12
Heavy walls and Foundation	0,44	0,12
Heavy walls and windows/doors	0,11	0,03
Light walls and widows/doors	0,3	0,03

The difference between present expectations for thermal insulation and standard values used in 60's and 70's is significant and there is obvious potential for energy renovation and at the same time thermal comfort improvement.

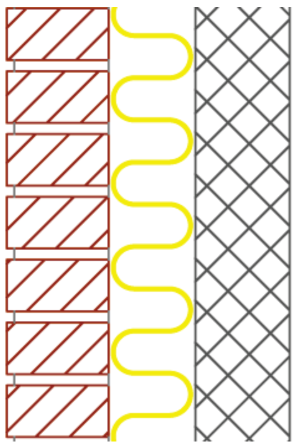
3.1.1 External heavy wall

In the period 1960-1976 external heavy walls were constructed either as cavity walls with insulation or as cavity walls with air gap, see Figure 8. The wall usually consists of 3 layers, internal layer is light concrete, in the middle is cavity with air or insulation and the external layer is made of bricks. **U –value for such external wall is approximately 0,46 W/m²K if cavity is insulated and if not approximately 1.5 W/m²K.**

If wall is constructed as air cavity then usually the first choice to improve insulation properties of the wall is to insulate the cavity by injecting granulated mineral wool or paper as presented in Figure 10.



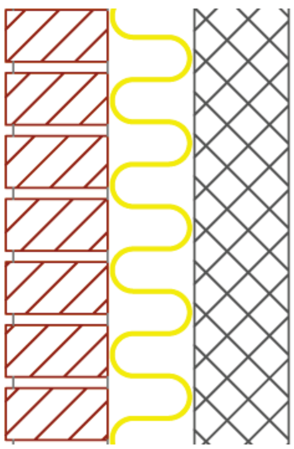
- 110 mm gas concrete
- 70 mm air cavity
- 108 mm massiv brick
Calculated U value 1,48 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,18 W/m²K additional insulation has to be added.



- 110 mm gas concrete
- 70 mm old mineral wool
- 108 mm massiv brick
Calculated U value 0,49 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,18 W/m²K additional insulation has to be added.

Figure 8. Cavity not insulated (top) and insulated (bottom), typical heavy wall construction in 1960 – 1976

If wall is already insulated then cavity insulation is still possible but process is more difficult and costly simply because old and of poor quality insulation has to be firstly removed to make space for new insulation . If wall is cavity insulated in the process of energy renovation then its aesthetics are not changed, it means no visible changes could be observed but U value could be assumed better than if wall was insulated in 60s or 70s. The better (lower) U value is obtained due to the fact that insulation properties were improved over recent years and thus recently insulated cavity wall will have better thermal properties. However, only cavity insulation is not sufficient (U value 0,43) , see Figure 9, to fulfill minimum insulation properties for external wall energy renovation according to Building Regulation 2015. Nevertheless, this technic is still allowed and broadly used and it is considered as economically reasonable.



- 110 mm gas concrete
- 70 mm granualted mineralwool
- 108 mm massiv brick
Calculated U value 0,43 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,18 W/m²K additional insulation has to be added.

Figure 9. Cavity insulated wall construction with injected granulated insulation.

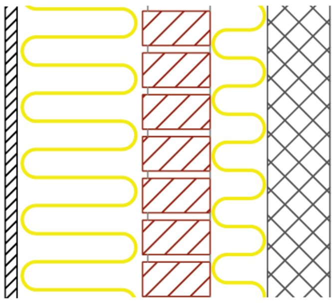
Figure 10. Cavity wall injection (left), view in the insulated cavity wall (right).

Technical solutions to renovate to nZEB

This chapter presents technical renovation solutions that fulfill recommendation for insulation of building construction elements according to Building Regulation 2015.

Cavity insulation + external insulation + mortar finish

In order to fulfill insulation properties for external wall energy renovation according to Building Regulation 2015 other insulating activities have to be considered. One solution could be to apply minimum 150 mm additional insulation on the external side of the wall as presented in Figure 11 and then finish façade with fiber mortar on the reinforcing net. Wall can be then painted to any color.



- 110 mm gas concrete
- 70 mm granualted mineralwool
- 108 mm massiv brick
- 150 mm mineral wool
- < 1 cm fiber facade mortar
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

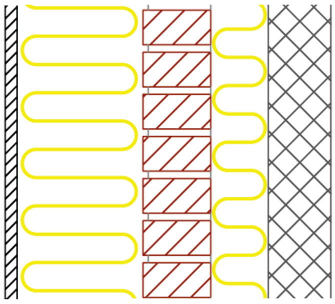
	- 110 mm gas concrete
	- 70 mm old mineralwool
	- 108 mm massiv brick
	- 200 mm mineral wool
	- < 1 cm fiber facade mortar
	Calculated U value 0,16 W/m²K
	* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 11. External wall insulation with fiber mortar finish. New insulation in the cavity (top) and old cavity insulation (bottom).

As can be observed, if wall is newly cavity insulated then 150 mm is sufficient to fulfill BR15 demands, but if it was originally insulated in the cavity, then external insulation has to be at least 200 mm to compensate for the worse insulation quality in the cavity see Figure 11. This solution does not require casting additional foundation to support insulation layer because mineral wool is attached with weight carrying pins to the façade.

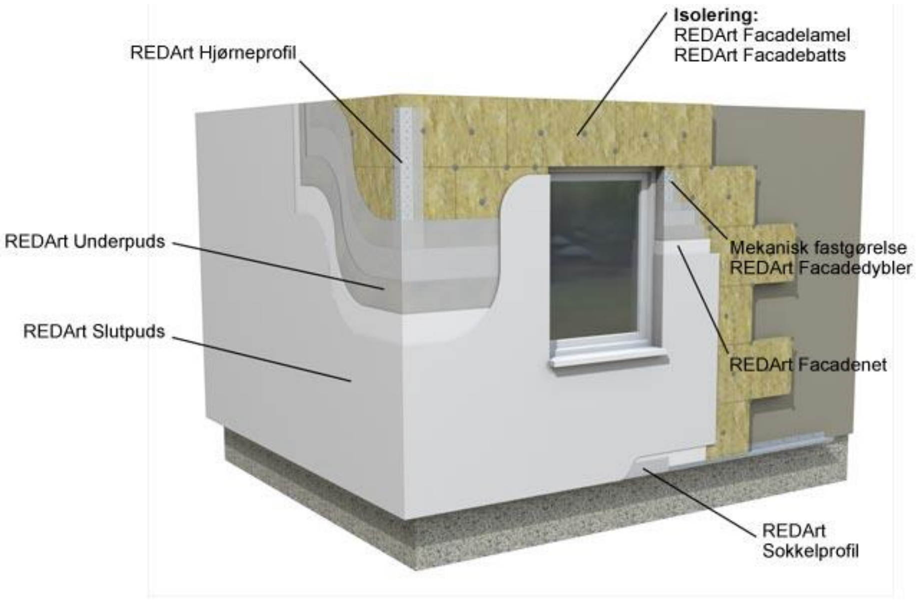
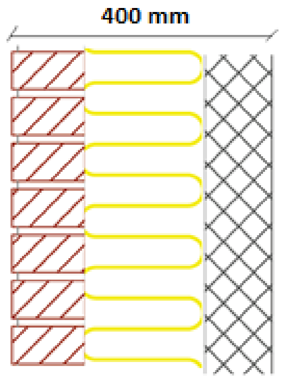


Figure 12. Illustration of external wall insulation with mortar finish using REDArt solution from Rockwool.

Demolition of existing brick work + new thicker insulation + new external brick work

This solution requires demolition of existing external brick work. Very often if cavity is insulated the old insulation is removed as well. In that place is inserted minimum 200 mm of new insulation, see Figure 13. To preserve architectural expression of the building new brick work would be applied as external finish, see

Figure 14. In such case additional foundation of approx. 100-150 mm has to be cast to support new brick work. Cheaper solution could be to apply light façade finish supported on timber construction. In such case additional foundation could be avoided but architectural expression is changed.



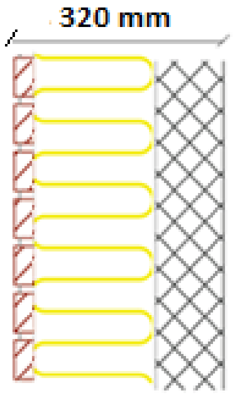
- 110 mm gas concrete
- 200 mm mineral wool
- 108 mm new massiv brick
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 13. New insulation and regular brick work on the external side of the wall.

Figure 14. Demolition of external brick work, new thicker insulation and brick work- solution requires additional foundation.

Demolition of existing brick work + new thicker insulation + new brick tiles

This solution requires demolition of existing external brick work. Very often if cavity is insulated the old insulation is removed as well. In that place is inserted minimum 200 mm new insulation attached on weight carrying pins to light concrete construction. To preserve architectural expression of the building and to avoid casting of new additional foundation as in the previous presented solution, special brick tiles can be attached directly on the insulation. On the market area already available new thin brick tiles, but old bricks, cut to that purpose can also be purchased. This solution allows decreasing price for façade renovation because costly new foundation and excavation works can be avoided. Additional advantage of using tile bricks is thinner external wall after energy renovation, see Figure 15 and Figure 16.



- 110 mm gas concrete
- 200 mm mineral wool
- 20 mm new brick tile
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 15. New insulation and thin brick tiles on the external side of the wall.

Figure 16. Demolition of external brick work, new thicker insulation and brick tiles- solution does not require additional foundation but might require lintels.

New insulation on existing wall + new brick wall or brick tiles

This technical solution assumes that existing external heavy wall is kept unchanged except optional cavity insulation and all energy renovation is applied on existing construction. In this concept, insulation would be applied on the external brick and then finish solution would be applied either in form of new brick work, brick tiles or light façade cover on timber construction attached to existing wall, see Figure 16, Figure 17, Figure 18 and Figure 19. This solution would have several disadvantages such as:

- Additional new foundation including excavation work would have to be done
- It is costly

- Wall becomes very thick
- Less natural light would enter into the building
- Not enough space under roof overhang (façade is more exposed to rain)

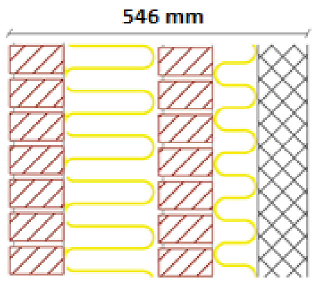
	- 110 mm gas concrete
	- 70 mm old mineral wool
	- 108 mm massiv brick
	- 150 mm mineral wool
	- 108 mm new brick
	Calculated U value 0,16 W/m^2K
	* Requirement from Danish BR15 for minimum U value 0,18 W/m^2K is reached

Figure 17. New insulation on existing wall and new regular brick wall façade finish.

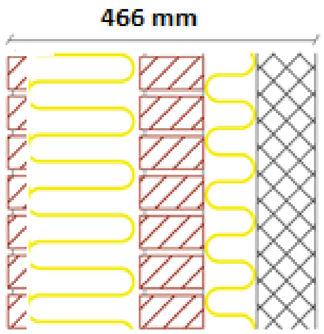
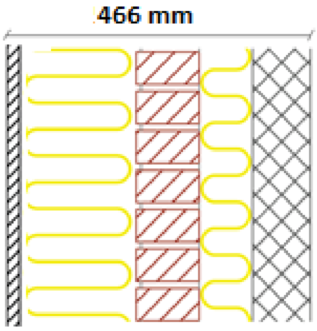
	- 110 mm gas concrete
	- 70 mm old mineral wool
	- 108 mm massiv brick
	- 150 mm mineral wool
	- 20 mm brick tile
	Calculated U value 0,16 W/m^2K
	* Requirement from Danish BR15 for minimum U value 0,18 W/m^2K is reached

Figure 18. New insulation on existing wall and new brick tile façade finish.

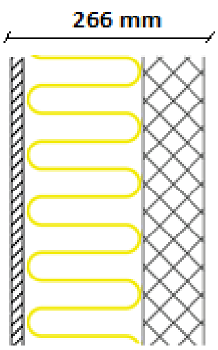


- 110 mm gas concrete
- 70 mm old mineral wool
- 108 mm massiv brick
- 150 mm mineral wool
- 20 mm new ligth facade solution
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 19. New insulation on existing wall and new light façade finish.

Prefabricated PUR renovation wall solution

This technology is based on prefabricated polyurethane foam panels enclosed on one side with 16 mm fiber cement plate. Panels offer very interesting solution for building renovation since with only 166 mm in total thickness of the panel, they fulfill BR15 demands for external wall insulation, see Figure 20. Additionally, solution does not demand additional foundation and only lintel profile attached to footing to carry the profile load is required. Elements are provided on side ready for installation and therefore renovation process is simple and time is decreased comparing to previous 4 more traditional solutions, see Figure 21. Cement fiber external finish offers multiple finish options such as painting, mortar, light facade cover, brick tiles, etc. The final advantage is that polyethylene foam is also vapor tight and acts as vapor membrane helping to avid condensation in the construction. At the same time envelope becomes air tight.



- 110 mm gas concrete
- 150mm polyurethane
- 16 mm cement fiber plate
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 20. PUR renovation panel attached to existing internal layer of light concrete.

Figure 21. (Left) PUR panels delivered on the site, (right) panels assembly in the new house.

3.1.2 External light wall

The external light wall from 1960 till 1976 was typically constructed of 3 layers. The internal layer in these walls is made of wooden framework of 70 – 100 mm thick and as much insulation in between. Internal finish is made of layer of plaster board and vapor membrane just behind. External finish is usually wooden cladding. **U –value for such light external wall is approximately 0,39 W/m²K.** Technical section view see in Figure 22.

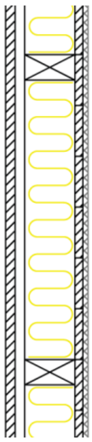
	- 25 mm 2 layers of plaster boards
	- Vapour membrane
	- 100 mm mineral wool on timber posts
	- 20 mm wooden cladding W/m²K
	Calculated U value 0,38 W/m²K
	* To reach requirements from Danish BR15 for minimum U value 0,18 W/m²K additional insulation has to be added.

Figure 22. Light wall construction in 1960 – 1976.

Technical solutions to renovate to nZEB

This chapter presents technical renovation solutions that fulfill recommendation for insulation of building construction elements according to Building Regulation 2015.

External insulation + new cladding on the outside

In order to reach BR15 demands for renovation light external wall would have to be thermally insulated with minimum 150 mm additional mineral wool assuming that existing insulation is kept in the wall, see Figure 23.

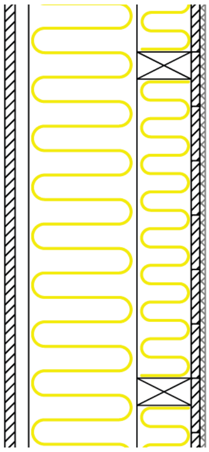
	- 25 mm 2 layers of plaster boards
	- Vapour membrane
	- 100 mm mineral wool on timber posts
	- 150 mm new mineral wool
	- 20 mm wooden cladding
	Calculated U value 0,15 W/m²K
	* To reach requirements from Danish BR15 for minimum U value 0,18 W/m²K additional insulation has to be added.

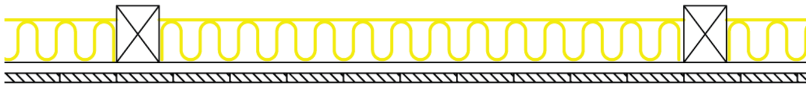
Figure 23. Light wall construction with additional insulation on the outside.

Due to technical aspects new insulation is usually added on the external side of the wall. It is also recommended to replace vapor membrane with the new one as execution quality of old membranes in that period was not good. New vapor membrane shall also air tighten the envelope.

Non- technical but very important aspect for the economy of the renovation project is the choice of external façade finish. As it will be later indicated in the investment cost chapter, chapter 3.2, the choice of the finish material on the façade can have significant impact on the final total cost of light external wall renovation.

3.1.3 Roof

If the roof is with slope it is usually covered with eternit tiles, concrete tiles, eternit slate. Flat roofs are covered with bituminous membrane. Roofs with slope have usually between 15 to 30 º slope. Houses with 1st floor have usually roof slope of 45 º or more. Flat roofs have little slope, usually in the range of 2-6 º. Roofs from that period are usually insulated with 100 mm mineral wool. Moisture membrane is on the worm side of the insulation and it is made of foil or aluminum , see Figure 24. Execution of the moisture membrane is not tight and craftsmen quality is rather poor. Internally roof is finished either with fillet wood panels or with smaller plaster boards 40x60. Roof has usually large overhang along facades and over gables. **Roof from that period have U value of approximately 0,39 W/m²K.**



- 25 mm two layer of plaster board
- 20 mm construction timber
-100 mm minerla wool between 100 mm rafters
Calculated U value 0,39 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,12 W/m²K additional insulation has to be added.

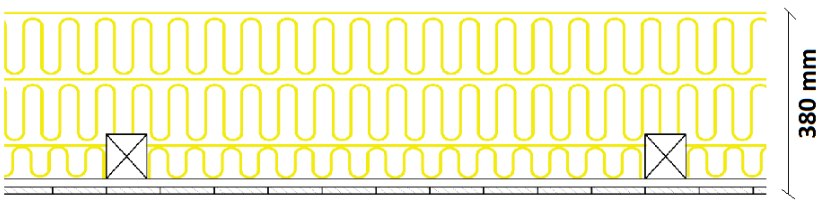
Figure 24. Roof insulation in 1960 -1976.

Technical solutions to renovate to nZEB

In this chapter are presented technical renovation solutions that fulfill recommendation for insulation of building construction elements according to Building Regulation 2015.

External insulation on the roof /ceiling

Thermal insulation of the roof is relatively simple process as long there is enough space for the new insulation and no modification to the roof cover has to be made. To fulfill BR15 demands additional required insulation thickness is around 250 mm, see Figure 25. It is also recommended to replace moisture membrane with the new one. It will help to avoid moisture condensation and will air tighten the building.



- 25 mm two layer of plaster board
- Vapour mambrane
- 20 mm construction timber
-100 mm minerla wool between 100 mm rafters
- 250 mm new mineral wool
Calculated U value 0,12 W/m²K
Requirement from Danish BR15 for minimum U value 0,12 W/m²K is fulfilled

Figure 25. Insulation of the roof according to BR15.

House owners often consider roof insulation as the one of the first renovation steps towards energy reduction. It is cost effective, relatively easy to execute and would contribute to thermal comfort improvement.

The two most often used technologies to insulate roofs are mineral wool mats and granulated mineral wool. They are represented in Figure 26.

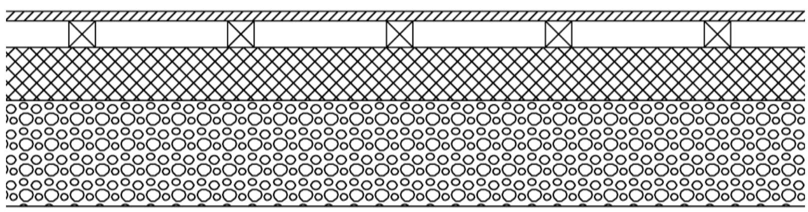
Figure 26. Mineral wool mats (left) and granulate mineral wool blown insulation (right).

3.1.4 Floor on the ground

Floor in parcel houses (1960-1976) consist usually of concrete layer that is cast directly on the ground. It is very rare these houses have basement but some of the first ones have crawl basement.

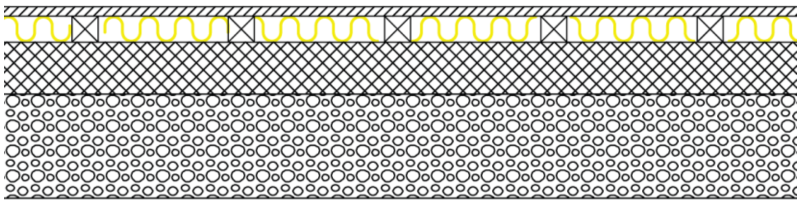
The best houses have capillary breaking layer made of lecca and on this layer is cast 80-100 mm concrete layer. On top of the concrete was laid moisture membrane. On the moisture membrane are laid wooden battens that support wooden floor. Underneath floor and between battens can be found insulation layer of 50 mm but in some cases no insulation was laid, see Figure 27 and Figure 28. **Such floor has U value of approximately 0,3-0,53 W/m²K.**

Floor in the toilets and bathrooms is very often without any insulation (although BR at that time specify 50 mm as minimum). In some houses thinner layer of 20 -30 mm of EPS/wool can be found under concrete slab. Edge insulation between floor slab and footing is also very rare.



- 20 mm wooden floor
- 50 mm wooden battens
-80 mm concrete
- 200 mm ligth lecca (capilary breaking layer)
Calculated U value 0,53 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,10 W/m²K additional insulation has to be added.

Figure 27. Floor without insulation between wooden battens in 1960-1976.



- 20 mm wooden floor
- 50 mm wooden battens and 45 mm mineral wool between
-80 mm concrete
- 200 mm ligth lecca (capilary breaking layer)
Calculated U value 0,31 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,10 W/m²K additional insulation has to be added.

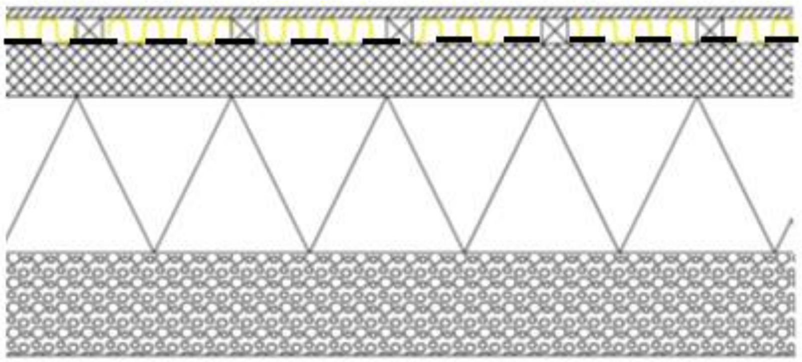
Figure 28. Floor with insulation between wooden battens in 1960-1976.

Technical solutions to renovate to nZEB

This chapter presents technical renovation solutions that fulfill recommendation for insulation of building construction elements according to Building Regulation 2015.

Floor insulation on the ground

To fulfill demands from BR15 floor on the ground established in years between 1960 and 1976 requires significant insulation improvements. That imposes necessity to demolish existing floor, excavation of soil under the floor, establishment of capillary breaking layer, new insulation layer of approx. 300 mm, casting new concrete, new vapor membrane and reestablishment of floor on wooden battens, see Figure 29. This is long and usually costly process that is not rentable. This means that investment costs are so high that payback time thanks to energy savings becomes very long. Therefore, it has to be stressed that this energy saving measure should be considered, for example, when it is right time to change floor to the new one as cost of the new floor cover can represent significant share of the total renovation cost. Other aspect that should be considered is significant improvement of thermal comfort. Thanks to the new thicker and better insulation the unpleasant feeling of cold feet disappears. Finally, eventual problem with condensation between existing thin insulation and moisture membrane laid on the concrete is solved.



- 20 mm wooden floor
- 50 mm wooden battens and 45 mm mineral wool between
- vapor membrane
-80 mm concrete
- 250 mm EPS insualtion
- 300-400 mm capilary breaking and stabilizing layer (sand, lecca)
Calculated U value 0,10 W/m^2K
*Requirement from Danish BR15 for minimum U value 0,10 W/m^2K is fulfilled

Figure 29. Energy renovated floor on the ground.

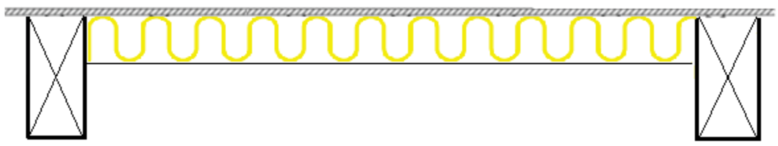
For bottom thick layer of insulation that is laid on the ground, hard extruded polystyrene (EPS) is very often used, see Figure 30. It should be consulted with construction engineer what pressure the insulation should be able to resist. Hard mineral wool bats specially developed for floor insulation can be used as well. Concrete layer might require reinforcing and therefore it shall also be consulted with construction engineer. For the upper thin layer of insulation that is laid between battens, mineral wool is usually used.

The insulation procedure is in the most of the cases similar to each other and therefore cost of this procedure is relatively constant. The variable cost in the renovation is related to the choice of the floor covering material. As it will be later indicated in the investment cost chapter the choice of the finish material on the floor can have significant impact on the final total cost of floor energy renovation.

Figure 30. Example of energy renovation process of floor on the ground.

3.1.5 Floor above unheated crawl basement

Some of the parcel houses had crawl basement. These basements are unheated and therefore for the energy savings and for thermal comfort it is recommended to insulate floor construction between ground floor and crawl space. Floors above crawl space were either poorly insulated or not insulated at all resulting in cold feet experience and significant heat downward losses, see Figure 31.



- 20 mm wooden floor
- 50 mm mineral wool
Calculated U value 0,53 W/m²K
* To reach requirements from Danish BR15 for minimum U value 0,10 W/m²K additional insulation has to be added.

Figure 31. Floor between ground floor and crawl basement in 1960-1976.

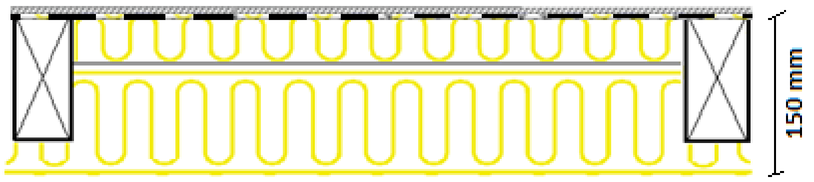
Technical solutions to renovate to nZEB

In this chapter are presented technical renovation solutions that fulfill recommendation for insulation of building construction elements according to Building Regulation 2015.

Insulation on the floor

Insulation of floor above crawl basement is usually easier than insulation of the floor laid directly on the ground. Work is similar to insulation of the roof but it is in reverse direction. The amount of work depends a lot on the access to the crawl space and height of the crawl space, see Figure 33. If access to the space under the floor is easy then floor can be insulated without demolition of existing floor.

Floor above crawl basement can be insulated up to 150 mm in order to avoid moisture in the crawl basement. On the warm side of the insulation, which is between insulation and wooden floor shall be carefully and tightly installed vapor membrane, see Figure 32.



- 20 mm wooden floor
- vapor membrane
- 150 mm new mineral wool
Calculated U value 0,23 W/m²K
* Requirement from Danish BR15 for minimum U value 0,10 W/m²K is not fillfiled but dispensation wuld be abtained in order to avoid moisture in crawl basement.

Figure 32. Energy renovation of floor above crawl basement.

It is recommended to use mineral wool as insulation material. It is flexible and therefore fills in very well the space between wooden floor beams. To avoid thermal bridges, mineral wool should cover wooden floor beams.

Another technology could be to build plenum under the floor and blow granulated insulation in the plenum.

Figure 33. Demolition of not insulated floor above unheated crawl space.

As a result of improved insulation between ground floor and crawl basement less heat will be lost to the crawl space. This will result in decreased temperature in the crawl space and might lead to moisture accumulation. To avoid this, crawl basement should be well ventilated and this means that additional ventilation openings might have to be drilled in the building footing.

3.1.6 Windows

If not changed in meantime the windows in parcel houses from 60s -70s are typically 2-panes windows with distance of 12 mm (thermo panes). **Typically, such windows have U value around 2,7 W/m²K and solar transmission factor of 0,75.**

New windows have significantly lower U value. For double glazing window U value is around 1,1 W/m²K and for triple glazing windows it is around 0,08 W/m²K. In the BR15 it is written that the energy gain through windows and glazed outer walls must not be less than -17 kWh/m²/year and that energy gain through roof lights and glazed roofs must not be less than 0 kWh/m² per year. Energy gain through the window is calculated according to formula presented in BR15 and it can be seen that it dependents on U-value and solar transmission factor g. Therefore, there can be different combination of U and g values that will fulfill BR15 demands regarding energy gain through the windows.

On the market is available countless number of window types and producers. Therefore decision about window type, style, opening possibility, glass type, frame finish, 2 or 3 pane glass at the end belongs to building owner.

Benefits related to installation of new windows are:

- Decreased energy use for heating
- Better aesthetics
- Tighter envelope
- Better thermal comfort
- Lack of condensation and therefore mold growth in the window corners

3.1.7 Foundation and footing

Footing is normally cast of concrete and reaches approximately 15 cm above ground level. From 1970 footing was finished with light clinker blocks. Foundations are cast of concrete and reaches usually 90 cm deep in the ground to the frost free depth, see Figure 34.

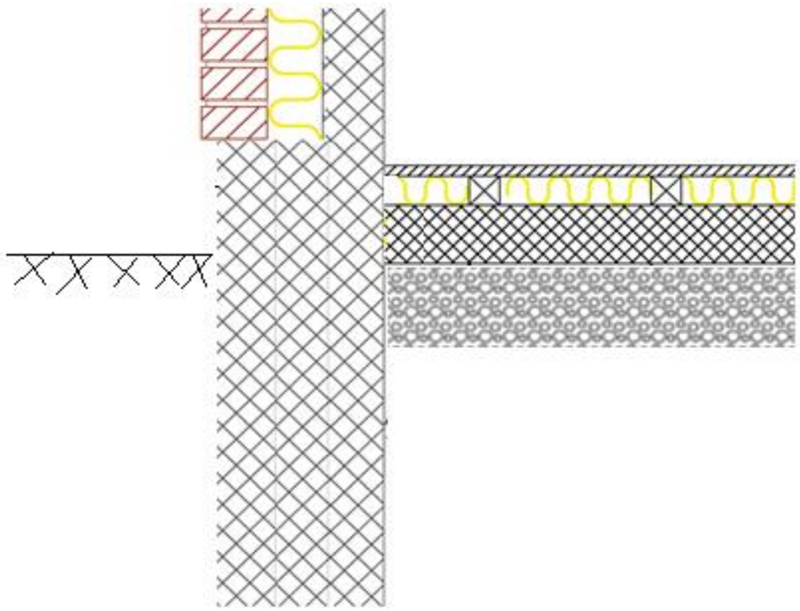


Figure 34. Foundation/footing construction in 1960-1976.

Technical solutions to renovate to nZEB

In this chapter are presented technical renovation solutions that fulfill recommendation for insulation of building construction elements according to Building Regulation 2015.

Foundation and footing insulation

Best effect of foundation and footing insulation is obtained when combined with external wall insulation and floor insulation, see Figure 35. If all three construction elements are energy renovated then line losses along foundation and wall can be significantly reduced.

Foundation and footing should be insulated from the outside. As insulated material can be used mineral wool or expanded polystyrene. To decrease line losses peripheral insulation should be considered around concrete floor deck where it meets with external wall.

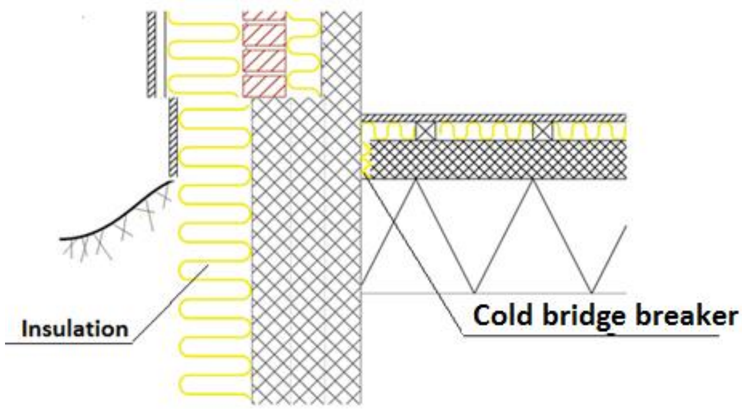


Figure 35. Insulated foundation and footing from the outside, cold bridge breaker at floor deck.

It is recommended to insulate footing and foundation with the same thickness as external wall. In the presented example, Figure 35. X and Figure 36 insulation would be 200 mm thick.

If there is a risk that ground moisture would press on the new insulation then it would be recommended to establish peripheral drainage tube around foundation.

Figure 36. Foundation and footing insulation together with establishment of peripheral drainage around the building.

3.2 Installations improvement

3.2.1 Ventilation

Parcel houses from 1960-1976 are mostly naturally ventilated by opening windows. The most of the Danish parcel houses would also have mechanical extraction fans from toilet, bathroom and kitchen. These are in the most scenarios demand control, for example, when turning light exhaust fan turns on or when cooking exhaust hood in the kitchen would be turned on but only when meal is cooked. Fresh air is supplied through windows, venting openings, untightens in the envelope. Such ventilation system does not allow for heat recovery. Moreover, in winter it usually results in very small air changes. Windows are kept closed due to risk of drought and high heating demand. Additionally mechanical exhaust fans operate in very short periods. Consequently indoor air is not changed many times and concentration of CO2, humidity and pollutants reaches unacceptable levels causing bad air quality, condensation on the window surfaces, unpleasant smell.

Centralized mechanical ventilation with heat recovery

Solution to that problem could be simple balanced mechanical ventilation system with heat recovery. Presently on the market can be found two typical solutions tailored for residential building market. They are centralized and decentralized systems. In centralized system, see Figure 37, air handling unit is placed usually in the attic, depot room or basement. Handling unit is a box in which can be found inlet and exhaust fans, filters, heat exchanger and in some cases heating/cooling coil. Central unit has 4 duct connections: one for supply air, one for return air, one for fresh air and one for exhaust air to the outside. Additionally air handling unit might have pipe connection for circulating hot water between unit and district heating/boiler/heat pump in order to heat up air in the winter. Air handling unit must also have electrical connection for automation and to run fans.

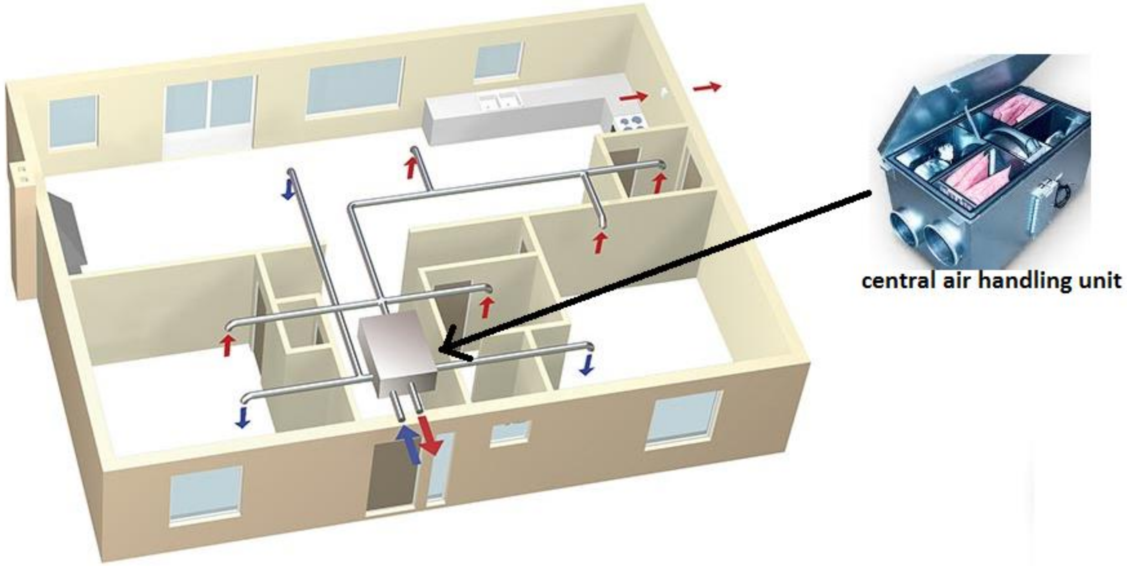


Figure 37. Centralized mechanical ventilation system.

Energy saving potential in using mechanical ventilation with regards to naturally ventilated solution is possible thanks to heat recovery. In winter in naturally ventilated buildings cold air enters the building and then is heated by radiators at the same time hot air leaves the building causing large heating demand (heat loss). In mechanical system with heat recovery, return hot air transfers heat to fresh and cold air. Thanks to heat recovery heat that is exhausted to the outside and lost is significantly smaller. Fresh air is preheated before it enters the room and therefore heating demand to obtain thermal comfort is significantly reduced comparing to naturally ventilated building. The energy saving potential depends on two parameters. First is heat recovery efficiency. This parameter for very good heat recovery systems varies between 80-85 % and the higher the recovery efficiency is the higher heating saving. Second parameter is specific fan power that describes how much energy is used by the fans to transport air through air handling unit and through the ducts. The lower specific fan power value is the more efficient is the system and less electric energy is used. Unfortunately, these two parameters are contradicting each other which means that the higher is heat recovery the higher becomes specific fan power and therefore optimum performance of the system is always a compromise between these two factors.

Decentralized mechanical ventilation with heat recovery

This technological solution draws more and more attention during recent years and therefore there are more and more product solutions offering this type of ventilation strategy. In decentralized ventilation system air is supplied, extracted, handled, and simply controlled at the room level. There is not one large air handling unit like in centralized system, but several smaller. What is more, in decentralized ventilation system there is no need for supply and extraction ducts. Decentralized ventilation units are small and can be fit into external wall or even in the panel assembled to the window frame. New decentralized units offer heat recovery and air filtering.

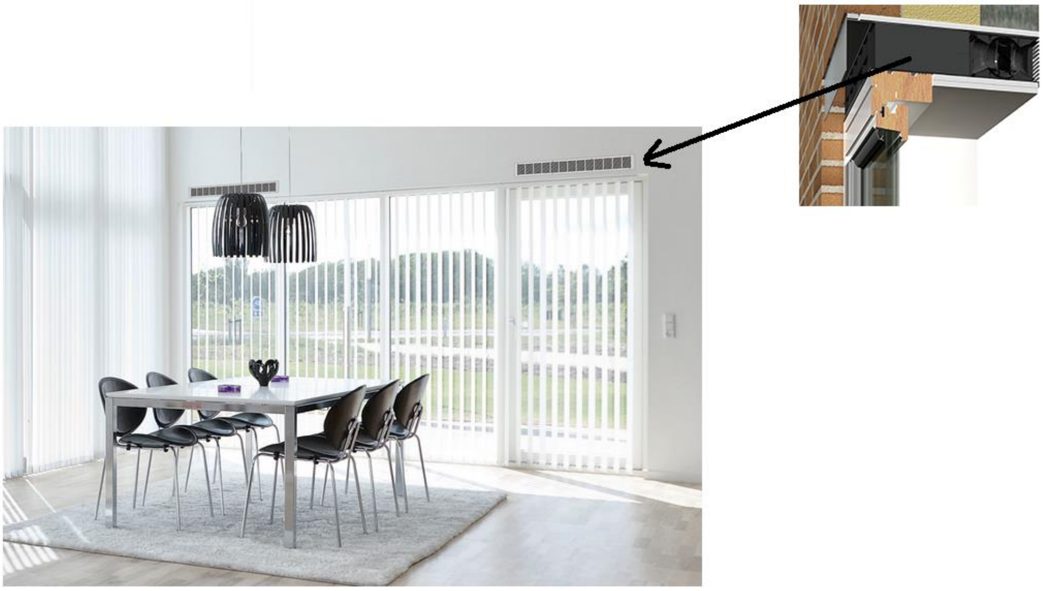


Figure 38. Decentralized ventilation units from Inventilate, source [3]

Conclusions and other technical aspects that should be considered when investing in mechanical ventilation system

One of the major advantages when installing decentralized ventilation system in the existing house comparing to centralized system is significantly less work related to installation of the ducts. Ventilation ducts require a lot of space that is very often difficult to find in already existing buildings. Therefore, installation of decentralized system is much cleaner and less disturbing to house owners and that is why it becomes more and more popular in renovation projects.

Disadvantage of decentralized system comparing to centralized is more maintenance (more units requiring service) and risk of worse acoustic performance since units are very close to occupied space.

In real operation, energy savings thanks to mechanical ventilation with heat recovery comparing to natural ventilation system are often not that significant and this is because in winter natural ventilation is simply not used and therefore heat is not lost but at the same time problems with air quality and humidity occur. With installation of mechanical ventilation indoor air quality and indoor comfort becomes improved and therefore investment in mechanical system should be regarded more as investment in better comfort than energy saving strategy.

3.2.2 Heating production

Energy for heating is the dominant share of the total energy use in residential houses and therefore heating generation system represent large energy saving potential.

Energy saving potential for the heating generation system in residential parcel houses from 1960-1976 depends on the condition found in each individual house.

Heating was provided originally by oil boiler standing in washing room, as electrical heating or from district heating system. Old oil boilers have low efficiency of around 60-70% and they were poorly insulated. If boiler was changed in meantime, it was usually changed to gas boiler. If it was changed before Year 2000 it was ordinary boiler and if after Year 2000 then it was condensing boiler.
If house was connected to district heating and if original shunt is not replaced by newer then it is usually one constructed on site. Pipes, pumps, heat exchangers and valves are not insulated. Newer shunts are more compact than older but very often still not insulated or poorly insulated.
In some houses electrical heating was established with electrical heaters in all rooms. This was legal until 1988.
Distribution system is 1 or 2 string system with radiators located under windows in the rooms and often floor heating in the bathroom and toilet. Distribution pipes are usually insulated with 10 - 20 mm and they are placed under the floor in the unheated crawl basement. Radiators are not of big size (not in 1 string system) since they were designed for high temperatures. Originally they might not be equipped with thermostatic valves but the most were equipped in meantime and in houses built after 1965 they were mounted on radiators valves.
In period between 1960 and 1976 in some of the houses was installed air based heating. In that system, hot air is distributed under the floor and is supplied through the grills located in the rooms. Common problem with such heating system is that hot air flows under the ceiling leaving occupied space not heated. Another disadvantage is very dry indoor air during the winter.

Investment in new heating unit is very often dictated by two factors. First is need for change because existing unit is worn out and requires replacement. As rule of thumb it is expected that boilers and heat pumps have life expectancy of 20-25 years. If building is connected to district heating then connection shunt might last for even 50 years with some smaller renovations. The second factor is simply very high heating bills due to old and inefficient boiler operation. In this case return on investment in new boiler can be relatively short, within 4-5 year, and together with perspective for lower bills in long term it is enough argument to convince building owner to invest in energy saving.

Boiler

New condensing boilers offer efficiency of up to 95 %. These boilers have modulated effect and therefore one model can cover relatively broad range of heating needs. Therefore investment in boiler for one family house is not very sensitive to the actual heating demand of the house. Still, oversized boilers working at low percentage of their capacity are expected to show decreased efficiency. Therefore, efficiency of the boiler and its modulation flexibility has to be checked with the producer.

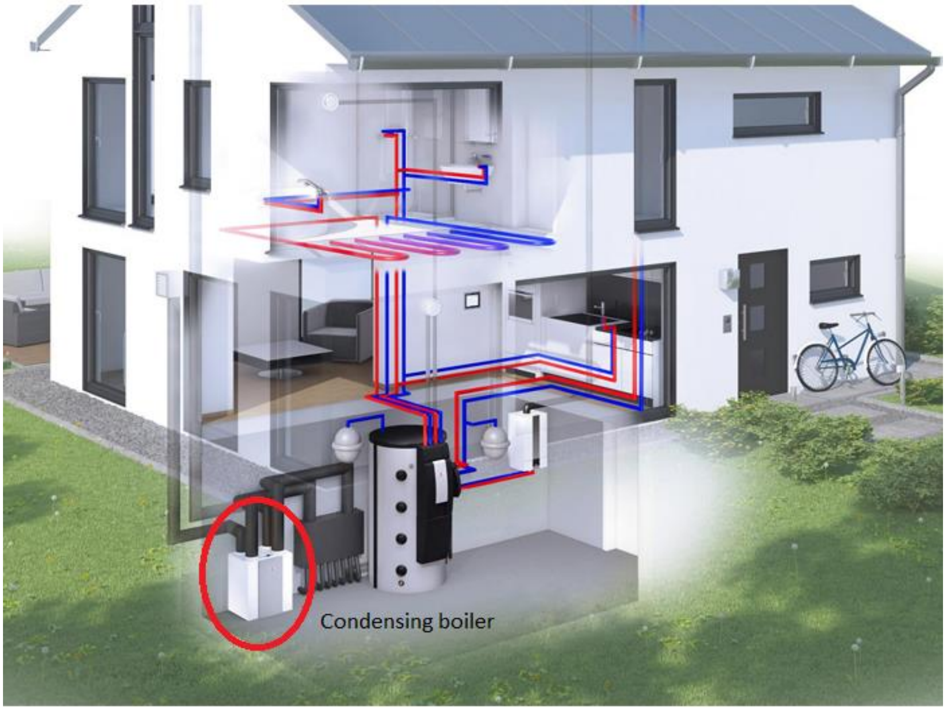


Figure 39. Schematic drawing indicating possible location of the boiler room with boiler and external hot water tank.

New boilers can be bought with integrated storage tank for domestic hot water and with possibility to connect to external storage tank, see Figure 39.

Due to price of fuels and CO2 reduction it is nowadays recommended to install boilers for gas rather than oil.

Subsidy from approximately 1.000 DKK to approximately 13.000 DKK incl. tax can be obtained when replacing old boiler with newer better boiler, heat pump or conversion to district heating. Subsidy rates vary depending on existing heating generation, conversion solution type and company where subsidy is sought. Below in Figure 40 is presented table indicating conversion possibilities that receive subsidiary support.

Som privat forbruger kan du søge om tilskud til næsten alle tænkelige former for energirenovering:

Varmekilder	
Konvertering fra	**Til**
Kondenserende oliekedel	Fjernvarme
	Jordvarmepumpe
	Luft/vand-varmepumpe
Kondenserende gaskedel	Jordvarmepumpe
	Luft/vand-varmepumpe
	Fjernvarme
Elvarme	Luft/vand-varmepumpe
	Jordvarmepumpe
	Luft/luft-varmepumpe i sommerhuse med og uden brændeovn

Figure 40. Table indicating heating generators conversions that receives subsidy in Denmark.

Heat Pump

Heat pump like boiler is a heating generating unit. It consists of heat pump and lower heat source. This lower heat source in all year occupied houses is usually horizontal ground heat exchanger or vertical boreholes, see Figure 41.

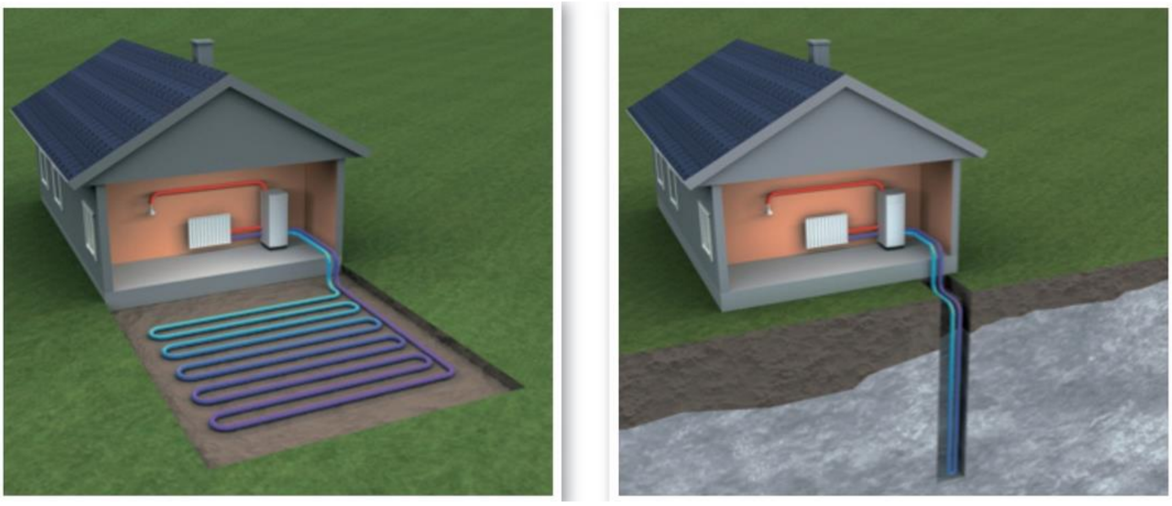


Figure 41. Heat pump connected to horizontal heat exchanger (left) and heat pump connected to bore hole (right).

In the heat pump no fuel is burned. Instead pump requires electricity for running compressor that heats up refrigerant to required temperature. This refrigerant later heats water that is sent to radiators and floor heating circuits. Thanks to lower heat source (ground, ground water, air) and refrigerant reversible process heat pump use significantly less electrical energy than for example electric heater. The efficiency of heat pump is represented by coefficient of performance (COP). The higher the COP factor is the more efficient heat pump is to convert electricity to heat. For example, if heat pump has COP =3 that means that from 1 kW of electricity it produces 3 kW of heat. Some typical heat pump COP solutions were gathered in Table 8.

Table 8. Typical COP of different heat pump systems.

System	COP
Water-water heat pump	4.5
Direct evaporator heat pump	4.2
Brine-water heat pump	4.0
Air-water heat pump	3.5

In Denmark water-water and direct evaporator heat pump systems are normally forbidden due to environmental reasons. Higher COP than one presented in in the table can be obtained by optimizing system.

Figure 42. Heat pump with its connection pipes.

Heat pump installation requires similar space as boiler, see Figure 42. Therefore, replacing boiler with heat pump should be possible without heavier indoor works. Large works are related to establishment of lower heat source, especially horizontal one. Home owner should be prepared for larger excavation works around the house.

Investment in heat pump is more costly than in new condensing boiler, but at the end energy bills for heating can be significantly lower. The final energy bill can vary from case to case.

Opposite to the new boiler installation, the heating demand of the house has significant influence on the total investment in the heat pump. The lower the heating demand the smaller becomes required lower heat source (less meters of expensive ground heat exchanger). Moreover, required heating effect of the heat pump is reduced and therefore smaller and cheaper heat pump can be bought.

It can be concluded that it is more economically reasonable to first energy renovate building envelope and afterwards invest in heat pump tailored to the new decreased heating demand. This analysis is further presented in this report in chapter 4.11.

3.3 Renewable energy production

There are two types of renewable energy sources that can be integrated in the single family houses. These are solar collectors and solar cells (photovoltaic) for producing electricity. Both of the panels looks similar to each other but serves different purposes. Solar collectors produce domestic hot water and solar cells produce electricity.

Both technologies produce renewable energy, in other words no fuel is burned to produce heat or electricity. None of the two technologies were implemented in the parcel houses in 1960 -10976 and therefore they should be considered as add-in technologies to the building from that period in order to help them to become nZEB. From the perspective of nZEB both technologies are very interesting and therefore they are presented in this chapter.

3.3.1 Solar collectors

Solar collectors are usually mounted on the roof and optimally if located on the slopes oriented towards south. Construction of solar collectors is relatively simple and is illustrated in Figure 43.

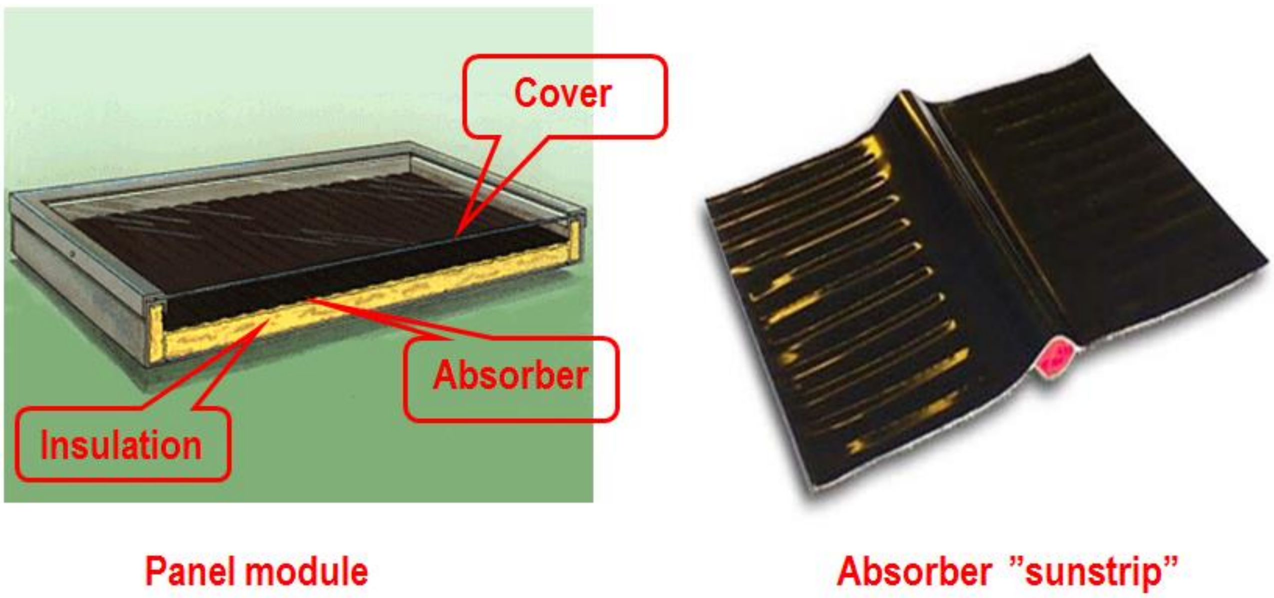
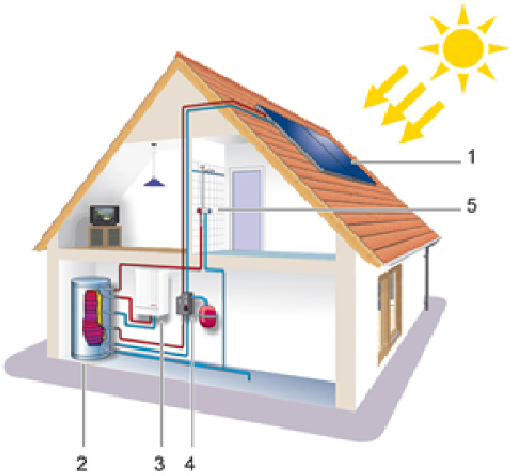


Figure 43. Solar collectors for hot water production.

Special antifreeze liquid that circulates through collectors is heated by the solar energy in the collector. Hot liquid is pumped to storage tank where it heats cold water. This hot water is stored in the tank until there is need for hot water in the tap. Because hot water is produced only when sun is shining it must be stored in the tank for later use. Therefore, solar collector installation always requires following components: Solar collectors, hot water storage tank, circulation pump and automation, see Figure 44.



1	Solar collectors
2	Hot water storage tank
3	Boiler or heat pump
4	Circulation pump and automatic
5	Water taps

Figure 44. Solar collector system with storage tank for one-family house.

Technical aspects that should be considered when investing in solar collector system

Solar collectors can be mounted on any kind of roof type without annoying work for building occupants. Storage tank can be installed in fast and clean manner in the technical room if there is enough space for it. If not enough space is available, building owner might expect smaller renovation works, such as moving internal wall, etc. Installation of the circulation pipes between storage tank and collectors might require some drilling and moderate renovation works inside in the house.

If possible, optimally collectors should be placed towards south. If that is impossible, then west and east directions should be considered. North orientation should not be considered for collector installations.

There is no demand for minimum nor for maximum area of collectors. Smaller installation will be cheaper but will simply cover smaller share of total domestic hot water need, whereas large installation will cost more and will cover larger share or even total need for domestic hot water.

3.3.2 Solar cells

Performance of solar cells depends on their orientation, slope, type, if they are integrated in the construction, if they are easily ventilated and if there is risk of shadow cast on any of the cells. In Table 9 is presented overview of solar cells efficiency (in percentage) depending on their orientation and slope comparing to the optimal location which is towards south and with 35 ^{o} slope.

Table 9. Solar cells efficiency with respect to orientation and slope.

Slope	west	south west			south			south east			east
	90°	60°	45°	30°	15°	0°	15°	30°	45°	60°	90°
0°	86	86	86	86	86	86	86	86	86	86	86
5°	86	88	89	89	90	90	90	89	89	88	86
10°	86	89	91	92	93	93	93	92	91	89	86
15°	85	90	92	94	95	95	95	94	92	90	85
20°	84	91	93	95	97	97	97	95	93	91	84
25°	83	91	94	97	98	99	98	95	94	91	83
30°	81	91	94	98	99	100	99	97	94	91	81
35°	80	90	94	97	99	100	99	97	94	90	80
40°	78	89	94	97	99	100	99	97	94	89	78
45°	77	88	93	96	99	99	99	96	93	88	77
60°	70	83	88	93	94	94	94	92	88	83	70
70°	66	78	82	86	88	88	87	86	88	78	66
90°	44	64	68	70	72	72	72	70	68	64	44

Optimal placemnt of soalr cells on the roof

Solar cells produce direct current (DC) and this must be inverted to alternate current (AC) to be able to use it in the home electrical installation. The machine that converts DC to AC is called inverter.

Technical aspects that should be considered when investing in solar collector system

Installation of solar cells is similar to installation of solar collectors. Solar cells require inverter to change direct current to alternating current. Inverter itself is of size of shoe box and usually hangs on the wall close to the el. energy meter. Its installation is fast and clean. New solar cell installations allows selling electricity to the network and that requires special energy meter that can calculate energy provided from the network to the building and from building to the network. All necessary component of the PV installation are presented in Figure 45. The remaining work necessary to complete solar cells installation is pulling the cables from the roof to inverter and from inverter main switch board and energy meter.

When installing cells special care must be paid so that it is free of any shadow.

1	Solar cells
2	Inverter
3	Plug loads in the house
4	Smart meter with netwark connection
5	Electric netwark

Figure 45. Photovoltaic cell system with its necessary components.

4 Part 3- Price calculation of proposed technical solutions

Price calculation for different energy renovation packages presented in this chapter are based on prices taken from V&S Price Database. For this specific case prices were taken from “Yellow V&S Book” that is specially dedicated to renovation projects. Prices callected in yellow V&S database are given for renovation projects on ordinary ground and for ordinary working condition.

Special conditions that could influnce complexity of work, work time, difficulty/ease are not considered in the analysis. This conditions might be:

- Gegraphical location (discount or extra cost)
- Time of work execution
- State of the market
- Deviation from standard work
- Not clear definition of work
- Difficult/easy work condition (discount or extra cost)
- Extraordinary material discount
- Extraordinary amount of internship hours
- Etc…

Above mentioned issues must be always considered individaully from project to project.

The toal work price include cost of: **sallary, materials, tools and material rental.** Prices are given for renovation projects on ordinary ground with ordinary working condition. All presented in this anlysis prices are brutto prices and should be considered as contractor offer price.

Prices in the V&S database are always adjusted with regards to amount/size of work to be done. Prices can become uncertain if 10 time smaller or bigger than suggested average price in the database. Prices are given for 3 quanities small, medium and large quantity . Prices between given prices are iterpolated and for smaller and bigger quantities than respectively minimum and maximum quantities prices are extrapolated, see Figure 46.

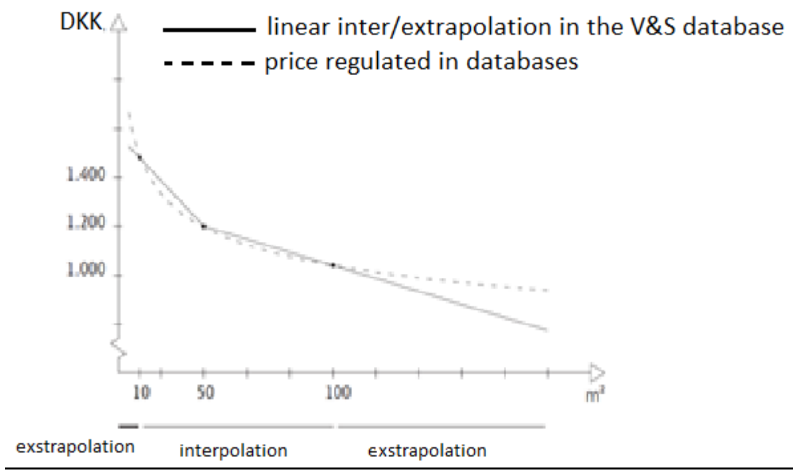


Figure 46. Example of price inter/extrapolation depending on quantity, source [4]

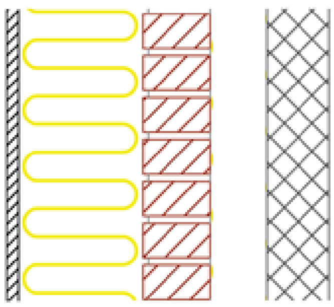
4.1 External heavy wall

External heavy wall can be renovated in many different manners to fulfill the same insulation goals. In this chapter is presented how total renovation price can vary depending on which technology is chosen to renovate heavy external wall from parcel house built in 1960 -76 to BR15 demand for renovation projects.

Prices are calculated for 1, 10 and 50 case houses and discount due that is taken into account. All prices are given in DKK.

4.1.1 External insulation + mortar finish (REDart technology)

In this scenario it is assumed that air cavity in the wall is not insulated and to fulfill BR15 demand it is required to add 200 mm of mineral wool, see Figure 47, on the external side of the envelope.



- 110 mm gas concrete
- 70 mm air cavity
- 108 mm massiv brick
- 200 mm mineral wool
- < 1 cm fiber facade mortar
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 47. Insulation solution with 200 mm REDart technology (no cavity insulation).

Price calculation for 200 mm REDart solution is presented in

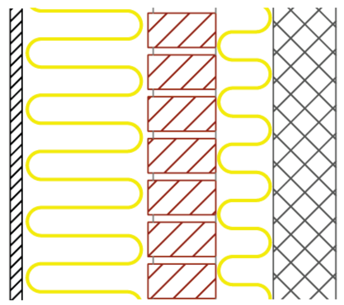
Table 10.

Table 10. Price calculation for 200 mm REDart façade insulation.

Rockwool REDart facadeinsulation (200 mm)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	1.842	153.828	
10 houses	835	1.732	144.620	6
50 houses	4175	1.668	139.305	9

4.1.2 External insulation + cavity insulation+ mortar finish (REDart technology)

In this scenario it is assumed that air cavity in the wall is not insulated and to fulfill BR15 demand it is required to insulate cavity with granulated mineral wool and also to add 150 mm of mineral wool on the external side of the envelope, see Figure 48. Insulation solution with 150 mm REDart technology and cavity insulation.. Price calculation for that solution is presented in Table 11.



- 110 mm gas concrete
- 70 mm granualted mineralwool
- 108 mm massiv brick
- 150 mm mineral wool
- < 1 cm fiber facade mortar
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 48. Insulation solution with 150 mm REDart technology and cavity insulation.

Table 11. Price calculation for 150 mm REDart façade insulation and cavity insulation.

Cavity insulation (70-80 mm)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	156	13.016	
10 houses	835	134	11.218	14
50 houses	4175	123	10.274	21

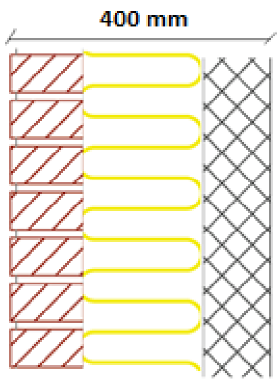
Rockwool REDart facadeinsulation (150 mm)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	1.658	138.434	
10 houses	835	1.560	130.277	6
50 houses	4175	1.504	125.567	9

Total price (cavity insulation+ 150 mm REDart)			
No. houses	Area (m2)	Price/m2	Total price/house
1 house	83,5	1.814	151.451
10 houses	835	1.695	141.495
50 houses	4175	1.627	135.842

Scenario 1 and 2 are very similar and from the comparison it can be concluded that scenario 2 is slightly cheaper than scenario 1. Another advantage of scenario 2 is that total wall thickness is smaller. Smaller wall thickness has several advantages: better aesthetic, more natural light can come inside the house. What is more, property area that in Denmark is calculated on the external perimeter is smaller and therefore property tax paid yearly per floor area will be smaller.

4.1.3 Demolition of existing brick work + new thicker insulation + new external brick work

In this scenario it is assumed that existing external façade is demolished, new thicker insulation is mounted and new brick work finish is executed, see Figure 49.



- 110 mm gas concrete
- 200 mm mineral wool
- 108 mm new massiv brick
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 49. Insulation solution accounting for demolition of existing external façade and replacement with new thicker insulation and new brick finish.

In this scenario several works have to be included in the total price, such as:

- Demolition of existing brick work and insulation
- Digging around building foundation

- Establishment of additional foundation to support new brick work
- New insulation
- New brick work

Price calculation for this scenario is presented in Table 12.

Table 12. Price calculation for demolition of existing external façade and replacement with new thicker insulation and new brick finish.

External brick work demolition				
No. houses	Area (m2)	Price/m2	Total price/hous	Saving [%]
1 house	83,5	72,42	6.047	
10 houses	835	54	4.471	26
50 houses	4175	46	3.823	37

Hand digging around perimeter							
	Perimeter (m)	Width (m)	Layers	Volume [m3]	Price/m3	Total price	Saving [%]
1 house	50,8	0,5	3	3,05	2.021	6.062	
10 houses	508	0,5	3	30,48	1.460	4.381	28
50 houses	2540	0,5	3	152,40	1234	3.751	39

Excavator digging around perimeter							
	Perimeter (m)	Width (m)	Layers	Volume [m3]	Price/m3	Total price	Saving [%]
1 house	50,8	0,5	3	12,19	592	7.105	
10 houses	508	0,5	3	121,92	428	5.134	28
50 houses	2540	0,5	3	609,60	361	4.409	39

Lecca blocks 600 foundation							
	Perimeter (m)	Width (m)	Layers	Area [m2]	Price/m2	Total price/house	Saving [%]
1 house	50,8	0,29	2	29,46	1.176	34.686	
10 houses	508	0,29	2	294,64	1.012	29.842	14
50 houses	2540	0,29	2	1473,20	925	27.254	21

25 MPa foundation under lecca blocks (without reinforcement)							
	Perimeter (m)	Width (m)	Layers	Volume [m3]	Price/m2	Total price	Saving [%]
1 house	50,8	0,33	1	16,76	2.371	39.602	
10 houses	508	0,33	1	167,64	2.060	34.400	13
50 houses	2540	0,33	1	838,2	1895	31.755	20

New mineral wool insualtion (200 mm)				
No. houses	Area (m2)	Price/m2	Total price	Saving [%]
1 house	83,5	199,09	16.624	
10 houses	835	168	14.025	16
50 houses	4175	152	12.695	24

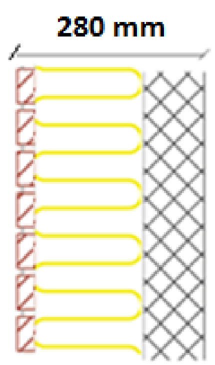
New facade brick				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	1.341	111.993	
10 houses	835	1.132	94.526	16
50 houses	4175	1.026	85.656	24

TOTAL PRICE	Price per house	Saving
1 house	222.119	
10 houses	186.780	16
50 houses	169.343	24

Technical scenario 3 is roughly 50% more expensive comparing to two previous scenarios. For this price, architectural expression of the house is preserved and modernized and probably fits to the neighborhood. This solution would be recommended in areas where local plans prohibit changing architectural expression of the building façade. Analysis indicates, as well, that home owner could expect large discount if house was renovated in organized manner with some other home owners from the neighborhood. Another advantage of this solution is that new brick facade, like old brick façade, is almost maintenance free. As main disadvantage has to be mentioned heavy works around building, for example, excavation and brick work that usually take long time.

4.1.4 Demolition of existing brick work + new thicker insulation + brick tiles

This technical solution provides almost the same thermal and aesthetical result as scenario 3, but it is cheaper, results in thinner external wall, and requires less work, thus its execution should be faster and less troublesome for the house owner. Solution is presented in Figure 50.



- 110 mm gas concrete
- 150 mm mineral wool
- 20 mm new brick tile
Calculated U value 0,23 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is not reached but propbably dispensation can be obtained

Figure 50. Demolition of external brick work, new thicker insulation and brick tiles- solution does not require additional foundation but might require lintels.

In this technical solution, contrary to scenario 3, it is not necessary to excavate and cast new foundation since wall thickness thanks to thin tiles is kept almost unchanged. If additional support would be necessary it can be solved with metal lintel screwed to the light concrete wall or to the existing footing.

Brick tile systems can be bought already mounted on the 150 mm mineral wool bats as module prefabricated product. Price per 1 m² is 1000 – 1150 DKK/m² and depends on the brick type. Price for mounting product is yet not available in the V&S database and for residential project purpose it is estimated at 500 DKK/m². Discount for larger quantities is not known and in this analysis it was assumed that for 10 houses discount on installation work would be at 16% (like for new brick work) and for prefabricated modules at 6% (like REDart solution). For 50 houses discount would be respectively 24 % for work and 9% for material.

Total price calculation is presented in Table 13.

Table 13. Price calculation for demolition of existing external façade and replacement with new thicker insulation and new brick tile finish.

External brick work demolition				
No. houses	Area (m2)	Price/m2	Total price/hous	Saving [%]
1 house	83,5	72,42	6.047	
10 houses	835	54	4.471	26
50 houses	4175	46	3.823	37

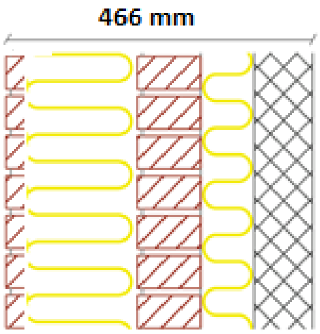
Prefabricated 150 mm mineral wool and brick tiles				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	1000	83500	
10 houses	835	940	78490	6
50 houses	4175	910	75985	9

Installation of prefabricated 150 mm mineral wool and brick tiles				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	500	41750	
10 houses	835	420	35070	16
50 houses	4175	380	31730	24

TOTAL PRICE			
No. houses	Area (m2)	Total price/house	Saving [%]
1 house	83,5	131.297	
10 houses	835	118.031	10
50 houses	4175	111.538	15

Brick tile prefabricated module solution with integrated 150 mm mineral wool bats for time efficient and easy mounting seems to be very interesting proposal for energy renovation of parcel houses. Total investment price is reduced, no excavation and additional foundation is required, final wall thickness is kept at around 280 mm, which is very good result for renovation projects.

The same technical solution could be applied on existing façade without demolition of existing brick work. In such case total wall thickness would increase to approximately 466 mm and additional foundation might be required to support new insulation and brick tiles, see Figure 51. In this case savings obtained for not demolishing existing brick work could be spent on excavation and new foundation.



- 110 mm gas concrete
- 70 mm old mineral wool
- 108 mm massiv brick
- 150 mm mineral wool
- 20 mm brick tile
Calculated U value 0,16 W/m²K
* Requirement from Danish BR15 for minimum U value 0,18 W/m²K is reached

Figure 51. New insulation on existing wall and new brick tile façade finish.

4.1.5 Demolition of existing brick work and insulation + PUR prefabricated panels for renovation

This technical solution allows energy renovation of one family houses to nZEB standards using polyurethane foam elements enclosed in cement based boards. In order to fulfill BR15 for renovation in this study are chosen element with 150 mm PUR and cement board of 16 mm on one side. Prices presented in Table 14 includes: finish joints, drilled bindings made of stainless steel, building materials required to execute work such as crane etc. If existing work brick and insulation is demolished then PUR elements can be installed directly on existing foundation. Prices are calculated only for one house but savings for larger orders are possible, however, they would vary depending on: complexity of the project, access to the site, client's economic situation (prepayment) .

Table 14 Price calculation for demolition of existing external façade and replacement with new PUR prefabricated element.

External brick work demolition

No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	83,5	72,42	6.047	

PUR panel of 150 mm with cement plate finish and necessary materials

No. houses	Area (m2)	Price/m2	Total price/house
1 house	83,5	750,0	62625

PUR panel installation including crane and other equipment

No. houses	Area (m2)	Price/m2	Total price/house
1 house	83,5	550,0	45925

TOTAL PRICE	Price per house
1 house	114.597

4.2 External light wall

Energy renovation of existing light external wall consists of:

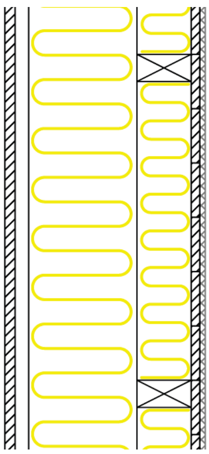
- Demolition of existing light façade
- Installation of new insulation
- Construction of new façade

If the wall has signs of condensation then existing moisture membrane is probably not tight and wall requires new moisture membrane that can be applied on the internal (warm side) side of the existing insulation before new insulation is mounted.

Figure 52. Three finish materials for light external wall: timber (left), fiber boards (middle), cedar wood (right).

Result of this analysis shows that major expanse in energy renovation of light external wall is related to material used for external material used for external finish, see Figure 52, and see price calculations for different renovation activity presented in

Table 15.



	- 25 mm 2 layers of plaster boards
	- Vapour membrane
	- 100 mm mineral wool on timber posts
	- 150 mm new mineral wool
	- 20 mm wooden cladding W/m²K
	Calculated U value 0,15 W/m²K
	* To reach requirements from Danish BR15 for minimum U value 0,18 W/m²K additional insulation has to be added.

Figure 53. Light wall construction with additional insulation on the outside.

Table 15. Price calculation for light weight external wall insulation; different finish materials considered.

Wooden facade disassembly				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	4	95	380	
10 houses	40	73	292	23
50 houses	200	63	251	34

New mineral wool insulation (150 mm)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	4	186	742	
10 houses	40	160	640	14
50 houses	200	151	603	19

Establishement of new facade - timber wood				
No. houses	Area (m2)	Price/m2	Total price	Saving [%]
1 house	4	52	209	
10 houses	40	43	174	17
50 houses	200	39	156	26

Establishement of new facade - fiber facade plates				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	4	466	1.864	
10 houses	40	385	1.541	17
50 houses	200	345	1.379	26

Establishement of new facade - Cedar wood				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	4	1.009	4.036	
10 houses	40	854	3.418	15
50 houses	200	774	3.096	23

TOTAL PRICE (CASE 1 - Timber)	Price per house	Saving (%)
1 house	1.332	
10 houses	1.105	17
50 houses	1.009	24

TOTAL PRICE (CASE 2 - Fiber plates)	Price per house	Saving (%)
1 house	2.986	
10 houses	2.473	17
50 houses	2.233	25

TOTAL PRICE (CASE 3 - Cedar wood)	Price per house	Saving (%)
1 house	5.159	
10 houses	4.349	16
50 houses	3.950	23

Total renovation price can vary with factor up to 4-5 and depends on which material is chosen to finish the façade. Insulation material and work related to the cheap finish solution represents approximately 50% of total cost, but in expensive finish solution it would represent only approximately 14%. This indicates that price of the material chosen for the external finish has major influence on the total price for this job.

4.3 Roof

Roof insulation is very often one of the first choices because it is relatively simple and fast renovation procedure. There are two main technics to renovate: using mineral wool bats and blowing granulated insulation directly on the existing insulation. It is recommended to check if existing vapor membrane is tight. If not, new membrane should be tightly mounted.

Price calculation for the case house is presented below in Table 16. Calculations cover two insulation methods, namely using mineral wool bats and blowing granulate.

Table 16. Price calculation for roof insulation; with insulation bats; with blowing granulate.

Air and moisture tightening with vapor membrane				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	127,5	28	3.556	
10 houses	1275	23	2.892	19
50 houses	6375	20	2.574	28
*price for removing old insulation is not included				

Additional roof insulation - 200 mm mineral wool kl. 37				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	127,5	197	25.132	
10 houses	1275	166	21.151	16
50 houses	6375	150	19.125	24

Additional roof insulation - 250 roof granulate kl. 44				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	127,5	270	34.389	
10 houses	1275	228	29.092	15
50 houses	6375	214	27.233	21

It can be observed that blowing granulated insulation might be more expensive than mineral wool bats. Moreover, because granulate has higher thermal conductivity it is required to apply 50 mm more insulation comparing to mineral wool bats.

4.4 Floor on the ground

Insulation of the existing floor on the ground is rather difficult, time demanding and expensive procedure. Several works have to be included in the total price, such as:

- Demolition of existing wooden floor and concrete beneath
- Removing of existing insulation
- Excavation of the ground and capillary breaking layer below existing ground
- Establishment of new capillary breaking layer
- New insulation
- Casting new concrete deck (reinforcement)
- Moisture membrane
- Wooden battens and insulation between battens
- New floor cover

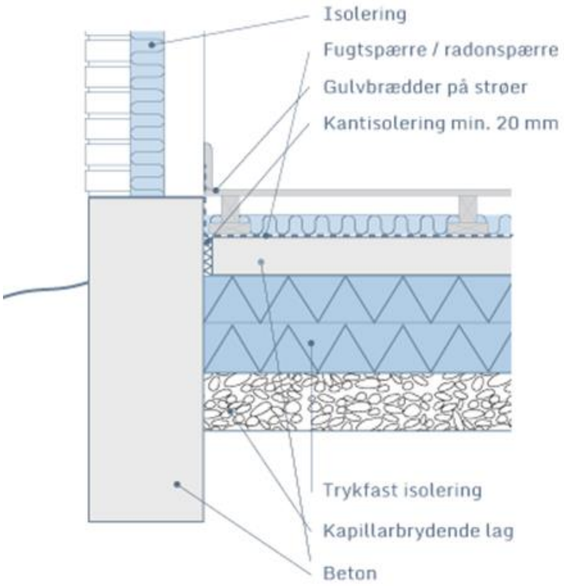


Figure 54. Schematic drawing indicating floor on the ground after insulation.

Price of each activity was calculated for the case house. Then prices were summed for all activities also including different floor finish scenario, see Table 17.

Table 17. Price calculation for floor on the ground insulation; with three different finish solutions.

Demolition of existing floor, hand work(not reinforced concrete 100 mm)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	401	49.980	
10 houses	1246	401	49.980	0
50 houses	6230	401	49.980	0
*without container to remove				

Removing existing insulation (50 mm)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	81	10.104	
10 houses	1246	67	8.374	17
50 houses	6230	60	7.518	26
*without container to remove				

Hand excavation of 60 cm for new insualtion and leca capilary breaking layer				
No. houses	Volume (m3)	Price/m2	Total price/house	Saving [%]
1 house	74,76	550	41.111	
10 houses	747,6	470	35.141	15
50 houses	3738	430	32.113	22
*Price includes removing soil from the site				

New capilary breaking layer 200 mm				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	128	15.958	
10 houses	1246	108	13.488	15
50 houses	6230	98	12.234	23

New insulation EPS 80, 200 mm				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	213	26.550	
10 houses	1246	186	23.146	13
50 houses	6230	171	21.325	20

New concrete casting 10 mm (20 Mpa)				
No. houses	Volume (m3)	Price/m2	Total price/house	Saving [%]
1 house	12,46	2.419	30.145	
10 houses	124,6	2.094	26.091	13
50 houses	623	1.922	23.954	21

New vapor barrier on the ground				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	14	1.729	
10 houses	1246	12	1.463	15
50 houses	6230	11	1.327	23

New 50 mm mineral wool insulation between battens				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	81	10.083	
10 houses	1246	69	8.551	15
50 houses	6230	62	7.771	23

New 47x50 mm battens on the concrete				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	81	10.083	
10 houses	1246	69	8.551	15
50 houses	6230	62	7.771	23

Floor finish was calculated for 3scenarios: standard, premium and delux.
All above listed in tables activities can be finished with one of the 3 floor finish.

STANDARD (laminats)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	536	66.784	
10 houses	1246	467	58.229	13
50 houses	6230	431	53.655	20
PREMIUM (wooden flors, wooden planks)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	677	84.308	
10 houses	1246	595	74.085	12
50 houses	6230	550	68.526	19
DELUX (parquet, merbau,oak, ash)				
No. houses	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	124,6	1.867	232.637	
10 houses	1246	1.649	205.515	12
50 houses	6230	1.530	190.588	18

Total price - **STANDARD** finish		
No. houses	Total price/house	Saving [%]
1 house	262.526	
10 houses	233.014	11
50 houses	217.650	17

Total price - **PREMIUM** finish		
No. houses	Total price/house	Saving [%]
1 house	280.050	
10 houses	248.870	11
50 houses	232.521	17

Total price - **DELUX** finish		
No. houses	Total price/house	Saving [%]
1 house	428.379	
10 houses	380.300	11
50 houses	354.582	17

It can be observed that total price for insulation of the floor on the ground is very high and it is never cost-effective to renovate floor on the ground. What is more, floor finish represents a significant share of the total cost and therefore it would be recommended to do thermal insulation of the floor when floor cover requires change to a new one. Calculations indicate that total price of floor insulation depends a lot on the material chosen for the floor covering. Investment in floor insulation should not be considered as investment in energy saving but investment in better comfort and new aesthetic of the interior.

4.5 Floor above unheated crawl basement

Insulation of floor above crawl basement is significantly easier and cheaper task than insulation of floor on the ground. Existing floor in the most of the cases, or majority of it, can be kept untouched during insulation works. In this price calculation that is presented in Table 18, it is assumed that crawl basement is under entire case house but in the most of the parcel houses built in 1960-1976, crawl basement was under only a part of the building and rest was floor on the ground.

Table 18. Price calculation for insulation of the floor above unheated crawl basement.

Insulation of floor above crawl space 145 mm)				
No. houses	Area (m2)	Price/m2	Total price	Saving [%]
1 house	124,6	178	22.136	
10 houses	1246	151	18.838	14
50 houses	6230	137	17.128	23

Presented prices are only estimates because actual price could depend on particular local condition, access to crawl basement, space to perform work, additional works necessary to complete insulation.

Floor above crawl basement should not be insulated to more than 150 mm because there could occur moisture problems in the crawl space.

Vapor membrane should be installed on the warm side of the insulation, see Figure 55. Price of the membrane installation would depend on accessibility to perform work.

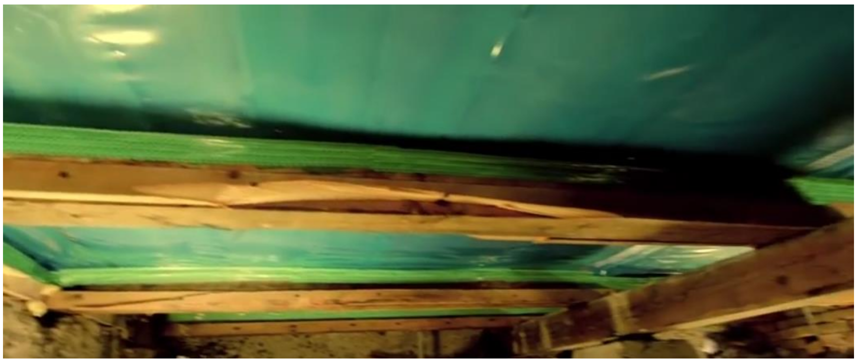


Figure 55. Vapor membrane under existing wooden floor above crawl basement.

4.6 Foundation and footing

If external walls are energy renovated from the outside it would be also recommended to insulate foundation and footing. This work requires digging around house perimeter. Although it is not included in the presented price calculations it is recommended to establish perimeter drain and moisture membrane along insulation works.

In the price calculations presented in Table 19, it is assumed that 20% of work requires hand digging and remaining 80% is done with excavator.

Table 19. Price calculation for insulation of the foundation and house footing.

Hand digging around perimeter							
	Perimeter (m)	Width (m)	Depth	Volume (m3)	Price/m³	Total price/house	Saving [%]
1 house	50,8	0,5	0,6	3,05	2.021	6.062	
10 houses	508	0,5	0,6	30,48	1.460	4.381	28
50 houses	2540	0,5	0,6	152,40	1234	3.751	39

Excavator digging around perimeter							
	Perimeter (m)	width	Layers	Volume (m3)	Price/m³	Total price/house	Saving [%]
1 house	50,8	0,5	0,6	12,19	592	7.105	
10 houses	508	0,5	0,6	121,92	428	5.134	28
50 houses	2540	0,5	0,6	609,60	361	4.409	39

Insualtion around foundation with 150 mm mineral wool						
	Perimeter (m)	Width (m)	Area (m2)	Price/m2	Total price/house	Saving [%]
1 house	50,8	1	50,8	320	16.237	
10 houses	508	1	508	278	14.137	13
50 houses	2540	1	2540	256	12.996	20

Alu drip cap 150 mm				
	Perimeter (m)	Price/m	Total price	Saving [%]
1 house	50,8	123,44	6.271	
10 houses	508	109	5.539	12
50 houses	2540	101	5.133	18

Total price	Price per house	Saving
No. houses		[%]
1 house	35.675	
10 houses	29.190	18
50 houses	26.289	26

Foundation insulation will decrease line losses related to connection between external wall and foundation. Heat losses through the floor will also be decreased.

4.7 Windows

Price of new windows varies significantly depending on the model, opening possibility, frame material, glass type and manufacturer. Variation for window of the same size can reach up to 50% and even higher. However, there are some rules of thumb indicating that price increase from two pane widow to triple pane windows is approximately 25-35% %. Price increase from wooden frame to wood and aluminum frame is around 25-35%. On Danish market when exchanging old windows to the new windows it should be expected that work for dismounting old windows and installation of new windows is approximately equal to purchase price of the new windows. Due to large variation in prices no exemplary calculations are presented.

4.8 Ventilation

As presented earlier in this document mechanical ventilation system can be either centralized or decentralized. In the presented analysis only prices for centralized were available and therefore only these are presented.

Centralized mechanical ventilation system

In the calculations it is assumed that ventilation system can provide 0.3 $l/s/m^2$ of heated floor area and this is to fulfill Danish BR15. For the analyzed case house total air flow is calculated to 147 m^3/h. The smallest air handling unit that could deliver up to 325 m^3/h was chosen. Unit has heat counter flow heat exchanger, filters and possibility for heating coil installation (but heating coil is not included in the proposed price calculation).

Centralized mechanical ventilation requires also ducts, inlet and outlet diffusers, regulation dampers, silencers, roof hoods, automation. Prices of these elements were summed up in separate table and finally total price was calculated for investment in 1, 10 and 50 houses. It can be observed that quantity discount is not large and this is because in the data base there is foreseen no discount for automation. In real project it might be that automation could be offered with discount depending on the quantity. Prices for entire system including central unit, ducts, automation and other components and are presented in Table 20. Prices in real life can vary though if significantly less or more work must be done to execute installation.

Table 20. Price calculation for mechanical ventilation system.

Instalation of new mechanical ventilation unit			
Ventilation unit	Price/unit	Total price	Saving
1 house	25.579		[%]
10 houses	22.620	226.200	12
50 houses	20.942	1.047.094	18

	1 house	10 houses	50 houses
Ducts			
Ducts Ø 100	12.708	106.920	484.200
Ducts Ø 125	7.940	66.400	299.000
Ducts Ø 160	4.500	37.400	168.000
Ducts total	25.148	210.720	951.200
Silencers	1.590	27.250	124.297
Inlet and outlet diff.	3687	31.762	145.454
Roof hoods	1.469	11.166	49.200
Regulaion manual dampers	1.076,03	37.300	171.300
Automatic	22.289	222.374	1.110.079
Total price	80.838	766.772	3.598.624
Price per house	**80.838**	**76.677**	**71.972**
Saving (%)		5	11

4.9 Boiler

New boilers have modulated effect and therefore one model can cover relatively broad range of heating needs. Presented prices include disassembly of old boiler and installation of the new boiler. Price does not include insulation of pipes, but this is relatively small cost in the total investment. Price analysis is performed for gas and oil boiler, but in both cases fuel is in the liquid state therefore in both cases in the total price is included storage tank for fuel and necessary ground work. For oil boiler analysis is done for normal boiler and high efficient condensing boiler.

4.9.1 Oil boiler (up to 18 kW)

Price calculation for oil boiler installation are presented in Table 21.

Table 21. Price calculation for oil boiler installation.

Normal boiler		
New boiler instalation	Price per house	Saving
1 house	41.404	[%]
10 houses	36.353	12
50 houses	33.542	22

Good condensing boiler with high efficiency and storage tank		
New boiler instalation	Price per house	Saving
1 house	59.209	[%]
10 houses	52.182	12
50 houses	48.232	21

Oil or gas tank instalation in the ground: 2500l		
New oil tank	Price per house	Saving
1 house	24.318	[%]
10 houses	21.135	13
50 houses	19.405	23

Ground work		
Ground work	Price per house	Saving
1 house	1.787	[%]
10 houses	1.450	19
50 houses	1.285	35

Total price - normal boiler	Price per house	Saving
1 house	67.510	[%]
10 houses	58.938	13
50 houses	54.231	23

Total price - high efficient boiler	Price per house	Saving
1 house	85.315	[%]
10 houses	74.767	12
50 houses	68.922	22

4.9.2 Gas boiler (modulated between 3 and 16 kW)

Price calculation for gas boiler installation are presented in Table 22.

Table 22. Price calculation for gas boiler installation.

Good high efficinet kondensing boiler		
New boiler instalation	Price per house	Saving
1 house	30.476	[%]
10 houses	26.590	13
50 houses	24.459	23

Oil or gas tank instalation in the ground: 2500l		
New oil tank	Price per house	Saving
1 house	24.318	[%]
10 houses	21.135	13
50 houses	19.405	23

Ground work		
Ground work	Price per house	Saving
1 house	1.787	[%]
10 houses	1.450	19
50 houses	1.285	35

Total price -condensing boiler	Price per house	Saving
1 house	56.582	[%]
10 houses	49.175	13
50 houses	45.148	23

4.10 District heating connection

Changing from older oil or gas boiler to district heating is also regarded as energy saving. Economic benefits depend on the local district heating prices. In Denmark prices for heat from district heating vary significantly and there is factor of up to approximately 5 between the cheapest and the most expensive district heating network. Therefore, prices and savings should be always checked individually with local heat supplier. House owner must expect expenses related to connection to district heating, if changing from oil or gas boiler, to district heating. In the analysis are presented, as example, cost for connecting house in Aalborg, Aarhus, Copenhagen and Fredericia, see Table 23, Table 24, Table 25and Table 26.

Table 23. District heating connection price in Aalborg.

Aalborg	Price (excl. tax)	Price (incl. tax)
Connection fee	12.500	15.625
Conduction in the footing	10.625	13.281
Connection pipe (10m)	11.250	14.063
Meter assembly and test	1.437	1.796

If one family house is renovated minimum to low energy building class 2015 specified in BR2010 then house owner receives discount of 3.750 DKK. Moreover, owner of such a house has possibility to negotiate further discount when converting from oil or gas to district heating.

Table 24. District heating connection price in Aarhus.

Aarhus	Price (excl. tax)	Price (incl. tax)
Connection fee	14.900	18.625
Conduction in the footing		
Connection pipe (10 m)	10.370	12.963
En. meter assembly and test		
Total (excl. tax)	25.687	

If house is at least renovated as low energy building according to BR10 (which is less than nZEB) then building owner receive total discount of 9.313 DKK.

Table 25. District heating connection price in Copenhagen.

Copenhagen	Price (excl. tax)	Price (incl. tax)
Average connection price	7.406	9.875
*Price is calcualted individualy		

Table 26. District heating connection price in Fredericia.

Connection fee	(House area +0,3* basemen area)* 80 DKK	Mulitplies with 1,25
Conduction of the pipe	10000	12500
En. meter assembly and test	Included in connection pipe	
Total (excl. tax)		

Moreover, all house owners can apply for energy subsidy for converting boiler to district heating. Stakes vary depending on type and year of installation of the boiler.

4.11 Heat Pump

Presented calculations consider heat pump with ground heat exchanger. Analysis include price calculation for heat pump installation with integrated and with external hot water storage tank. Analysis is conducted for heat pump effect from 4 up to 12 kW. Correspondingly, ground heat exchanger was sized and its price was estimated depending on heat pump heating effect capacity.

In the price calculation it is assumed that:

- Ground heat exchanger is machine excavated
- Ground heat exchanger can provide 20W/m
- Pipes are located 1,5 m deep and with 1 m spacing

4.11.1 1Heat pump with external storage tank

In Table 27 are presented prices for heat pump systems with external storage tank.

Table 27. Price calculation for heat pump system with external storage tank.

Heat pump without storage tank					
Type DHP-L	1 house	10 houses		50 houses	
Effect	Price /unit				
[kW]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	99.927	86.962	13	79.893	20
6	104.195	90.662	13	83.286	20
8	111.833	97.359	13	89.461	20
10	118.303	102.923	13	94.544	20
12	124.011	107.812	13	98.999	20

Storage tank to DHP-L heat pump						
Type DHP-L	Storage tank volume	1 house	10 houses		50 houses	
Effect		Price /unit				
[kW]	[l]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	200	15.400	13.398	13	12.320	20
6	200	15.400	13.398	13	12.320	20
8	200	15.400	13.398	13	12.320	20
10	300	20.460	17.800	13	16.368	20
12	300	20.460	17.800	13	16.368	20

Assembly of well for manifold		
exchanger	Price [DKK]	Saving
1 house	3.142	[%]
10 houses	2.632	16
50 houses	2.372	24

Horizontal heat exchanger						
Type DHP-L		1 house	10 houses		50 houses	
Effect	Length of pipe in heat exchanger	Price /house				
[kW]	[m3]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	200	48.406	41.110	15	37.429	23
6	300	70.353	60.138	15	54.958	22
8	400	91.797	78.819	14	72.214	21
10	500	112.885	97.252	14	89.274	21
12	600	133.700	115.494	14	106.185	21

Total price with external storage tank (Heat pump+storage tank+ground heat exchanger)					
Type DHP-L	1 house	10 houses		50 houses	
Effect	Price /unit				
[kW]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	166.875	144.102	14	132.014	21
6	193.090	166.830	14	152.937	21
8	222.172	192.207	13	176.367	21
10	254.790	220.607	13	202.559	20
12	281.313	243.738	13	223.924	20

4.11.2 Heat pump with integrated storage tank

In Table 28 are presented prices for heat pump systems with integrated storage tank.

Table 28. Price calculation for heat pump system with external storage tank.

Heat pump with storage tank					
Type DHP-H	1 house	10 houses		50 houses	
Effect	Price /unit				
[kW]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	79.511	68.970,43	13	63.264	20
6	85.736	74.410,67	13	68.272	20
8	92.288	80.140,86	13	73.549	20
10	99.736	86.575,38	13	79.440	20
12	106.205	92.140,05	13	84.523	20

Assembly of well for manifold		
exchanger	Price [DKK]	Saving
1 house	3.142	[%]
10 houses	2.632	16
50 houses	2.372	24

Horizontal heat exchanger						
Type DHP-L	Length of pipe in heat exchanger	1 house	10 houses		50 houses	
Effect		Price /house				
[kW]	[m3]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	200	48.406	41.110	15	37.429	23
6	300	70.353	60.138	15	54.958	22
8	400	91.797	78.819	14	72.214	21
10	500	112.885	97.252	14	89.274	21
12	600	133.700	115.494	14	106.185	21

Total price with integrated storage tank (Heat pump with integrated storage tank+ground heat exchanger)					
Type DHP-L	1 house	10 houses		50 houses	
Effect	Price /unit				
[kW]	[DKK]	[DKK]	Saving [%]	[DKK]	Saving [%]
4	131.059	112.712,51	14	103.066	21
6	159.232	137.180,99	14	125.603	21
8	187.227	161.591,38	14	148.135	21
10	215.763	186.458,84	14	171.346	21
12	243.047	210.266,31	13	193.080	21

Total investment cost of each scenario was plotted for different heat pump effect together with heat demand calculated for case house before renovation (case 0) and for 15 different renovation packages presented in chapter 2.7.

As an example, it is indicated what would be investment cost in a heat pump before house is energy renovated, comparing to renovation case 14. Example is valid for installation of one heat pump with external storage tank. It can be observed in Figure 56 that due to energy renovation of the envelope smaller and cheaper heat pump can be bought and approximately 50.000 DKK could be saved.

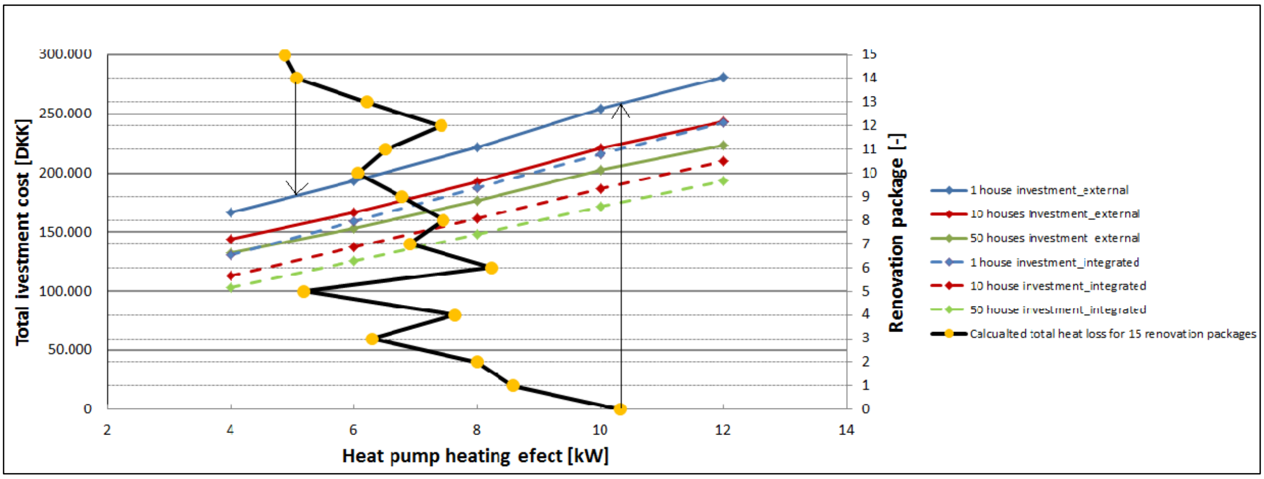


Figure 56. Relation between heating demand/renovation package scenario and investment cost in heat pump.

It can be concluded that significant money saving can be obtained when investing in the new heat pump with ground heat source is installed after building envelope is energy renovated.

What is more, this study indicates that further significant savings could be obtained if investment in new heat pump was organized by larger group of home owners. Total savings for entire installation can reach between approximately 13 and 20 % depending on the number of houses.

4.12 Solar collectors

There is no demand with regards to amount of solar collector that should be installed on the renovated house. The more collectors the bigger share of domestic hot water will be covered by renewable heat source and at the same time the less energy will be used from fossil fuels. Analysis presents 3 standard collector installation sizes of 2.2, 4.4 and 6.6 m². In Table 29 can be found estimate of the annual energy production and estimate installation cost of the 3 installations sizes ranging between 2.2 and 6.6 m².

Table 29. Price calculation for three solar collector installations ranging from 2.2 up to 6.6 m².

1 house			
Panels area [m²]	2,2	4,4	6,6
Cover [person]	1-2 person	2-3 person	3-4 person
Storage tank [liter]	200	300	400
Energy production south[kWh]	615	1229	1845
Energy production west/east[kWh]	392	784	1176
Nominal effect [kW]	1,4	2,9	4,3
Automatic	yes	yes	yes
Mounting	yes	yes	yes
Pipes	yes	yes	yes
Liquid	yes	yes	yes
Circulation pump + valves	yes	yes	yes
Installation work	yes	yes	yes
Price [DKK]	**32.164**	**40.009**	**47.854**

10 houses			
Panels area [m²]	2,2	4,4	6,6
Cover [person]	1-2 person	2-3 person	3-4 person
Storage tank [liter]	200	300	400
Energy production south[kWh]	615	1229	1845
Energy production west/east[kWh]	392	784	1176
Nominal effect [kW]	1,4	2,9	4,3
Automatic	yes	yes	yes
Mounting	yes	yes	yes
Pipes	yes	yes	yes
Liquid	yes	yes	yes
Circulation pump + valves	yes	yes	yes
Price [DKK/1 house]	**27.994**	**34.887**	**41.779**

50 houses			
Panels area [m²]	2,2	4,4	6,6
Cover [person]	1-2 person	2-3 person	3-4 person
Storage tank [liter]	200	300	400
Energy production south[kWh]	615	1229	1845
Energy production west/east[kWh]	392	784	1176
Nominal effect [kW]	1,4	2,9	4,3
Automatic	yes	yes	yes
Mounting	yes	yes	yes
Pipes	yes	yes	yes
Liquid	yes	yes	yes
Circulation pump + valves	yes	yes	yes
Price [DKK/1 house]	**25.720**	**32.082**	**38.443**

2,2 m² panel installation		
	Price per house	Saving
1 house	32.164	
10 houses	27.994	13
50 houses	25.720	20

4,4 m² panel installation		
	Price per house	Saving
1 house	40.009	
10 houses	34.887	13
50 houses	32.082	20

6,6 m² panel installation		
	Price per house	Saving
1 house	47.854	
10 houses	41.779	13
50 houses	38.443	20

Presented calculation indicate that for 10 and 50 houses investment expected savings are respectively at 13% and 20%.

4.13 Solar cells

There is no demand with regards to amount of solar cells that should be installed on the renovated houses. The more cells the bigger share of electricity will be covered by renewable source and at the same time the lower electricity will be used from fossil fuels. Most cost effective scenario is when on the annual electricity use equals annual electricity production from the cells.

Analysis presents 3 standard photovoltaic module installation sizes ranging between 11.5, , 17.9 to 24.3 m². In Table 30 can be found estimated annual electricity production and estimated cost of the 3 installation sizes.

Table 30. Price calculation for three solar cell installations ranging from 11.5 up to 24.3 m².

1 house			
Set number	1	2	3
Number of modules (0,8x 1,6 m)	9	14	19
Area [m²]	11,5	17,9	24,3
Energy production south [kWh]	1622	2540	3458
Energy production west/east [kWh]			
Inverter	yes	yes	yes
Mounting set	yes	yes	yes
Cables	yes	yes	yes
Power switch	yes	yes	yes
Installation work	yes	yes	yes
Price [DKK]	**45.992**	**71.198**	**96.403**

10 houses			
Set number	1	2	3
Area [m²]	11,5	17,9	24,3
Energy production south [kWh]	1622	2540	3458
Energy production west/east [kWh]			
Inverter	yes	yes	yes
Mounting set	yes	yes	yes
Cables	yes	yes	yes
Power switch	yes	yes	yes
Installation work	yes	yes	yes
Price [DKK]	**40.879**	**63.282**	**85.685**

50 houses			
Set number	1	2	3
Area [m²]	11,5	17,9	24,3
Energy production south [kWh]	1622	2540	3458
Energy production west/east [kWh]			
Inverter	yes	yes	yes
Mounting set	yes	yes	yes
Cables	yes	yes	yes
Power switch	yes	yes	yes
Installation work	yes	yes	yes
Price [DKK]	**37.937**	**58.728**	**79.518**

11,5m² cell installation		
	Price per house	Saving
1 house	45.992	
10 houses	40.879	11
50 houses	37.937	18

17,9 m² cell installation		
	Price per house	Saving
1 house	71.198	
10 houses	63.282	11
50 houses	58.728	18

24,3 m² cell installation		
	Price per house	Saving
1 house	96.403	
10 houses	85.685	11
50 houses	79.518	18

Primary energy factors should be used when integrating electricity production in the annual theoretical energy balance of the house. In Denmark for electric energy production primary energy factor is 2.5.

Presented calculation indicate that for 10 and 50 houses investment expected savings are respectively at 11% and 18%.

5 Part 4 – Cost efficiency calculation

Cost efficiency calculations are made with the purpose of sorting the proposed renovations and solutions in respect to investment cost, lifetime and saved energy. The sorting is later used to choose which technical solutions are included in the packages and in which order.

Cost efficiency calculation is based on the investment cost, lifetime and saved energy for each technical solution. Investment cost of each solution is previously presented in section 3 of this report. The amount of energy saved by implementing each of the technical solutions is presented in Figure 57. Lifetime of a given technology depends on variety of factors, such as, type of technology, quality of the product, quality of installation, correct use, maintenance and etc. For the current calculation, lifetime of the technologies are taken from Annex 6 of the Danish Building Regulations 2015.

Cost efficiency is calculated by the formulas given below. The results from the calculation for all technologies are presented in Table 31 and Table 32.

$$Investment\ cost\ per\ year = \frac{Investment\ cost}{Lifetime}\ \left[\frac{DKK}{year}\right]$$

$$Cost\ Efficiency = \frac{Investment\ cost\ per\ year}{Saved\ energy}\ \left[\frac{DKK}{year} per\ saved\ \frac{kWh}{m^2}\ per\ year\right]$$

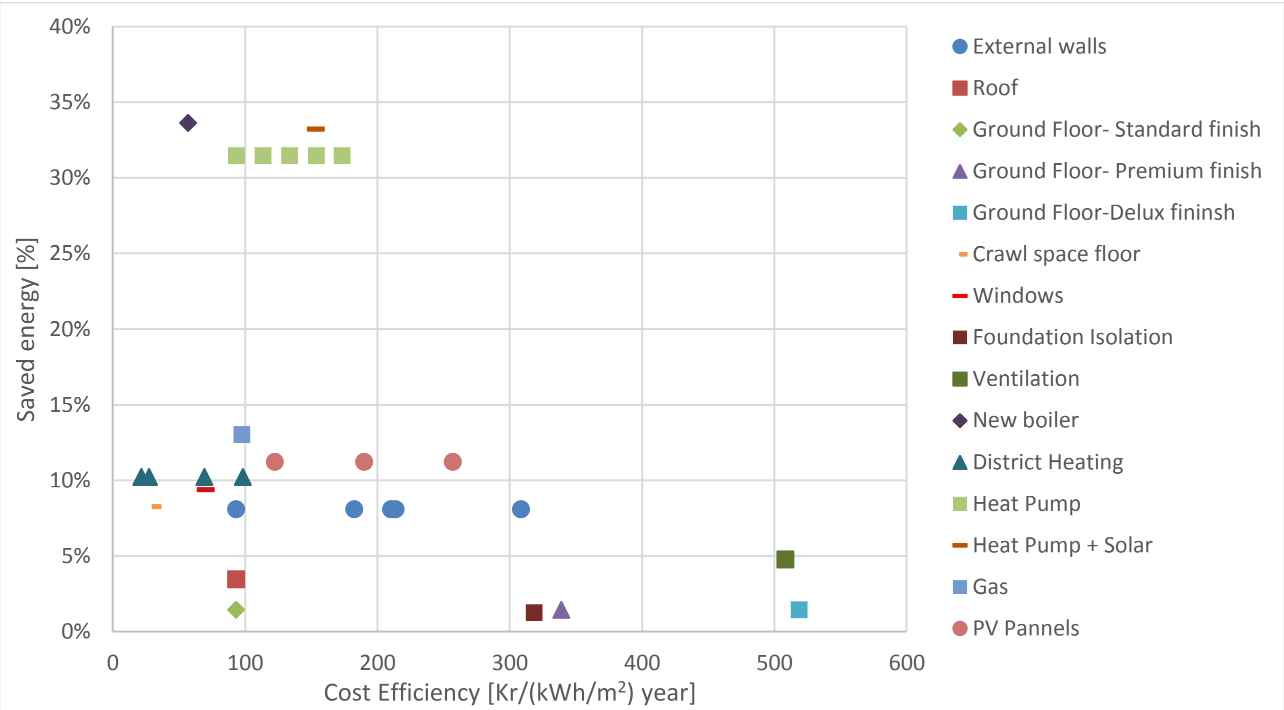


Figure 57. Saved energy of each technology as a function of cost efficiency.

Figure 57 shows the saved energy obtained by each 'one at-a-time' renovation as a function of its cost efficiency. As one can observe in Figure 57, some of renovated elements have more than one price. This is result of the different options provided for some of those elements. For example, in the case of external walls 4 different investment cost (4 different technical solutions) provide the same energy savings.

Table 31. Sorting of Investigated technologies according to cost efficiency

Sorted according to cost efficiency		
Envelope	Systems	DKK/(kWh/m²) year
	District heating - Copenhagen	22
Crawl space floor		25
	District heating - Fredericia	27
	New boiler	57
	District heating - Aarhus	69
Windows		70
Roof insulation		93
	Heat Pump – heat + water - 4 kW	93
	Gas Boiler	98
	District heating - Aalborg	98
	Heat pump – heat + water- 6 kW	114
	PV cells 11.5 m^2	122
	Heat Pump – heat + water - 8kW	134
	Heat Pump - heat + water 6kW + 4.4m^2 solar	135
	Heat Pump -heat + water- 10 kW	154
	Heat Pump - heat + water- 12 kW	173
Demolition of existing external wall + new thicker insulation + brick tiles		182
	PV cells 17.1 m^2	190
External wall – Cavity insulation + REDart		210
External wall - Rockwool REDart		214
	PV cells 24.3 m^2	257
Demolition of existing external wall+ new thicker insulation + new ext. wall		308
Ground Floor- Standard finish		318
Insulation of foundation - Line Loss		319
Ground Floor - Premium finish		339
	Ventilation	508
Ground Floor-Deluxe finish		518

Table 32. Sorting of investigated technologies according to investment cost.

Sorted by total investment cost		
Envelope	Systems	Cost [DKK]
	District Heating - Copenhagen	9,875
	District Heating - Fredericia	12,500
Insulation of crawl space floor		18,337
Roof Insulation		28,688
	District Heating - Aarhus	31,588
Insulation of foundation - Line Loss		35,675
Ground floor - Standard finish		40,664
Ground floor - Premium finish		43,397
Windows		43,981
	District Heating - Aalborg	44,765
	PV cells - 11.5 m^2	45,992
	Gas	56,582
Ground floor - Delux finish		66,354
	PV cells 17.1 m^2	71,198
	Ventilation	80,838
	New boiler	85,315
	PV cells 24.3 m^2	96,403
	Heat Pump - heat + water - 4 kW	131,059
External wall - Demolition of existing + new thicker insulation + brick tiles		131,297
External wall - Cavity insulation +REDart		151,451
External wall - Rockwool REDart		153,828
	Heat Pump - heat + water - 6 kW	159,232
	Heat Pump - heat + water - 8kW	187,227
	Heat Pump –heat + water - 6kW + 4.4m^2 solar	199,241
	Heat Pump - heat + water - 10 kW	215,763
External wall - Demolition + new thicker insulation + new ext. wall		222,119
	Heat Pump - heat + water - 12 kW	243,047

6 Part 5 – Development of final renovation packages examples

The starting point for developing the final renovation packages is using methodology focusing on getting the best energy savings for the investment. Therefore, priority is given to technologies with high cost efficiency (as sorted in Table 31). Initially it was agreed that 5 packages with value starting from 200,000 up to 1,000,000 DKK would be prepared. To achieve systematic but also realistic selection, the methodology is applied alongside engineering considerations related to construction processes (for example if the external wall is refurbished the insulation of the foundation is prioritized as works would be happening in the same area of the building).

The method for selection of renovation package is as follows

- Select the most cost efficient option as sorted in Table 31.
- Check the investment cost of the selected technology from Table 32.
- Compare the cost of the technology with the available amount of funds in the package.

From this point on there are few possible outcomes depending on the available funds and investment cost of the technology. Those are:

1. In case where the cost of the technology is lower than the available funds in the package, new iteration as described above is made.
2. In case where the cost of the technology is equal or ±10 - 15 % of the available funds for the representative package, the package is fulfilled and formation of the next package can begin.
3. In case where the cost of the technology is greater than the available funds of the package, the next most cost effective technology is chosen and its investment cost is compared to the available funds in the package. This is done as some of the technologies may have low cost efficiency, but also low investment cost.

As it can be observed from Table 31 and Table 32 the investment cost of district heating varies depending on the location in the country. Furthermore, as district heating is not readily available in the whole country, this technological solution was excluded from the initial renovation package. The initial five packages, shown in Figure 58, were developed by performing the methodology described above.

After development, the initial renovation packages were subjected to a number of rounds of discussion between the Danish partners in the project. Furthermore a stakeholder meeting with home-owners was held in order to receive feedback regarding the different renovation concepts. The different discussions and the stakeholder meeting resulted in several iterations of the packages. Brief description of the content of the performed discussions, iterations and applied changes are described further in bullet points at the end of this chapter. The final renovation packages can be found in [1] and in the [5].

	Package 1	Package 2	Package 3	Package 4	Package 5
Insulation crawl space floor	✓	✓	✓	✓	✓
New boiler	✓	✓			
Roof insulation	✓	✓	✓	✓	✓
Demolition of existing insulation + new thicker insulation + brick tiles		✓			
Foundation insulation	✓	✓	✓	✓	✓
Mechanical ventilation		✓	✓	✓	✓
Change of windows			✓	✓	✓
Ground floor - Standard finish				✓	✓
External wall - Rockwool REDart			✓	✓	
Demolition of existing insulation + new thicker insulation + new external wall					✓
Heat pump - 6 kW			✓	✓	
Combined heat pump + 4.4 m^2 Solar cells					✓
11.2 m^2 PV cells					✓
Energy savings relative to a house with energy use of approximately 298 kWh/m^2 year	33%	40%	72%	76%	85%

Figure 58. Initial, cost-optimal renovation packages.

- As some home owners would not have the possibility or will to invest in one of the most comprehensive renovation packages but have high NZEB-ambition a step-by-step approach was developed. Such step-by-step (staged renovation) was developed alongside the renovation packages, where home-owners can build up gradually to complete renovation. This renovation concept could be applicable to empty nesters or young families with limited investment possibilities.
- Windows are prioritized and should be included in the first renovation package. This decision was made as windows are fairly easy to replace, when compared to other investigated technologies shown in Figure 58. Furthermore, besides energy saving, new windows bring both comfort and esthetic improvements to the house, thus rather significantly increase its value.
- Despite district heating connection price variation and limited availability this heat source possibility should be considered. As District heating is a green solution with primary energy factors lower than 1, it is always considered as first step in the renovation process for both package and staged renovation scenarios. Given that in suburban areas district heating network is not available, but in urban areas usually is, 2 scenarios were developed; one with and one without district heating are developed for both package and stage renovation scenarios.
- Even though gas boiler are not green, those are included in the packages or stages when district heating is not an option. This is done on the basis that a gas boiler can be a transition solution for the period until 2050, and then exchanged with more sustainable option. Furthermore it is yet unknown to if and to what extent bio gas would replace gas.
- Throughout the iteration process it was decided that the number of packages and stages should be reduced from five to four.

- Furthermore the starting investment sum in package/stage 1 is reduced from 200,000 DKK to 100,000 DKK.
- Insulation of the external wall is excluded from the packages/stages. This is done as the external wall insulation is very expensive as the renovation in the majority of the cases includes demolition and construction of one of the brick 'leafs' of the external walls.
- Technological solutions that provide comfort improvements are marked and ranked in tree scales. The scale distinguishes from small, medium and high comfort improvement achieved by the given technology. Another indication for improvement in esthetic/architectural improvement is also integrated for different technological solutions.

7 Reference

[1] M. Pomianowski, Y.I. Antonov, P. Heiselberg, P. Rathje, Development of optimized renovation packages as essential value in creation of the successful compelling offer, under publication in proceeding of ICARRC, 20th International Confernce on Architectural Renovation, Restoration and Conservation, 2018.

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