NTNU – Trondheim
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Science and Technology

Dynamics of energy and carbon emissions in residential building stocks.

The role of solutions for single-family houses
built between 1980-1990.

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Master in Industrial Ecology
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MASTER THESIS

for

Student Marta Baltruszewicz

Spring 2014

Dynamics of energy and carbon emissions in residential building stocks –
The role of solutions for single-family houses built between 1980-1990.

Endringer i boligmassens energiforbruk og karbonutslipp –
Betydningen av løsninger for enfamiliehus bygget mellom 1980-1990.

Background and objective

The background of this master thesis is the current high priority of R&D and practical implementation of new solutions for minimising energy consumption of buildings, and the corresponding expected environmental life cycle impact reductions. For this to happen it is important to understand the aggregated energy and carbon emission situation of the standing residential building stock, and its dynamic changes over time due to stock growth, stock ageing, renovation opportunities, new building codes and building occupancy behaviour. The EPISCOPE project (using the TABULA method) examines such questions for the Norwegian residential building stock, and the student studied one part of the building stock in her project work during the 2013 fall semester. Together with dynamic modelling research at IndEcol, this provides a good basis for more in-depth dynamic analysis in a master thesis.

The objective of this master thesis is to contribute to the understanding of long-term dynamics of energy and carbon emissions in residential building stocks. The student shall focus on the role of solutions for single-family houses, including scenarios for refurbishment strategies, energy generation and occupancy behaviour. Additionally, the student shall examine the influence of using CO2/kWh as the indicator in choosing between refurbishment scenarios (standard vs ambitious scenarios) for given cohort. Analysis shall include accounting for embodied energy in materials used for measures and emissions from energy used for operation of the single-family house (after refurbishment).

The following tasks are to be considered:

1. Carry out a literature study on state-of-the-art strategies, technologies and/or methods that are relevant for your work.
2. Provide a systems definition of the system you are analysing, including description of goal and scope, system boundaries, data inputs and assumptions, for selected scenarios and/or configurations of technological solutions within your system.
3. Develop a quantitative model for your system, including relevant indicators and/or metrics that can be used to document the energy and carbon emission performance of the system.
4. Report results from the energy and carbon emission performance analysis of your system (including scenarios and/or configurations of technological solutions) and the particular importance of critical system variables, components or assumptions leading to these results.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his/her project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analysed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14th January 2014

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Abstract

The objective of this study is to assess the environmental impacts of renovating an exemplary single-family house built between 1980 and 1990 to the TEK10 or NS3700 (passive house) standard. The scope of the analysis is split in two steps. First, one exemplary house is analysed and impacts from renovation depending on the refurbishment scenario and different shares of primary energy mix are compared against each other. Subsequently, the analysis of the whole stock of single –family houses built between 1980 and 1990 is presented. Dynamic modelling is used for assessment of changes due to demolition, renovation rate and erection of new buildings.

The scope of this study includes analysis for two characterizations: cumulative energy demand (CED) and climate change (CC). Both materials used for renovation and energy needed for the operation of the house are investigated. Beyond the scope of this thesis is assessment of the demolition of the house and materials and impacts related to the construction of the exemplary house.

The results indicate that retrofitting with the NS3700 scenario gives bigger energy and GHG savings than with the TEK10 scenario. During renovation, the biggest impacts occur due to usage of high-density insulation and production of solar collector system. Overall, the renovation package for NS3700 scenario contributes more to the CC impact than for TEK10 scenario. The total difference between those two scenarios is 2.38E+03 kgCO2-eq (11%). This difference is relatively small when compared to the GHG reduction potential for both scenarios.

Results from dynamic modelling shows that cumulated GHG savings during period 2010-2050 with reference to 2010 level were very low for TEK10 scenario. By 2050 the cumulated saving potential was estimated to be 112 ktoneCO2-eq which was 8% of cumulative saving potential for NS3700 scenario achieved by the same time.

For NS3700 scenario, the accumulated GHG emissions saving potential would be positive for all of the energy scenarios, assuming that either 7% or 12% of electricity is imported from Nordic or EU mix for Norwegian use. The saving potential would still be positive even when assuming, the worst-case scenario for the EU mix (red scenario). That shows the potential and role of renovating the existing building stock. The level of renovation as well plays a significant role. If the existing single-family houses stock built between 1980 and 1990, would be renovated to the TEK10 standard the cumulated GHG emissions saving potential would be positive for only the ultra-green EU mix scenario, which is the most optimistic. If the shares of imported electricity will increase and the EU mix would be imported, the potential for saving GHG emissions could be highly dependent on the level and quality of deep renovations. That is assuming that other variables such as behavior linked to energy use would not change.

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Introduction

Globally, residential buildings are responsible for more than half (62%) of the overall CO_2 emissions linked to building stock dwellings. As part of Norway's commitment to help hold global temperature change to <2°C, the country has set as its goal to reduce emissions from the level of 130 kg/m^2 per year in 1997 to zero emissions buildings by 2030.
Residential buildings are the largest consumers of energy in the Norwegian dwelling stock. In 2007 36 TWh energy was used for commercial buildings and 44 TWh was used for residential buildings. That means that approximately 40% of the total energy use was related to buildings [2]. The dwelling stock in Norway is relatively new and it consists of 3,8 million buildings [2]. Almost one third of this is single-family detached houses. According to the IEA it is estimated that 73% of the existing building stock will be still in use by 2050[3]. Renovation and modernization can improve buildings' energy efficiency. However, renovation in Norway occurs slowly, with just 1,5% of the stock renovated each year. In order to meet the 2°C target more dwellings must be renovated each year. Therefore, the future refurbishments have to be planned carefully and policymakers must incentivize homeowners to renovate. The main focus from the government's side is now to implement new building requirements in order to be able to achieve zero emission building standards in 2030. This goal is possible for new dwellings that will be built in upcoming years, but it is more challenging to meet zero energy building targets for the existing building stock. Desired energy use reduction for building sector is 50% of the 2007 level (23TWh saved by 2040).
Thus, it is necessary to plan ahead for smart and innovative ways of refurbishing the existing stock to move it closer to the newest building standards. In 2001, 69% of buildings had been using electricity as their primary source of heating energy[1]. This project aims to show how by applying different standards to single-family detached houses built between 1980 and 1990 energy demand for this dwelling segment could be reduced. This particular cohort was chosen because most of the single-family houses built between 1980 and 2010, were built in the '80s [1]. They account for around 14% of today's total single-family housing stock. Dwellings from the 1980 also have the highest energy use compared to any other average building in the given periods. At the same time,

houses from the ‘80s are at the stage of their life where refurbishment is likely needed within the next 10 years [2].

Renovating a building changes its ongoing energy use, but the renovation exercise itself requires an energy expenditure of materials, transport, labor, and so on. In this study we seek to consider not just the change in primary energy use but also the emissions pulse associated with the renovation activity itself. To do this, we use the tool of life cycle assessment. Life cycle assessment (LCA) is a method that allows for assessment of the environmental aspects and potential impacts associated with extraction, production, use and maintenance of the entire life cycle of a given product. By applying this holistic environmental assessment technique and using methods based on the international LCA standard ISO14040, it is possible to measure the total lifecycle impacts associated with both renovation and operation of the existing building stock.

This thesis presents results from an LCA evaluation of housing renovation options. This LCA study is combined with several scenarios of the future Norwegian electricity mix and also incorporates from a dynamic model of Norwegian segmented dwelling stock [4] . The analysis is based on an exemplary single-family house built between 1980 and 1990 and located in the Oslo climate zone. The aim of using an exemplary building was to show the average values (according to the type, climatic zone and age of building) that would be representative for all of the single-family houses built in that period. Two scenarios: *NS3700* and *TEK10*, each with three renovation cycles, were considered. Both scenarios assume an extensive renovation in 2020, during which the house is renovated to the current Norwegian Building Code requirement (*TEK10*) or to the passive house standard (*NS3700*).

The study has a cradle-to gate (including use and maintenance phase) perspective. The embodied energy and GHG emissions related to energy use and operation of the exemplary house are calculated for 2010-2050 period. The analysis takes into consideration the total upstream energy use associated with the renovation activity itself (including extraction, production, transportation, use, and maintenance) as well the pre- and post-renovation change in total primary energy needed for the operation of the building (heating and ventilation, domestic hot water, electrical appliances and lighting). In this study we have not considered the demolition phase as it was considered to be only a minor contributor to the building’s total lifecycle energy use.

We then scale this exemplary house up to the entire Norwegian single-family house stock built between 1980 and 1990. We calculate the energy and GHG saving potential and compare it to emissions reductions targets set by the Norwegian government. Finally, we conducted a sensitivity analysis to see how feasible these goals are in light of various possible storylines for the future development of the electricity generation mix in Norway. We considered six energy scenarios to check what are the possible energy and GHG savings potentials if the Norwegian production technology changes or electricity imports increase.

1.2. The objective and scope.

Existing studies on retrofitting housing stock focus on entire dwelling stock. However, current studies do not consider various building age cohorts, and how changes to particular cohorts can affect the entire emissions of the stock as a whole. This thesis tries to propose methods to fill this gap. There are studies on energy use for the dwelling stock, however they do not investigate the impacts from future development of primary energy sources used for electricity production on the energy use related to the Norwegian building sector.

The objective of this study is to assess the environmental impacts of renovating an exemplary single-family house built between 1980 and 1990 to the TEK10 or NS3700 (passive house) standard. The scope of the analysis is split in two steps. First, one exemplary house is analysed and impacts from renovation depending on the refurbishment scenario and different shares of primary energy mix are compared against each other. Subsequently, the analysis of the whole stock of single –family houses built between 1980 and 1990 is presented. Dynamic modelling is used for assessment of changes due to demolition, renovation rate and erection of new buildings.

The scope of this study includes analysis for two characterizations: cumulative energy demand (CED) and climate change (CC). Both materials used for renovation and energy needed for the operation of the house are investigated. Beyond the scope of this thesis is assessment of the demolition of the house and materials and impacts related to the construction of the exemplary house.

1. Current standards and building requirements

2.1. Passive house

The concept of the passive house was developed by Bo Adamson and Wolfgang Feist in 1988 in Germany [6]:

A passive house is a building in which thermal comfort [EN ISO 7730] can be guaranteed by post-heating or post cooling the fresh-air mass flow required for a good indoor air quality.

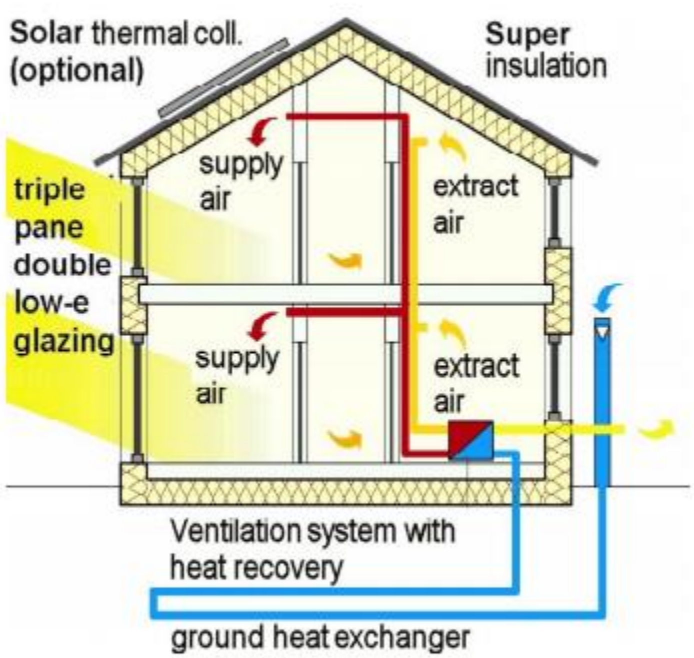


Figure 1 The exemplary solutions for a passive house using principles from the passive house concept. Source: [7]

The basic principles utilized in the passive house concept are:

- An air tight envelope achieved with very good insulation of the building envelope.

- High performing windows, with very low heat loss (facing south and west orientation in the northern hemisphere).

- Ventilation system with high efficiency recovery system.

- Minimal cold bridges.

- Efficient building services, electrical devices and lighting.

Although Norway adopted the passive house standard in April 2010 (NS 3700) builders do not have to comply with it. Nonetheless, the concept of the passive house has been adopted to the Norwegian conditions: The climate and annual energy demand for space heating is defined for different types of buildings and useful areas accordingly to the local annual mean temperature.

2.2. Building Regulations

The development of the Norwegian standards is coupled with the development of new building technologies. Below in table [*Table:1*] a short overview over the Norwegian regulations and standards that were valid in previous years are displayed (historical overview).

U-value W/(m2K)					
Part of building	Standard 1949	Standard 1969	Standard 1985	Standard 1987	Standard 1997
Wall	0.93-1.16	0.58-1.28	0.25-0.35	0.30	0.22
Roof	0.93	0.46-0.58	0.23	0.30	0.15
Floor	-	0.46	0.23-0.30	0.20-3.0	0.15
Window	-	-	2.10-2.70	2.40	1.60

Table 1 U- Value requirements from Norwegian Standards for fully heated buildings (with Oslo as a reference climate).

Since 1997, the technology for production of building materials has improved along with development of new solutions for construction methods. Moreover, policy makers started to acknowledge that in Europe 40% of the total final energy use comes from energy consumption in residential and commercial buildings while at the same time this sector is responsible for 36% of the European Union's total CO_2 emission [8]. Norway included the implementation of sticker building requirements into their policy for achieving the 20/20/20[1] targets and identified the building sector as one of the key sectors for their emissions reduction goals. The short overview of the current building requirement TEK 10 and the passive house standard is presented in table 2 along with a more detail description in following section.

[1] 20% of GHG compared to 1990 levels, 20% energy savings by2020 (compared to business as usual scenario) and 20% share of renewables in 2020

Requirements for detached house: comparison between the TEK and NS3700 standards	TEK 10	NS3700 (passive house)
	Minimum demand	Minimum demand
External wall	0.22 W/(m2K)	0.1-0.12 W/(m2K)
Roof	0.18 W/(m2K)	0.08-0.09 W/(m2K)
Floor	0.18 (W/(m2K)	0.08 W/(m2K)
Windows, doors	1.60 W/(m2K)	0.08 W/(m2K)
Normalized thermal bridges **Ψ** (psi)	0.03 W/(m2K)	0.03 W/(m2K)
Airtightness	$N_{50} \leq 3.0$	$N_{50} \leq 0.6$
Annual Mean temperature efficiency factor for heat exchanger **η**	70%	80%
Specific fan power for ventilation system, SFP- factor	2.5 KW/(m3s)	1.5 KW/(m3s)

Table 2 Requirements for detached houses: comparison between TEK10 and NS3700 standards.

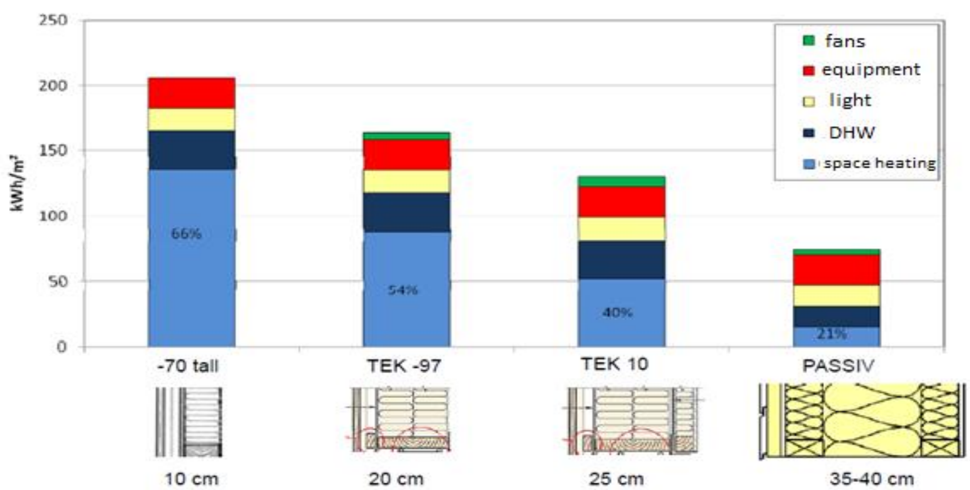


Figure 2 Development of insulation thickness with changing requirements over time. Source: Enova.

2.2.1. TEK 10 - current requirements

TEK-10 was introduced in 2010 is an add-on to the earlier plan and building laws from 2008 (TEK-97). It acknowledges technological solutions implemented in the building sector over time (for example: new insulates like rock-wool, which is used to insulate external walls and roofs and much higher thermal resistance of the windows due to developing triple glazed windows). Development and popularization of new technology solutions drives the tightening of these requirements for buildings. The TEK-10 standard can be further divided into three main parts:

1) General rules for quality of the building materials, environment (indoor and outdoor), security and land use. In this part, one can find specific technical requirements for different building measures (competitive and non- competitive). Verification of requirements is also included. Products for building and CE labeling are linked with EU regulations. TEK 10 sets up general rules for operation, management and maintenance of the building. Requirements for use (BRA-brukareal), outdoor and parking area, building height, and methods for calculations and measurement rules are given.
2) Attention is given to the nature and its forces. Building should be secured from floods, storm or landslides. Placement of the building should be plannedalso with respect to the nature of terrain. Adaptation building to the nature (not opposite).
3) Requirements for building: construction safety and fire-safety. Placement of lifts, rooms, bathrooms, terrace is regulated. Requirements for environment and health: ventilation, thermal indoor clima, radiation, noise and vibrations, light and electrical installations. Low energy demand: here TEK 10 takes to consideration district heating and sets up minimum demands for measures.

The main goal of TEK-10 was to improve performance of the new buildings and achieving a high level of energy efficiency. Building or renovating, one has to take to consideration TEK 10 standard. The building owner is obligated by this and responsible for following the regulations.

TEK-10 also regulates energy sources for DHW and space heating systems. The oil ovens were banned from use. The standard sets minimum of 40% of energy demand for space heating that should be covered by different energy source than direct electricity and/or fossil fuels.

2.2.2. Passive house standard (NS3700)

Passive house standard is not a standard that binds builders to comply. It is a guide for those who are showing long time perspective in choosing requirements for the house. NS3700 is a guideline for those who want to obtain a passive house standard. There are few new regulations written in this standard:

- The energy demand for heating should be calculated in accordance with NS3031 standard but it should use local climate data.

- Estimated amount of delivered electrical and fossil energy should be less than the total net energy minus 50% of net energy for hot water.

$$E_{del,el} + E_{del,oil} + E_{del,gas} < E_t - 0.5 * Q_{W,nd} \qquad (1.1)$$

- The strict regulations of NS3700 include climate data for monthly calculations on the basis of data in NS3031 (table M1 and M2). The NS3700 standard gives two ways of calculating energy demand for space heating for an external average temperature below 6.3°C:

$$15 + 5.4 * \frac{(250-Aff)}{100} + (2.1+0.59*\frac{(250-Aff)}{100}) *(6.3-\theta ym) \qquad (1.2)$$

And for external average yearly temperature bigger or equal to 6.3°C:

$$15 + 5.4 * \frac{(250-Aff)}{100} \qquad (1.3)$$

- The NS3700 requires the use of at least 40% of required energy the be obtained from sources other than direct electricity or oil. Also for DHW systems it is required to use not only direct electricity.

- The new lowest requirements for U-Values for different parts of envelope were also introduced with differentiation between passive houses and low-energy buildings.

Building element	Passive house (W/m²K)	Low-energy building (W/m²K)
External wall (U-value)	0.10-0.12	0.15-0.16
Roof (U-value)	0.08-0-09	0.10-0.12
Floor (U-value)	0.08	0.10-0.12

Table 3 Typical U-values for passive house and low-energy building in accordance with NS3700.

2.2.3 NS3031 Calculation Method

The full name for this standard is the NS3031:2007+A1:2011 calculation of energy performance of buildings, methods and data. This standard is a baseline for all calculation methods in NS3700. The NS 3031 standard is designed to provide a common basis for energy calculations for: o building regulations and energy requirements and for energy labeling of buildings. In this standard the methodology for calculation is presented. The parameters of the calculation and definition for different bases for evaluation (such as “Net energy” and “delivered energy") are given. The NS 3031 standard is therefore an important prerequisite for the development of NVE (Norwegian water resources and energy directorate) energy labeling system. Good knowledge of this standard is also necessary to assess which parameters can be changed, in order to obtain a better grade on the energy label for example. Experts are assumed to know this standard. In NS3031, the changes are adapted to new criteria for passive and low energy houses. In the standard the energy requirements, with technical requirements for construction, are presented for buildings built from 2010. The minimum allowable airflow and internal loads for lighting, equipment and DHW are also included.

2.2.4. Cross comparison of building requirements in Nordic countries

Among all of the Nordic countries, the Norwegian regulations are in the middle of the range of U-values. Table 4 presents an overview for maximum allowed U-values in the Nordic countries. Sweden has the most strengthen requirements, whereas Norway is placed on third place after Finland, with overall U-value for detached building equal to 0.70 W/m^2K (30% drop since 1987).[3]

U-value (W/m2K)	wall	roof	window	door	floor	overall
Denmark	0,30	0,20	1,80	1,80	0,20	1,06
Finland	0,17	0,09	1,0	1,0	0,16	0,62
Iceland	0,25	0,15	1,70	1,70	0,20	0,94
Norway	0,18	0,15	1,20	1,60	0,15	0,70
Sweden	0,18	0,13	1,20	1,20	0,15	0,50

Table 4 Maximum allowed U-value in Nordic countries. Source: [3]

2.2.5.EU directives

According to article nine of the Energy Performance of Building Directive (EPBD) 2010/31/EU:

Member States shall ensure that by 31 December 2020 and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero energy buildings.

Although Norway is not a member state of the EU, they also agree to comply with those new regulations and set up the targets for zero energy buildings development. The definition of a nearly zero energy building is clearly defined in article 2 of the same act:

A building that has a very high energy performance. The very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby[9].

Norway's plan to achieve nearly zero energy buildings in 2020 is defined by implementing several helping packages. The national targets for improved energy performance of existing buildings undergoing major renovation were set to the following levels [10]:

- By 2015 the low energy standard should be achieved.
- By 2020 passive house standard should be implemented.

In order to achieve these targets new regulations and policy packages were established. Some key elements of them are as follows:

- Regulations: TEK10 with new technical requirements; NS3700 for low energy and passive house and analogous Norwegian standard for non-residential buildings NS3701.
- Economic incentives from Enova and Husbanken, which give financial support related to the reduction of energy consumption and favourable loan with lower rates.
- Energy performance certificates, which are obligatory for new or major renovated buildings and existing non-residential buildings.
- Recommendations for homeowners provided by professionals on how to achieve an energy efficient house retrofit.

2. Study background: towards energy and CO2 reductions in the building sector – a strategic review.

3.1 Two degree scenario – global perspective for building sector

To be able to hold global mean temperature below 2 degrees Celsius, many improvements in the global industrial sectors have to be made. McKinsey & Company introduced a greenhouse gas abatement curve with the global mapping of opportunities to reduce the emissions of Greenhouse Gases (GHG). In the report, the potential of meeting the 2 degree scenario in 2030 is presented with a recipe of what would be done and in which sector. The approximation of costs was also presented. Overall, it was concluded in the report that it would be challenging for mitigating the two-degree scenario on the global scale. Looking on the building sector, if nothing will be done global emissions are forecast to grow by 1.7 percent annually, increasing by 53 percent overall between 2005 and 2030 [11]. Taking action and implementing the best practices, the potential for GHG reduction can fall from 12.6 GtCO2e per year to 9.1 GtCO2e per year in 2030. The main reasons for why the reductions are not occurring fast enough are traced to information gaps, program costs, high perceived consumer discount rates and misaligned incentives.

Globally, residential buildings are responsible for more than half (62%) of the overall emissions linked to dwellings. This situation makes the challenge for energy reduction substantially harder to meet. Most of the solutions and measures that are required in the building sector are in hands of private homeowners and their willingness to apply energy efficiency measures and change their behavior linked to energy usage. Figure 3 presents the global GHG abatement cost curve for the building sector as well as changes that should be implemented in order to meet the 2 degrees Celsius target. The biggest changes should be done were the most emissions occur.

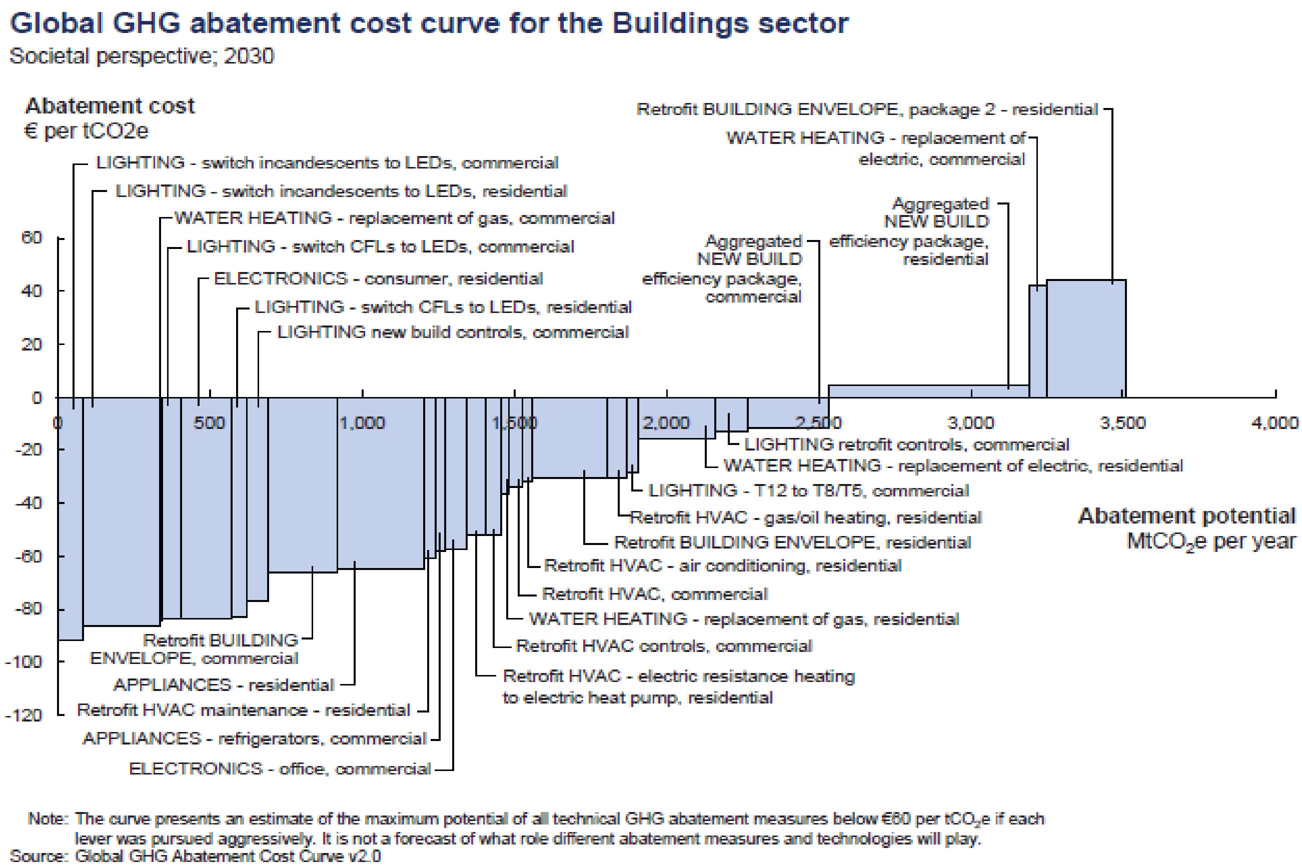


Figure 3 Global GHG abatement cost curve for the Building sector. Source: [11]

For the building sector, the most emissions are produced from heating, ventilation and cooling systems, closely followed by lighting and appliances. The biggest contributor to emissions is electricity generation, due to amount of primary energy required for it generation.

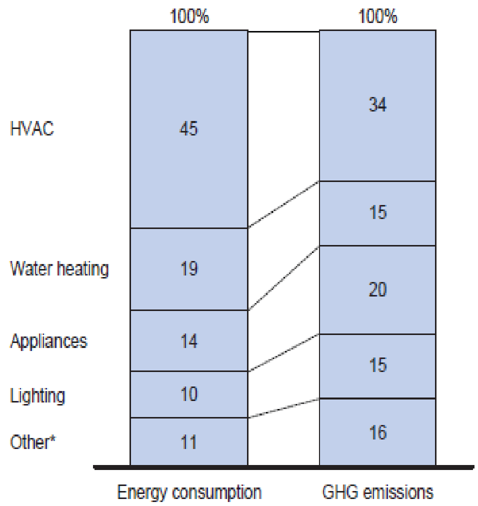


Figure 4 End-use energy consumption and emissions in the Buildings sector, 2005. Source: [11]

McKinsey & company are proposing several options for abatements in the building sector, which include:

- New building-efficiency packages (reduction potential of 920 MtCO_2e per year in 2030 with the implementation of the passive house standard)
- Retrofit building envelope (reduction potential of about 740 MtCO_2e per year)
- HVAC for existing buildings (reduction potential of around 290 MtCO_2e per year)
-Water heating for existing buildings (350 MtCO_2e reduction potential per year)
- Lighting (for example, using LED lights could give a reduction potential of around 670 MtCO_2 per year).
- Appliances and electronics (estimated reduction potential of around 550 MtCO_2e per year).

3.2. Two degrees scenario – Nordic perspective on the building sector

In the two degree scenario the aim is to reduce GHG by 70% by the year 2050 compared with the year 2010; however, Norway have chosen to set an even higher target reduction [3]. Norway is linked to the Nordic electricity market. Therefore, it is important to be familiar with the Nordic market and plan for CO_2 related reductions.

Figure 5 presents the energy scenarios for Nordic countries determined by both Energy Technology Perspectives 2012 (ETP) and International Energy Agency (IEA, 2012). Five scenarios are taken to consideration: four degree, two degrees, carbon neutral, carbon neutral high bioenergy, carbon neutral high electricity scenarios. The figure 5 shows shares of different primary energy sources according to those five scenarios (figure from [3])

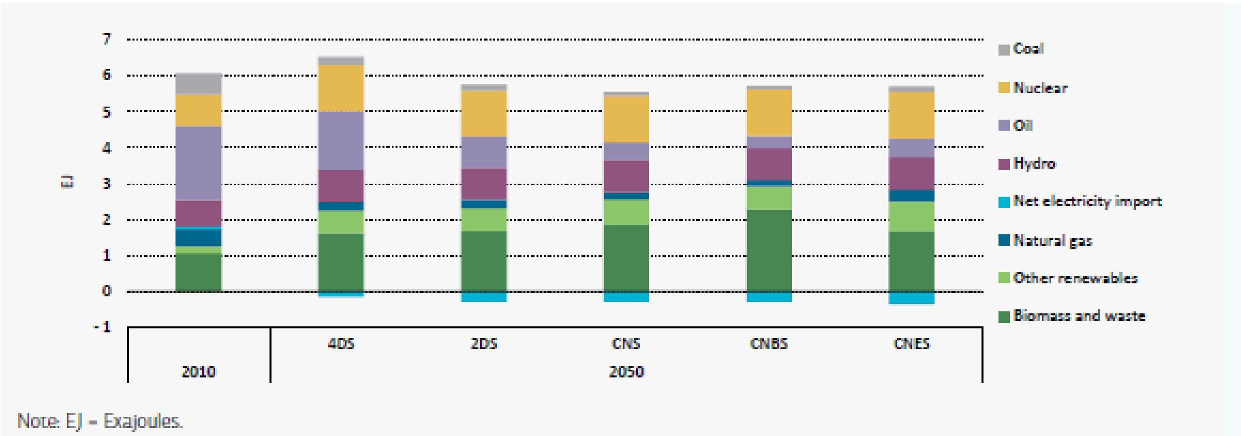


Figure 5 Primary energy supply by scenario (Nordic countries).

Nordic countries set the goal to be carbon neutral by 2050. Norway has an ambitious plan to achieve this goal by 2030. This cannot be realized without changes made in the building and transportation sectors that constitute for one third of total final consumption of primary energy (figure 6).

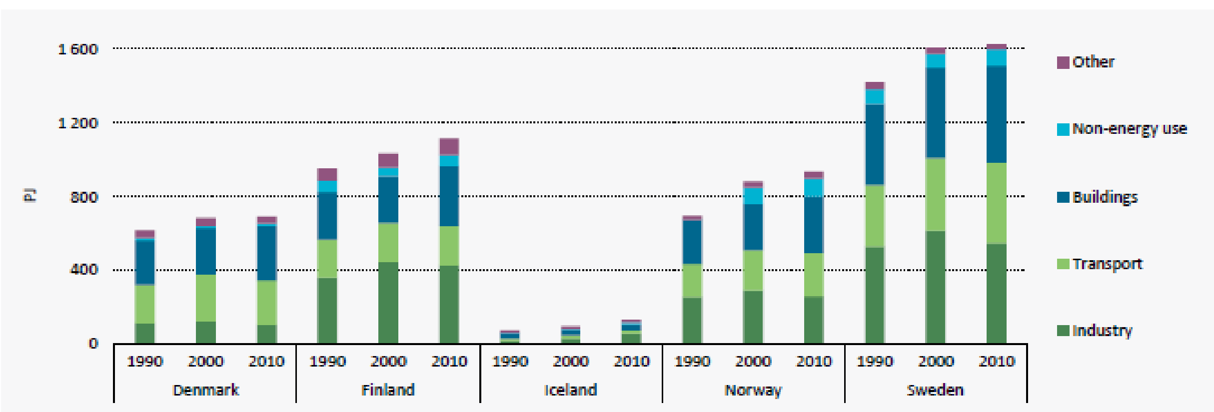


Figure 6 Final energy consumption by sector in the Nordic countries. [3]

Energy use related to the building sector in Nordic countries accounted for 1.527 petajoules in 2010 (33% of total energy use in the Nordic countries) [3]; however, in the residential sector alone, 965

PJ was used in 2010. The greatest share for energy use in buildings went to space heating, followed by appliances and equipment (similarly to Mckinsey report and global shares given by them). The scenarios developed by EPT assume 20% CO_2 reduction compared with 2010 levels for the four-degree scenario and 60% reduction in the two-degree scenario. The changes supposed to come from the decarbonization of electricity, increased energy efficiency and fuel switching.

3.3. Norwegian strategy to meet the two degrees Celsius scenario

The Norwegian building sector is a main source of energy (40%) and electricity (50%) use in Norway [12]. Therefore, the attention is focused on this sector while planning for reduction of CO_2 emissions. The main impacts are related to energy use for the operation of the houses, hence the main initiatives that are undertaken in Norway nowadays are focused on reduction of electricity use by buildings. In Norway the main source used for heating floor area is direct electricity (70% of heating demand is covered by electricity [13]. Norwegian policy is to reduce this percentage by implementing new standards and developing strategies and incentives that would help achieving those goals. The new policy law established in 2007 requires that 40% of energy for space and domestic hot water heating must come from energy sources other than electricity or fossil fuels in new and refurbished houses (TEK10). Replacing direct electricity with heat from renewable energy sources is one of the key points in the policy. The stricter requirements for newly constructed buildings is supposed to be revised every five years. The objective is to tighten up requirements in a step wise fashion, implementing new regulations that lead to Zero Emission Buildings. The goal is to achieve reductions from baseline of 130 kg/m^2 per year in 1997 to zero emissions buildings in 2030. One of the other incentives from Norwegian government was introducing a requirement of energy labeling scheme. All of the new buildings, sold or rented should obtain the energy label.

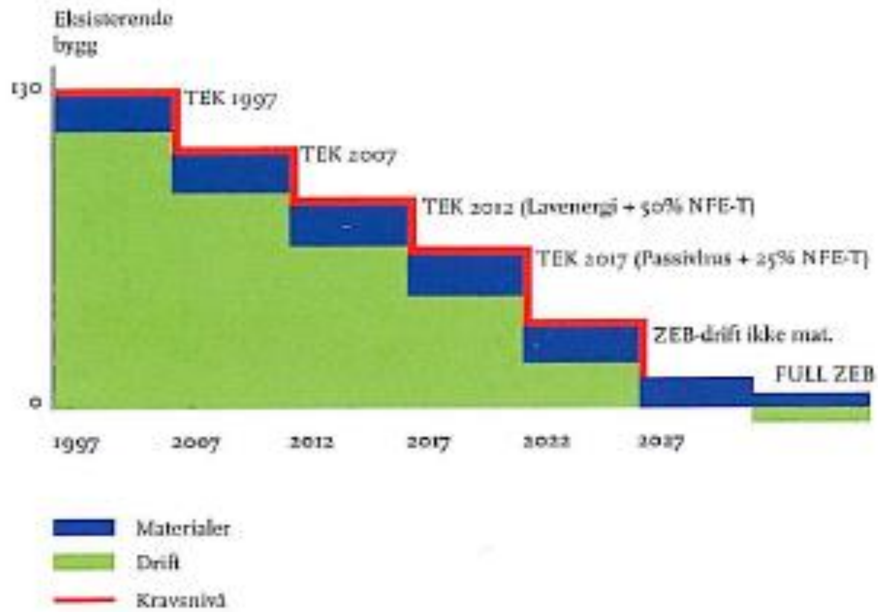


Figure 7 GHG emissions (kg/m2 year). Schematic estimation of greenhouse gas emissions from buildings of different technical standards. ZEB- Zero Emission Buildings; NFE – New Renewable resources. Illustration made by Tor Helge Dokka (Sintef-Byggforsk).

3.3.1.Norwegian energy saving potential

Many variables have to be accounted for when forecasting into the future and predicting the development of renewable energies. The energy and emissions saving potential from the residential stock is especially difficult to predict. The policies developed by Norwegian authorities set up high targets for the reduction of GHG from building stocks. As long as the implementation of targets is easier to control for the commercial buildings stock, it is up to the homeowners to decide if they want to renovate at all. The residential building stock is the highest consumer of energy in the Norwegian dwelling stock, 36 TWh energy use for commercial buildings and 44 TWh was used for residential buildings in 2007 [14] Statistically, the ratio for renovation stays on a very low level (1.5%) and in order to be able to meet the two degrees Celsius targets, more dwellings should be renovated each year. The EPBD assumes 2.5 % rate for renovations [15] and according to the EED there is 3% goal for renovation of public buildings [16]. In order to be able to meet those targets buildings should also go through deep renovation earlier than with 30 year cycle. The main focus of policy makers is now to implement new building requirements in order to be able to achieve zero emission building standards in 2030. This goal is possible for new dwellings that will be built in upcoming years, but is more challenging to meet zero energy building targets for the existing building stock. Desired energy use reduction is 50% of the 2007 level (23TWh saved in comparison to 44 TWh delivered in 2007 for residential building sector) [17].

3.4. Building sector in Norway

In 2005, there were around 1.2 million single-family houses. This number is constantly growing due to demand for new living space. In general, most of the existing Norwegian dwelling stock (around 90%) was built after The Second World War. In a short 20 year period (from 1982 to 2005) the number of dwelling units increased by 40%. According to SSB, during the same time period the number of square meters per person increased by around 35%. On average, single-family types of building have bigger energy demands per square meter than blocks or apartment houses. The more compact the house is, the less energy is used per square meter for space heating (ratio between numbers of floors versus total number of units per building).

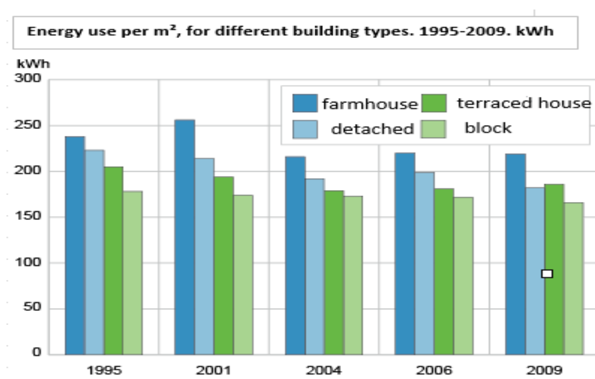


Figure 8 Energy use per m², for different building types. 1995-2009. kWh.

Although the number of dwellings is increasing along with number of square meters of living area per person, the energy demand is slowly decreasing. This can result from better insulation in houses and more energy-efficient electric appliances that are nowadays in use.

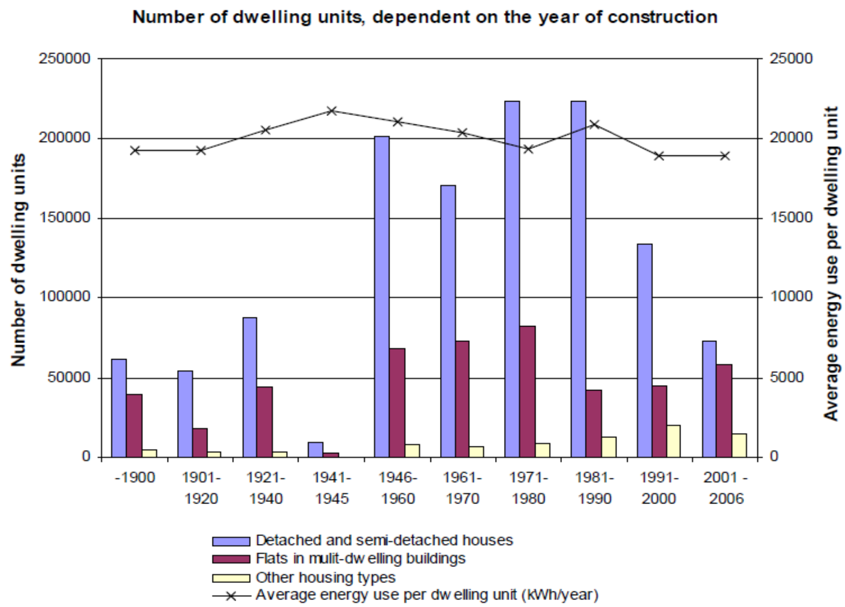


Figure 9 Number of dwellings depending on the year of construction.

Electric heating is the most common heating system in Norway (70% of the dwelling uses only this source or in combination with other energy sources). Even hydronic systems that are installed in new dwellings are based on electricity. This high use of electricity for space heating and DHW systems is special among European countries and can be linked to the lower prices for electricity on the Norwegian market, compared to other European countries

The energy use for production of electricity in Norway is due to use of hydropower, almost free from CO_2 emissions; However, the increasing demand for energy challenges Norwegian production. Therefore, more import of energy from other countries is required. That means more of a European mix of energy, which is 'dirtier' (using coal for example for electricity production) than Norwegian energy. In the same time, Norway is a part of bigger electricity market (the Nordic pool) that is most likely going to influence the future emission factor linked to electricity production. One of the strategies for the future is to reduce dependency on the Nordic electricity market and increase clean energy production (for example with increased district heating services, that could be used for space heating instead of direct electricity [18]). Nowadays, the main energy sources for production of the district heating come from waste burning, biomass and use of heat pumps (70%) [19]. The rest of the energy comes from the production of gas, oil and electricity. Investments in energy sources other than direct electricity, is crucial for reduction of emissions related to building sector (since the emissions from electricity are most likely rise in future). There is an increased need for using other sources than direct electricity and/or fossil fuels for space heating, DHW systems and ventilation (which account for 75% of the total energy use in dwelling stock).

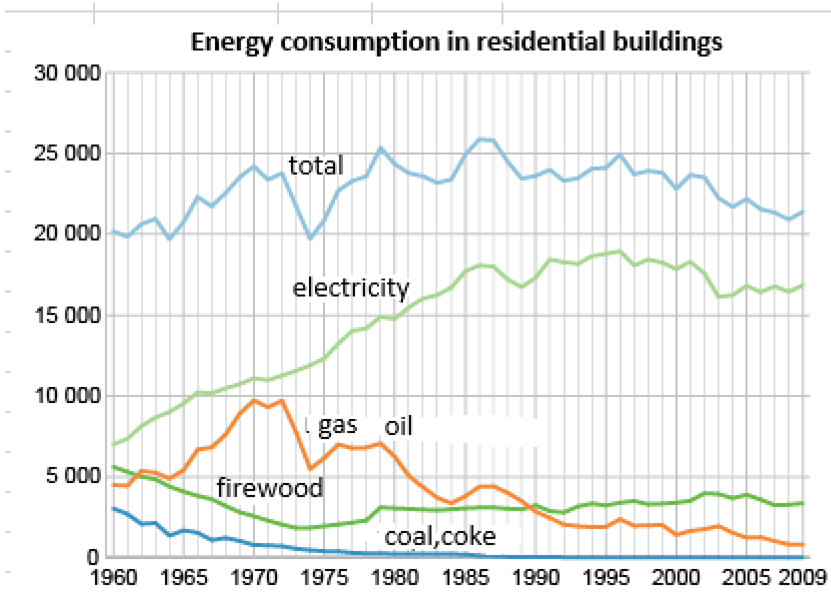


Figure 10 Energy consumption in residential buildings,

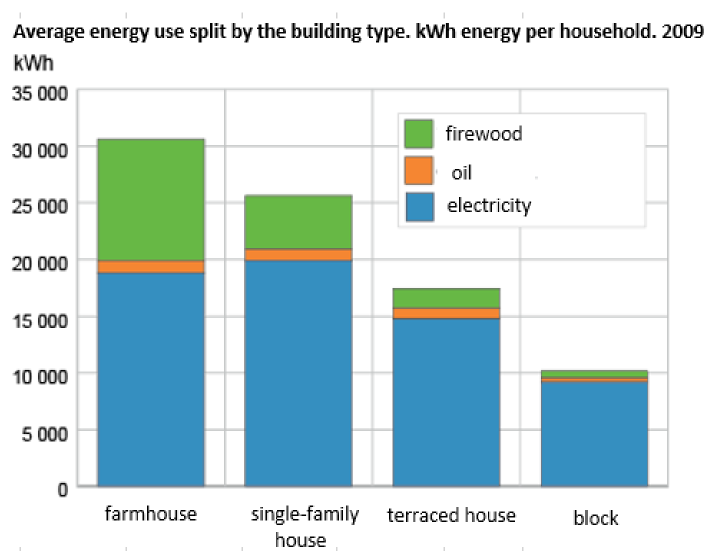


Figure 11 Average energy use split by the building type (kWh per household

In 2010 around 66% of total delivered energy to residential houses was due to demand from detached houses [1]. Within this, 16% was delivered to the single-family houses built between 1980 and 1990. Overall, in 2010 4.9 TWh was delivered to this cohort of buildings.

Energy use in Norwegian building stock since 1996 has been on average about 45 TWh per year [17]. Since 1990, the energy use per square meter was reduced from 230 kWh/m^2 year to 200 kWh/m^2 year. According to the Bellona and Siemens report, the energy saving potential is estimated to be 4.7 TWh with the starting point in 2007[20]. The estimations for the energy saving potential differ in different studies between 8-12 TWh. Among this values for energy saving potential, around 11% would come from single-family houses built between 1980 and 1990. This percentage is based on data from Central Statistics Bureau (SSB) from the year 2010. Figure 13.

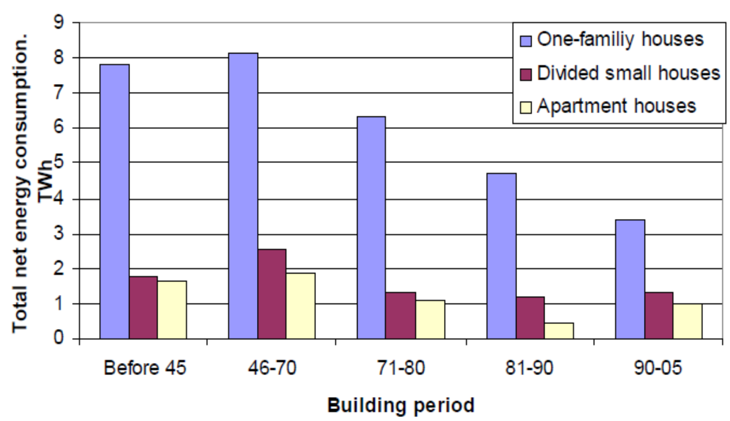


Figure 12 Total useful energy consumption per year for the housing sector (divided by types and building period).

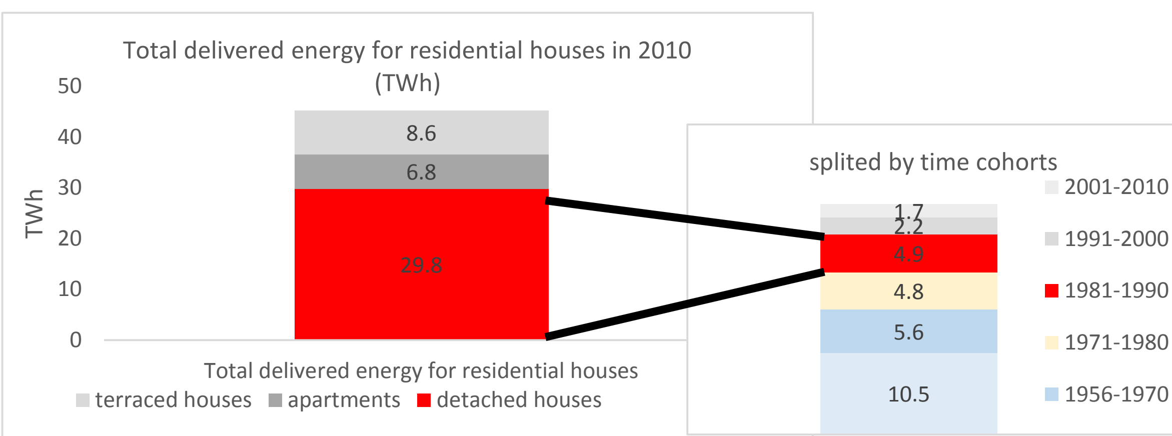


Figure 13 Total delivered energy for residential houses in 2010, split by time cohort (right site of figure). Source: [1]

3.4.1. Renovation rate

According to Zero emission building project report, it is estimated that 1.5 percent of total residential buildings stock is renovated each year [14]. That means that around 3.28 million m2 of the total 218.5 million heating area is renovated each year. Energy efficiency rate is estimated to be 2% of total buildings stock each year, which gives reduction potential of around 20% by 2020. With this rate, in the next 50 years all of the buildings will undergo some of the energy efficiency renovations (that do not include the ambitious deep renovations) [17]

In the same time, the demolition rate is estimated to be around 0.6 % for the complete residential building sector (1.31 million m2 per year based on 2007 statistics)

Residential buildings [2] (million square meter of useful area)	
Yearly rate for new buildings	2.91 (1.33 %)
Yearly rate for renovation	3.28 (1.5 %)
Yearly rate for energy efficiency renovations	4.37 (2%)
Yearly ratio for demolition	1.31 (0.6%)

Table 5 Yearly rates for new built, demolition, renovated, and applied energy efficiency measures and demolition for residential buildings. Source: Dokka report [14]

With implementation of stricter building requirements, the lowering energy use per square meter is estimated based on the given renovation rate (1.5%).

Requirements	New residential buildings	Renovated residential buildings
TEK 2007 (kWh/m2 year)	130	160
TEK 2012 (kWh/m2 year)	100	125
TEK 2017 (kWh/m2 year)	65	85
TEK 2022 (kWh/m2 year)	30	50
TEK 2027 (kWh/m2 year)	0	30

Table 6 Expected levels of future building codes from 2007 to 2027, both in new construction and major rehabilitation. Source: [14]

According to the Project report 40 (Sintef Byggforsk, [5]; the potential for reduction of energy use in residential building sector with reference to the level of year 2007 is 4.5 TWh per year in 2020, 13.6 TWh in 2030 and 23 TWh in 2040.

[2] Without garages, not heated basements and summer houses

3.4.3. The reduction potential from renovations.

Although there are many high-end materials available on the market and highly efficient heating solutions, the best technology is not necessarily chosen while renovating. Choice of heat pump might be a good example. Although an air to air heat pump is the most popular kind of heat pump on the market (95% of all bought heat pumps in Norway are air-to-air heat pumps [Enova,2012]) it is not the most efficient type. Very often the choice of materials is based not only on the cost basis, but it can be influenced by advice given by shop owners, or personnel that are providing renovation services. Without professional expertise and unbiased advice, it is difficult to make proper cost and energy efficient choices [2].

In the Amended working plan under the Ecodesign Directive [21] the most energy efficient measures were ranked. The ranking is a subjective assessment of the energy saving potential. In the final ranking (green column in the table 7 some measures are downgraded due to uncertainties regarding either the saving potential, the suitability of the policies to address this potential or both [21]. The project was based in The Netherlands, hence it might be uncertain to what degree it is applicable for Norway. Nevertheless, it gives a good review on what incentives need to be done by governments in order to address the most energy saving measures.

Study for the Amended Ecodesign Working Plan

Final Report Task 4 (version 16 December 2011)

Table 1 Saving potential and final ranking (executive summary)

Product group	Saving potential (PJ/year, 2030)	Energy ranking	Final ranking
Taps and showerheads	885	2	1
Window products for buildings	785	3	2
Positive displacement pumps	270	6	3
Fractional HP motors	258	7	4
Power cables	182	8	5
Servers and data storage equipment	135	11	6
Steam boilers / systems	177	9	7
Heating controls	319	5	8
Lighting controls	610	4	9
Elevators, escalators etc.	57	12	10
Medical equipment	44	14	11
Blowers	43	15	12
Electric kettles	37	17	13
Small fans <125 W	21	21	14
High temperature fans	17	22	15
Point-of-sale / ATM equipment	16	23	16
Clothes ironing products	11	25	17
Non-domestic hot beverage equipment	7	27	18
Traffic lighting	7	28	19
Toilets	5	29	20
Thermal insulation products for buildings	1500	1	21
Detergents	155	10	22
Logistic systems	50	13	23
Base station subsystems	30	19	24
Mobile phones	13	24	25
Home audio/video equipment	4	32	26
Stationary agricultural equipment	39	16	27
Mobile agricultural machinery	33	18	28
Mobile construction machinery	22	20	29
Mobile power generation sets	8	26	30
Lawn and riding mowers	5	30	31
Handheld power tools	5	31	32
Stationary construction equipment	2	33	33
Kitchen appliances	2	34	34
Hot tubs / Spa's	1	35	35
Sauna's	0	36	36

Table 7 Saving potential and final ranking. Source: Study for the Amended Eco design Working Plan.

In order to see the energy saving potential for measures related to buildings, the table 8 specifies these:

Product group	Saving potential (PJ/year, 2030)	Energy ranking	Final ranking
Taps and showerheads	885	2	1
Window products for buildings	785	3	2
Positive displacement pumps	270	6	3
Fraction HP motors	258	7	4
Power cables	182	8	5
Steam boilers/systems	177	9	7
Heating controls	319	5	8
Elevators, escalators	57	12	10
Electric kettles	37	17	13
Small fans <125 W	21	21	14
Thermal insulation products for buildings	**1500**	**1**	**21**

Table 8 Saving potential and final ranking for measures applied for the building sector,

Although thermal insulation for buildings has the highest energy saving potential, is not ranked the highest. Measures that have the biggest energy saving potential are not always the first choice for the end consumer. Due to high cost of implementing the measure, not enough awareness of savings potential, and lack of economic incentives from the government, the highly beneficial measures for energy savings might not be the most favorable to homeowners.

According to Enova [1] the most energy efficient measures that should be applied nowadays in Norwegian houses are presented in the table 9. Presented measures are the most common when one decides to renovate a given part of building envelope or heating system.

Measure type	Materials
Building’s envelope	Isolating of external wall (from outside or inside), roof, basement, around windows and doors; change of windows, doors;
HVAC	Solar panels, solar cells, heat pumps, heat-controller, heat exchanger with balanced ventilation, change of oven.
Equipment	Taps and head showers, lighting
Behavior	Energy consciousness, choosing energy efficient equipment, turning off lights and appliances, reduction of inside temperature

Table 9 Energy efficient measures for residential buildings.

3.5. Previous LCA studies on retrofitting detached houses

The embodied energy for a low energy building can be higher than conventional ones (Thormark). Nowadays the embodied energy in materials in new built buildings is accounting sometimes for more than half of the total embodied energy. The question which arises from this is what the payback time in respect to the GHG emissions and embodied energy is. There is not many LCA studies on renovation of existing building stock. The ones that are existing are investigating buildings that are of different age, type (blocks, terraced houses, detached) in various climate zones and have different energy performance levels. Furthermore, usually the inventory for materials is left out of scope in presentation of results, or said to have negligible influence on overall results compared to energy savings/use that is achieved in building after applying them. Therefore it is challenging to be able to use these studies for cross comparison. Moreover, standards to which given buildings are renovated do not always comply with what is presented above (the minimum demand of energy use per square meter also differs) . The scope of LCA studies is not always clear. Some studies are not specifying the system boundaries of the examined renovation, whereas others do not specify if they used primary energy or direct energy or net energy for the operation of the given building while calculating for the total energy use. In the table 10 several examples are given for the LCA studies of renovation with energy or emission saving potential that resulted from retrofit. In their studies, authors were giving either very detail information of type of retrofit with a detailed list of applied measures, or they were vaguely mentioning the inventory.

Author/reference	GHG emissions	Embodied energy	Main characteristics of the building	System boundaries
Goushu [22]	Total of 110 kgCo2-eq/m2	480 kWh/m2	Brick house, added insulation to the wall, floor, roof, changed windows, solar thermal, heat pump	From cradle to site (primary energy)
Verbeeck [23]	35 kgCO2/year avoided (no data on emissions embodied in materials were available)		Solar collectors (5m2 to cover 50% demand for DHW), PV panels triple-glazed windows, insulating roof, floor and façade	From cradle to gate (30 years of usage phase); primary energy. The values are without emissions for the energy saving measures
Farmuybo A.[24]		110 kWh/m2 year With 13.5% contribution from retrofit and maintenance (14.85 kWh/m2 year)	Passive house, 4m2 solar-hot water, PV, ground source heat pump, mechanical ventilation	From cradle to gate (including 50 years of usage phase)
Thormark [26]		231kWh/m2 of 120m2 house for 50 years lifetime	120m2, 45kWh/m2 energy need for operation; 0.215 m mineral wool+0.22 m EPS in the walls; 0.45m mineral wool+9.93 m EPS in the roof, 0.25 m EPS under foundation slab, windows 0.85 W/m2K; solar collectors on the roof used for DHW (covering 50% of the annual req.) recycled materials are used for renovation	From cradle to site (with usage and maintenance phase) 50 years of usage)

Table 10 Overview of the current LCA studies on retrofit of existing detached houses. rom [3, 27] [28]. [1].

4. Methodology

4.1. LCA methodology

The methodology used in this study was adopted from ISO 14040. Life cycle assessment addresses *the environmental aspects and potential environmental impacts throughout product's life cycle from raw material acquisition through production, use, end of life treatment, recycling and final disposal.* Assessment is done in four steps: the goal and scope definition phase, the inventory analysis [29], the impact assessment phase and the interpretation phase (figure 14). LCA uses single or multiple indicators to assess the environmental performance of a given product/service, at the midpoint or endpoint level. If more indicators are available, more information can be obtained on the environmental performance; however, single indicators are easier to use and understand. The common characteristic for all of the indicators is that they are problem oriented. If the given indicator has a high score, the environmental performance is bad. The endpoint indicators have high level of uncertainty in the results. They are representing the final consequences of negative environmental impacts to humans and ecosystems. On the other side, midpoint indicators are showing a direct impact on the environment.

In this thesis inventory data was collected using Ecoinvent v2.0 and environmental product declarations. Inventory calculations for materials used for renovation and primary energy used for operation of the building were calculated either using SimaPro v7 or calculated individually using a developed model for obtaining results for specific energy and renovation scenarios. The ReciPe methodology was used for all of the products in the inventory. In this methodology, each indicator set has the possibility of being calculated in three different cultural perspectives: egalitarian, individualist and hierarchic perspective. In this analysis the hierarchic view was used, which is the most common strategy of evaluation regarding time frame and impacts[30].

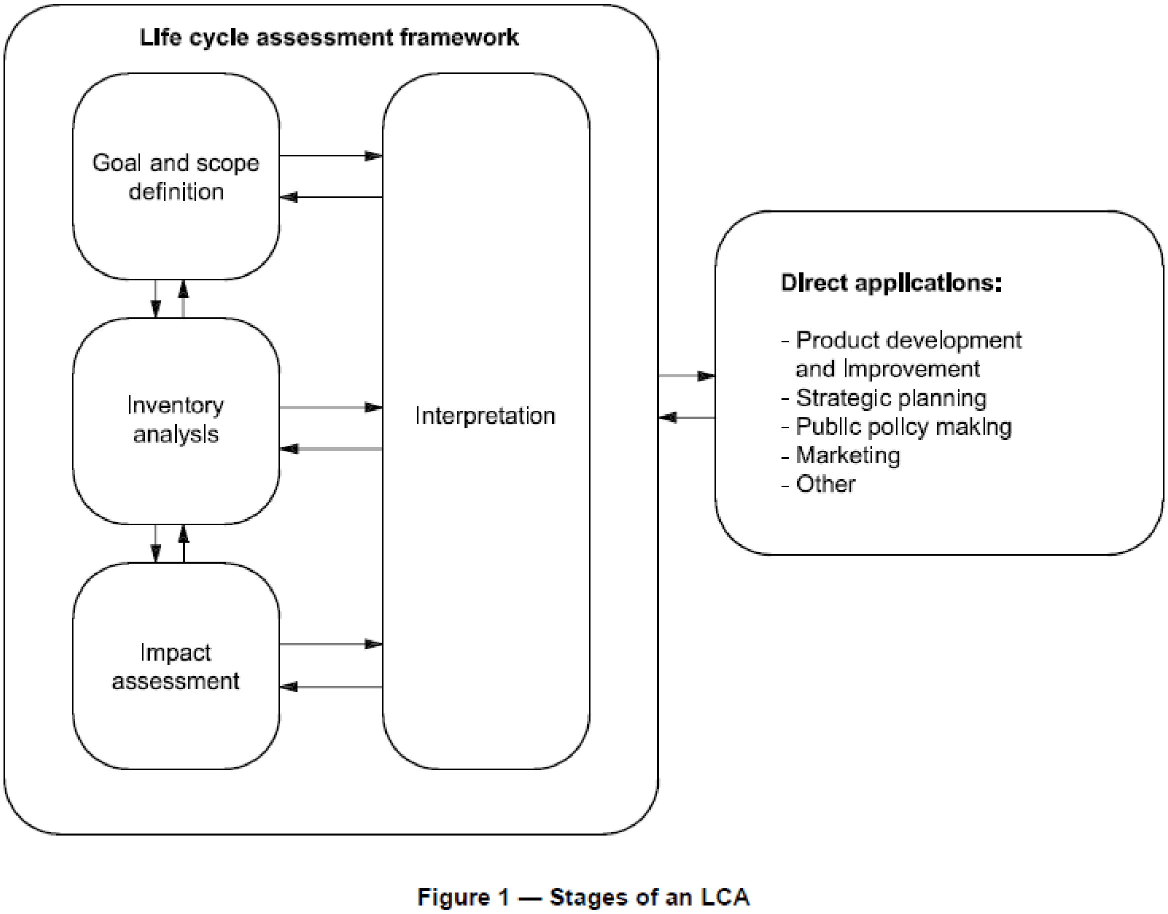


Figure 14 Life cycle assessment framework. Source: [29]

4.1.1. Impact categories

Two impact categories were selected for the analysis:

- Primary energy demand (MJ-eq) according to CED method.

- Climate Change (in kg CO2-eq) according to ReCiPe method.

CED is not a part of ReCiPe method and it is not an impact category but it is the method of calculating the entire accumulated primary energy in the system. Therefore, The Cumulative Energy Demand method is an indicator for energy systems. It takes into consideration the entire demand for primary energy from the extraction of raw materials, production, and the use and disposal of an economic good, product or service. The cumulative energy demand presents impacts in two categories, renewable and non-renewable primary energy sources. CED was published by Ecoinvent version 2.0.

Climate change (CC) is a ReCiPe midpoint indicator. In the ReCiPe method, 18 characterization midpoints are considered. For this study only CC was considered and calculated using the hierarchic cultural perspective. The reason for choosing only one midpoint indicator was that the objective of this study was to focus on the evaluation of certain energy and environmental specifications of products needed for renovation and the related energy needed for operation. Considering current energy and environmental problems related to primary energy sources and the additional need to reach 20-20-20 targets and the nearly zero energy building directive, the climate change indicator and CED method seem to be the best to reflect obtained results.

4.1.2. CED – renewable vs non-renewable primary energy sources.

The Environmental Product Declarations and results presented in the SimaPro program differ between themselves in a manner of presenting renewable and non-renewable primary energy resources. The labeling of different sources varies. In the EPD documentation, some declarations are only using differentiation between renewable and non-renewable sources. To give an example, in a EPD from the window manufacturer NorDan the following terms are used: renewable/non-renewable primary energy resources used as energy carriers and renewable/non-renewable primary energy resources used as raw materials. In SimaPro, labeling for non-renewable energy sources is as follows: fossil fuels, nuclear and non-renewable biomass; while for renewable energy sources: renewable biomass, wind solar geothermal and water. Due to differences in labeling and assigning different primary energy resources to the main categories, the unified system for presenting the results had to be chosen with following assumptions:

• Non-renewable primary energy resources

→ Coal – if the data was stating non-renewable biomass, the values were assigned to the label coal.

→ Fossil oil.

→ Natural gas.

→ Uranium – if the data was stating nuclear, the values were assigned to the label uranium.

→ Non-renewable energy in general - If the obtained data was giving only the total values for non-renewable primary energy sources without dividing them into sub-groups, the overall results then were assigned to the label non-renewable energy general.

• Renewable primary energy sources

→ Biomass.

→ Hydropower – if the data was stating water, it was assigned to the hydropower label.

→ Wind power.

→ Renewable energy general - If the obtained data was providing with only the total values for renewable primary energy sources without dividing them into sub-groups, the overall results then were assigned to the label renewable energy general.

In addition, the last category "other" was created due to use of this label by several EPD's. The values for this category are not big (assumed to be negligible) and do not have big influence on the overall non-renewable and renewable primary energy results; however, it could not be assumed that "other" belongs to one or the other category. This assumption would not have a solid background; therefore, it had to be left in the same state as it is presented in EPD in order to sustain transparency of the presentation of the overall results.

4.1.3. Functional unit

The functional unit is: *40 years of operation, retrofitting and maintenance of one exemplary single-family wooden house built between 1980-1990 with 181m2 of useful floor area and with 4 inhabitants.* The other properties like construction and demolition of the building and costs are not considered in the functional unit.

4.1.4. System boundaries – analysis from cradle to gate. Excluding demolition phase.

The figure 16 is representing the chosen system for the analysis. Raw materials for the renovation scenarios are extracted, transported, produced and transported to the building site. During operation of the house, maintenance of the inputs installed during renovation phase are included. The demolition phase is not considered in this study. There is no common agreement on how to attribute the energy savings from recycled materials to the demolished house. It is also uncertain what exactly will happen in the future with materials used for renovation; for example, if they were recycled, what are the potential energy savings from this process. Most of the existing studies are also taking this approach of excluding the demotion phase from the scope. The environmental declarations of the product are also in most cases excluding this phase in the life cycle assessment. Of course, it would be desirable for energy from recycling or reusing would be incorporated in the life cycle energy estimation, but that is left to the uncertainties and discussion analyse. Moreover, many studies show the demolition phase accounts for approximately 1% of the total energy requirement for the life cycle of the building [31]. The operation of the building has the major share (80-90%) of energy demand followed by embodied energy in materials needed for construction, renovation and maintenance of the building (10-20%). [31]

All of the energy flows are considering the primary energy sources. This allows for presenting results for both the operation of the house and the emissions embodied in materials needed for renovation within the same scope. For better understanding of the system boundaries for the primary energy used for operation of the house, refer to figure 15.

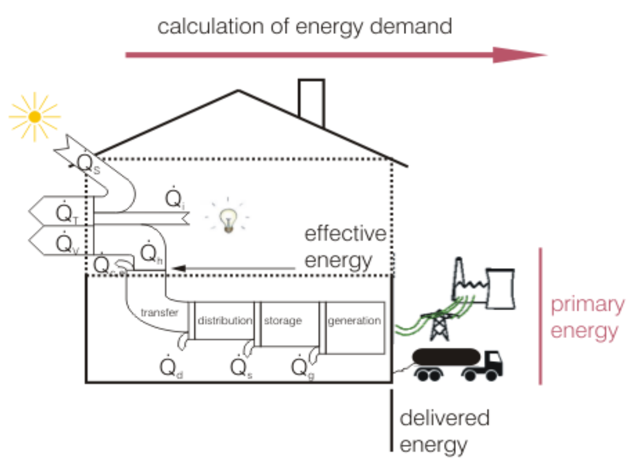


Figure 15 Presentation of primary energy. Source: [32]

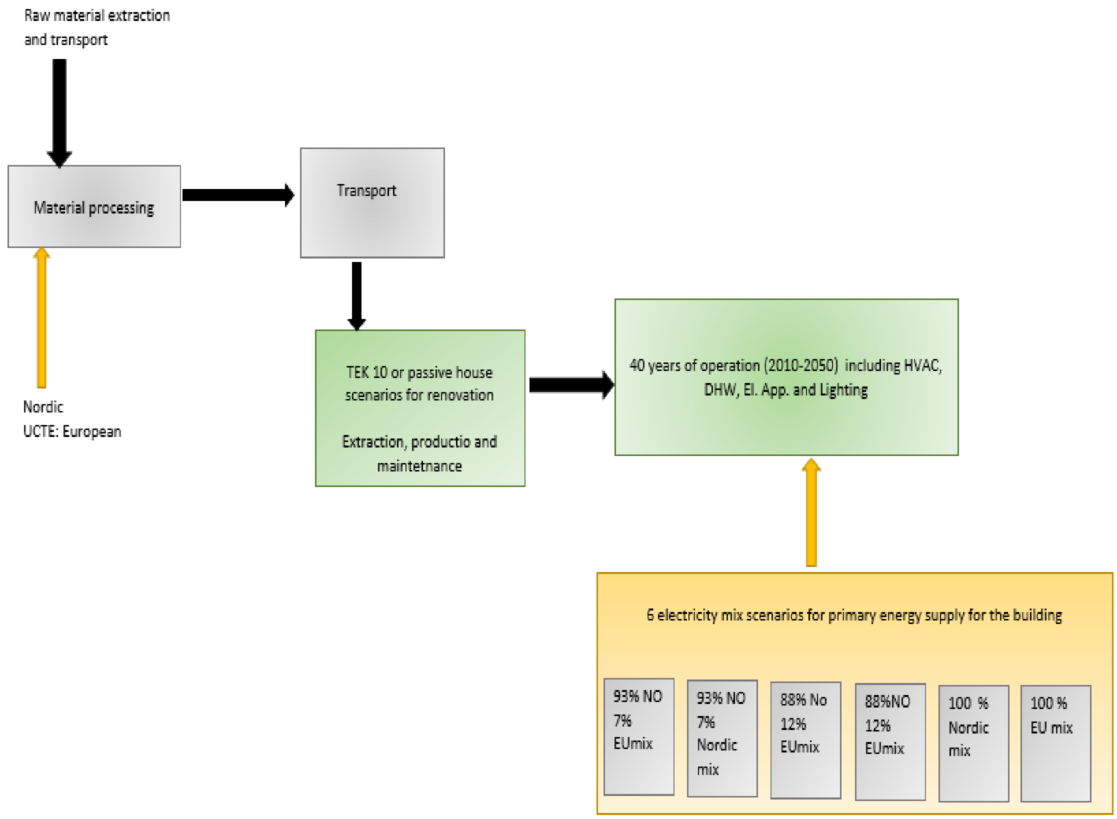


Figure 16 Flowchart for the functional unit and its system boundaries

4.1.5. Life cycle inventory data - EPD

Most of the inventory was collected on the basis of the Environmental Product Declarations. Each EPD used in this study has its core structure based on the European standard: EN 15804:2012. This standard provides a structure to ensure that all EPD of construction products, construction services and construction processes are derived, verified and presented in a harmonized way[33]. All of the calculations and results presented in EPD are based on the LCA methodology. The LCA based information in an EPD may cover different product life cycle stages of a given product. Figure 17 represents different types of EPD with respect to life cycle stages covered, and life cycle stages and modules for the building assessment. The modules that are considered for this study are A1, A2, A3, A4, A5, B1 and B2. This constitutes an EPD of type *Cradle to gate with option* that in this case includes maintenance and use phase (that is in line with the described system boundaries in this study). The background inventory databases and calculation methods that are used in EPD vary. All of the EPD use CED methodology for calculating embodied energy in a given product, and other methodologies like ReCiPe, CML 2 Baseline 2000 and Eco-indicator for calculation of other indicators like Climate Change indicator. Several EPD's used in this study did not specify used calculation methodology.

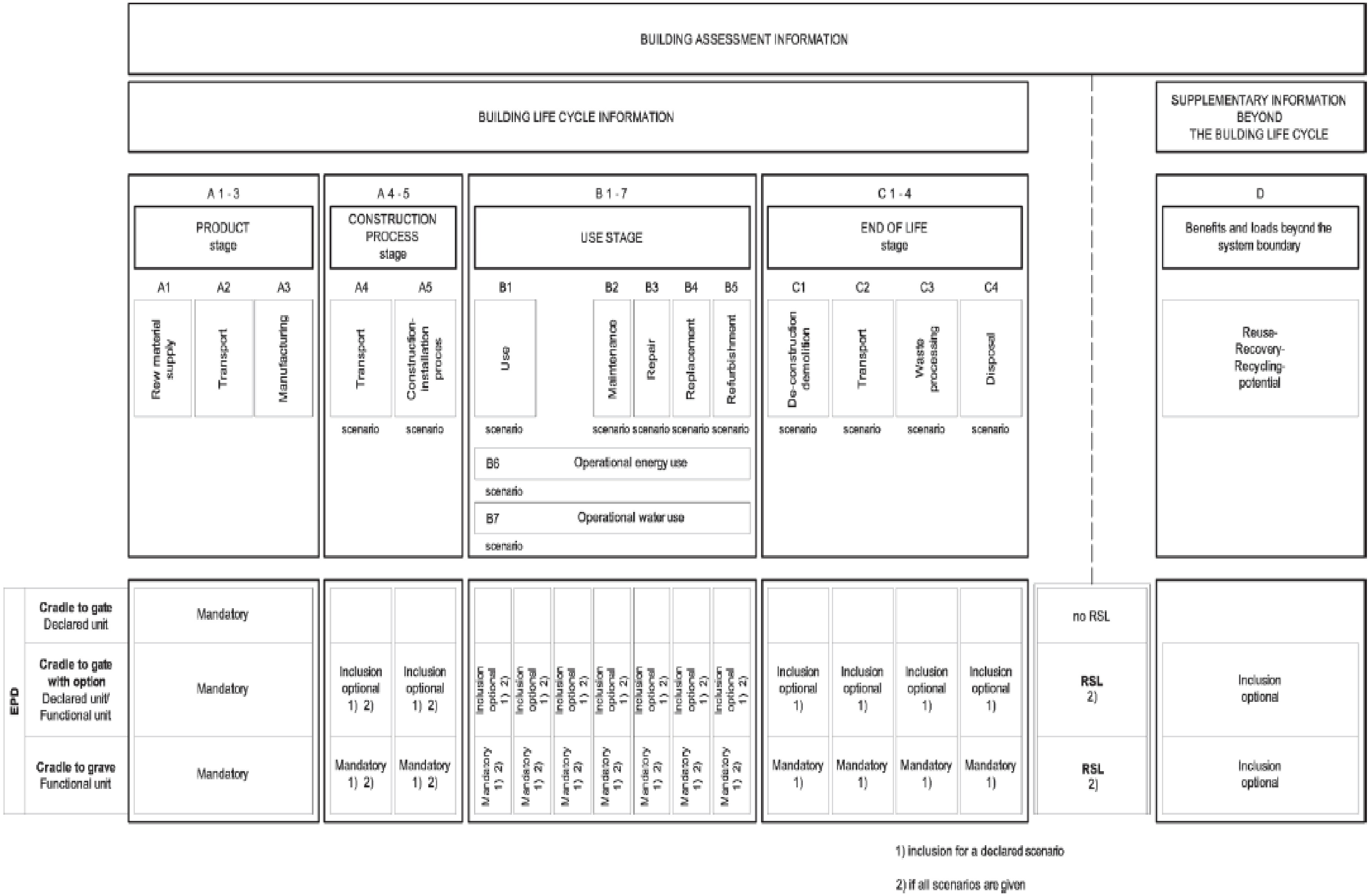


Figure 17 Types of EPD with respect to life cycle stages covered and life cycle stages and modules for the building assessment. [33]

4.2. Tabula Calculation Method

In the calculation of the final energy demand for HVAC and DHW the method developed in the Tabula project was initially used.

Tabula's Typology Approach is used to compare building stock for energy assessment between European countries. Each of the countries has its own methods, comprehensive with national standards, to account for their own dataset. The Tabula calculation method is giving one way of categorization of the residential stock in Europe and its own dataset according to which, each country can build a tabula dataset.

Tabula is considering only residential buildings. According to the authors, making the typology for the non-residential building sector would be difficult due to many factors like data availability and variety of uses.

In Tabula, for each country there is a standardized typology matrix, which includes exemplary buildings by their size classes (single-family houses, terraced houses, multi-family houses, and apartment blocks).

In the Tabula Calculation Method, the focus is to evaluate what is the energy consumption for hot water and space heating for different types of residential buildings considering different parameters like age of the building, insulation and internal temperature. It is important to notice that cooling, air conditioning, lighting and electrical appliances are not included in the calculation method. This has its implications in the choice of parameters used for calculation (assumed parameters). Simplification of calculation method is to 'ensure transparency of the calculations'

The calculation procedure in the Tabula project has its aim to be simple and to be easily applied by users.

The calculations are defined in accordance with European Committee for Standardization. The method takes standard values for the utilization and national and regional climatic data.

4.3. Segmented dynamic model for building stock

The dynamic model used in this study was developed by Nina Sandberg to analyse the long-term development in a dwelling stock. The metabolism of the given stock is measured using input parameters like population, number of persons per dwelling, lifetime and renovation probability functions. The model is designed to present changes for overall stock and for the segmented types and construction periods. One of the purposes of this model is to see the turn-over and renovation cycles in the dwelling stock (Sandberg). In contradiction to other dynamic models, this one is presenting changes of the given stock measured in the number of dwellings. According to Sandberg this helps to avoid uncertainties related to the average floor area per dwelling. The total dwelling stock is calculated using the two main parameters population, and number of persons per dwelling. Change in the stock is then derived with reference to the previous year. In the model, two probability functions are used, the demolition probability function (using Weibull distribution) and the renovation probability function (using normal distribution). The cycle for renovation is the average time between two renovations of the same type. In this study a 40 year renovation cycle is used. Although the model uses the time period from 1800 to 2050 for Norwegian building stock, only the period from 1980 and 1990 was taken into consideration in the analysis. Other adjustments and assumption made using the dynamic model are:

→ The lifetime of the buildings (set to be 100 years).

→ The assumed renovation cycle is 40 years. In the model, the forty year cycle represents deep renovation of facades. This type of retrofit is in line with second renovation described in both the *TEK10* and *NS3700* scenarios.

→ The analysis was run for single-family houses built between 1980 and 1990.

→ No renovations are assumed before the year 2010. If renovations would start in year zero (that is 1980 for analysed cohort), some of the buildings would undergo renovation more than once within the assumed 40 year cycle and time horizon between 2010 and 2050. The assumption that no renovations had taking place before 2010 helps to present transparently how many buildings were renovated after 2010 assuming different renovation scenarios. In the dynamic model, the number of renovated stock before 2010 was deducted from the original accumulated stock. The same was assumed for demolished buildings (deducted from original stock). In that way the mistake of renovation of the building that supposed to be demolished was avoided.

→ The rate of the renovation and demolition is in line with the one used in the dynamic model by Sandberg using the same distribution functions.

→ The detached houses in the model are assumed to consist of single-family houses, farmhouses, semi-detached house, terraced houses and other residential houses with less than three stories; however, in the presented analysis, all of the results are referring only to the single-family houses. Therefore, the energy saving potential for this type of dwelling will be overestimated. Due to lack of possibility for selecting only single-family houses using the dynamic model, the assumption that results are representative only for one type of dwelling had to be made. This partly could be justified with a fact that single-family houses built between 1980 and 1990 have the biggest energy usage among all of the other detached houses, and this group of dwellings has the biggest share in the total number of detached buildings [1].

Figure 18 is representing the accumulated number of detached dwellings built between 1980 and 1990. On the graph, the stock of demolished buildings is separated out from the original stock, just as renovated stock is. The latter one is renovated within the 40 year cycle with starting year in 2010. In 2050 all of the dwellings are retrofitted within the forty year cycle (assuming deep renovation). This model and results for accumulated number of dwellings was used in further analysis.

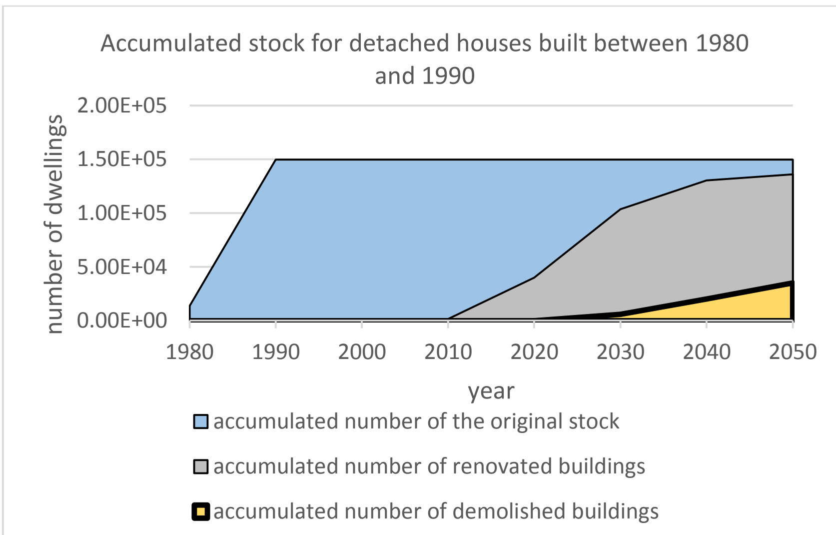


Figure 18 The accumulated number of detached houses built between 1980 and 1990, renovated within the 40 year cycle and demolished (assuming 100 years of lifetime).

4.4. Renovation and energy scenarios description

In this part of the chapter, three renovation scenarios are presented. The baseline (without renovation), TEK 10 and Passive house (NS3700) scenarios and further references to each of the scenario will be made by the name of the standard for better understanding. Section 4.4.3 presents the delivered and net energy needed for the operation of the house; however, it is important to highlight that this section does not consider the primary energy. The detailed methodology for use of the primary energy in the study is presented in next section 4.5., together with description of future energy mix development and energy scenarios.

4.4.1. Baseline: the exemplary building in the original state.

The exemplary building is defined after the Tabula Project, in which, for a specific year and type of construction a standard building was developed. Each of the exemplary buildings is a non-real, virtual building that has typical parameters for its defined group (single– or family house, block etc). Those standard values are established based on the statistically typical values for given element of the house in a given country.

For the analysis presented in this thesis, the baseline building is an exemplary single-family house located in the Oslo climate and built during the 1980's. The aim for using the exemplary building was to show the average values (according to the type, climatic zone and age of building) that would be representative for all of the single-family houses built in that period. Looking on this time period, most of the single-family houses that exist today were built in that time [1]. They account for around 14% of today's single-family house stock. Dwellings from the 1980's have the highest energy use compared to other exemplary single/family buildings built before 1980 or after 1990. In the same time, houses from this period are in the stage of their lifetime where refurbishment is needed during the next 10 years [2]. There are several reasons for choosing Oslo for a localization of the buildings. The average values and methods of calculations that are taking into account climate zones are using Oslo as reference location (NS3031, Enova rapport, Asplan Viak rapport). The other reason for choosing this climate zone where Oslo is situated is that most of dwellings in Norway are situated in a region with average yearly temperatures similar to that of Oslo.

Single-family house located in:	Number of inhabited houses	Percentage of inhabited houses (%)	Average yearly external temperature [°C]
1 Southern Norway, inland	4.15E+05	38%	5.2
2. Southern Norway, cast	3.25E+05	30%	7.0
3. Southern Norway, mountains	1.16E+05	11%	3.3
4. Mid-Norway, coast	1.12E+05	10%	5.8
5. Mid-Norway, inland	1.82E+04	2%	2.9
6. Northern Norway, coast	7.08E+04	7%	3.8
7. Finnmark+inland Trømso	2.38E+04	2%	1.1

Average temperature for Norway	4.1
Average temperature for Oslo (according to NS 3031 table M1)	6.2

Table 11 Avergare values for different types of buildings (average yearly external temperature and number of inhabited houses) [1, 34]

The analysis is based on average values for different types of buildings described in Enova rapport (table 11) [1]. Table 12 is a summary of average values for dimension and energy systems used in single/family houses built in the 1980's. Enova's report was also a base for analysis made by Asplan Viak on energy saving potential and economical calculations for retrofitting building stock in Norway[35]. Therefore, for better comparison and availability of data values provided by Enova were chosen.

Exemplary building – single family house built between 1980-1990 – in its original state		
		U-value
Reference area [m²]	181	-
Area of external walls [m²]	131	0.28
Windows area [m²]	27	2.2
Floor area [m²]	121	0.21
Door area [m²]	4	2
Roof area [m²]	121	0.21
Number of floors	2	-
Fraction of heat generators for space heating system		
Wood stove	0.2	-
Direct electricity	0.8	-
Fraction of heat generators for DHW system		
Electric boiler	1	-

Table 12 Single-family house built between 1980-990. Average dimensions and U-values for original state of building.

Physical dimensions

- The single-family houses from 1980's have on average 180 square meters of floor area. One of the most popular model was so called Block 180 with over 200 square meters [2].

Figure 19 Exemplary single-family house built between 1980 and 1990.

Ventilation/Infiltration

- The natural ventilation was typical for most of the houses in the 80's. Due to this, the average rate during heating season is 0.41/h, which has improved after the implemention of mechanical ventilation.
- Single-family houses built in 1980 were not as air-tight as buildings constructed in 1990's and 2000's. Later on availability of better insolents and development of construction technology lowered average air change by infiltration, which created in the same time demand for mechanical ventilation.

U-values

- Since the 1970's the U-value for the windows was improved (Bøhn, 2006). Double glazed windows gave better result for thermal resistance than their preceding single glazed windows. Total solar energy transmittance for radiation perpendicular to the glazing due to lower quality of windows, was also higher.

Energy carrier/internal environment

- In the early 1980's the price for electricity was rising, but direct electricity was on average used as a main source for space heating. The same was for heating hot water (DHW) with electric boilers. Recoverable heat loss of the storage of domestic hot water systems had higher values for the single-family house built in 1981-1990, than for houses built in later periods. Heat losses from storage and distribution in DHW systems were therefore bigger.

4.4.2. TEK 10 and Passive house scenario

Both TEK 10 and NS3700 (passive house) scenarios assume the same time horizon for rehabilitation. The first, minor rehabilitation is assumed to happen in 2010, the second, a deep renovation is assumed to take place around 2020 and the last one, third rehabilitation would take place around 2040

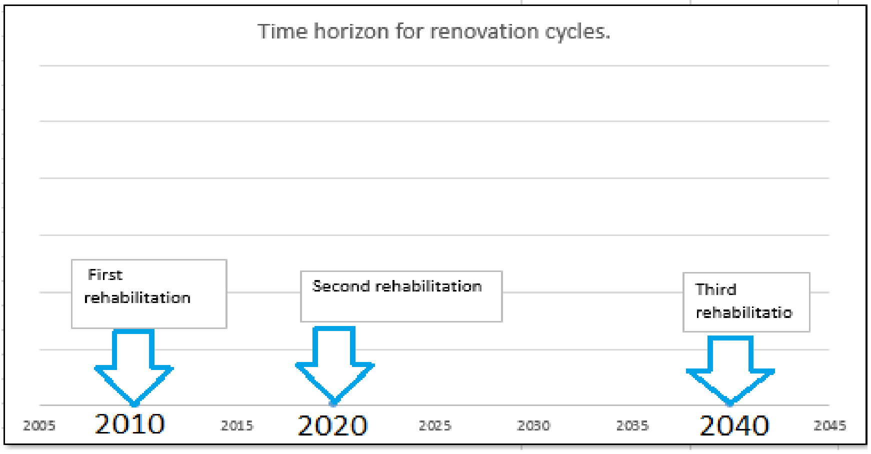


Figure 20 Time horizon for renovation cycles for both TEK10 and NS3700 scenarios.

Each scenario assumes deep renovation in 2020. The reason for this is that this buildings cohort assumes to be the next one to go through deep renovation in next 10 years [36]. The matter of choice of materials and the standard to which the house will be renovated is depending on many factors. House owners will decide how much they would like to invest in the renovation and what kind of energy reduction they would like to obtain. According to their choices the house will be upgraded to a given level and stay with fixed energy usage for the following years. The energy lock-in effect can be a significant problem, which should be avoided if possible. But home owners very often lack the right advice and their choices concerning the type of materials and energy savings, are not the most efficient [2]. For that reason the TEK 10 scenario does not represent the best solution for renovations that one could choose. The measures used in this scenario are fulfilling TEK 10 standard with the usage of the most common and popular materials available on the market. The choice of system heating is not dictated by the highest efficiency that one could obtain, but by the popularity of choice made by single-family house owners. During each of the renovations in the TEK 10 scenario, the following measures are assumed to be applied:

	Measures **TEK10** scenario					
Renovation cycle	**Space heating system**	**DHW**	**Windows &doors**	**External wall**	**Roof**	**Floor**
First renovation	80% covered by direct electric heat generator, 20% by wood oven	100% covered by electricity for electric boiler	Changed for two-pane windows with new U-value=1.2	No renovation	No renovation	No renovation
Second renovation	40% covered by air-to-air heat pump, 60% covered by the direct electric heat generator; ventilation with heat exchanger installed	No changes	New doors U-value=0.8	Old insulation removed, new added, U-value= 0.21	Old insulation removed, New added U-value=012	Old insulation removed, New added U-value=0.11
Third renovation	Improved efficiency of the heat pump 50% covered.	No changes	No changes	No changes	No changes	No changes

Table 13 Measures applied during renovations for TEK10 scenario.

For the passive house scenario the measures are chosen in order to fulfill the passive house scenario. For the domestic heating system a solar collection system is chosen, which assumes to provide 65% of heat demand to the DHW. The choice of materials is again dictated on the basis of the most available materials on the market, but the alternatively used materials are also discussed in the discussion chapter with presentation of the potential for energy savings.

	Measures **NS3700 (passive house)** scenario					
Renovation cycle	**Space heating system**	**DHW**	**Windows &doors**	**External wall**	**Roof**	**Floor**
First renovation 2010	80% covered by direct electric heat generator, 20% by wood oven	100% covered by electricity for electric boiler	Changed for three-pane windows with new U-value=0.8	No renovation	No renovation	No renovation
Second renovation 2020	Vacuum solar collector with water based heating system (new boiler and radiators)	65% heat demand covered by heat from solar collector and 35% by direct electricity	New doors U-value=0.8	Old insulation removed, new added, U-value= 0.11	Old insulation removed, New added U-value=0.08	Old insulation removed, New added U-value=0.11
Third renovation 2040	No changes	Improved efficiency of solar collector to 80%	No changes	No changes	No changes	No changes

Table 14 Measures applied during renovations for NS3700 scenario

The first and third rehabilitations are assumed to be minor for both case scenarios. In 2010 the window change is planned to already have happened. Depending on the standard of the window, there is a different energy saving potential. For the TEK 10 scenario, double glazed windows are assumed to be installed. Whereas for the passive house scenario, triple glazed windows are assumed to be installed. According to Asplan Viak research the energy saving potential with double glazed windows for the 181m² signle-family house built in 1980-1990 is 16.6 kWh/m² of reduction of energy use for space heating, whereas for the right installation of triple glazed windows it is around 39% more – 23.1 kWh/m² [35]. Therefore even a choice of just one measure can be a significant decision for overall energy potential reduction. Taking into consideration the lifetime of materials (for windows it is 40-60 years), one can quickly understand how important it is to be conscious about the choice of measures for renovation, if the energy lock-in effect is to be avoided.
The third renovation cycle assumes technological improvements in the future. For the TEK 10 scenario it is assumed that the efficiency of the heat pump would improve and it would be possible to cover 50% of energy demand for space heating with it. In the passive house scenario, the

efficiency of solar collectors is assumed to be better in the future and additional solar collectors are also taken to consideration to cover more energy demand for heating hot water. After the second renovation, no changes are assumed to be made to the external walls, roof, floors, windows and doors. The insulation added to the house, along with new windows and doors, are assumed to have a lifetime of approximately 60 years. Given the time horizon used in the analysis (2050), measures installed in 2020 will be changed around 2070, if the house will not be demolished.
The deepest renovation for both scenarios is around the year 2020. Summary of the most important changes with the reference to the original building is presented in the table 15.

Changes in U-value	**Original building**	**TEK 10 scenario**	**Passive house scenario**
External wall	0.28	0.21	0.11
Roof	0.21	0.12	0.08
Floor	0.21	0.15	0.11
Windows	2.2	1.2	0.08
Doors	2	1.2	0.08
Normalized thermal bridges	0.12	0.05	0.03
Airtightness	$N50=4$	$N50\leq2.5$	$N50\leq0.6$
Energy heating system	Direct el./wood oven 80%/20%	Direct el./air-to-air heat pump 60%/40%	Water based system with radiators and solar vacuum collector 70% for DHW
Ventilation and heat pumps			
SFP factor	-	2.5 kW/(m³*s)	1.5kW/(m³*s)
Air change rate	-	1.2m³/(h* m²)	1.2m³/(h* m²)
Heat recovery	-	70%	80%

Table 15 Changes with the reference to the original building in TEK10 and NS3700 scenarios.

4.4.3. Delivered and net energy for the operation of the exemplary house.

In the description of the system below, the terms net and delivered energy are used. According to standard NS3031 and NS-EN15603:

Net energy – building's energy needs without taking to consideration the building's energy system efficiency and losses in the energy chain.

Delivered energy – is the energy expressed per energy carrier, supplied to the technical building systems through the system boundary, to satisfy the uses taken into account (heating, cooling, ventilation, domestic hot water, lighting, appliances etc.) or to produce electricity [37].

To be able to present the most representative data for a net and delivered energy demand for operation of a typical single-family house built in 1980-1990, different sources were taken to account.

The method for calculating the net energy demand was based on the previous semester project, where the Tabula calculation method was used. The results for the net energy are presented in the table [38]. On the basis of values taken from the Enova report, the net and delivered energy demand was calculated, using Tabula Method Calculation. In table 16 the demand is presented for space heating, domestic heat water and ventilation, and all of the heat generators. The values do not include energy demand for electrical appliances and lighting. Further calculation and the final results for the net energy demand is presented in the results chapter 6.2.1.

kWh/m²	original state	TEK10	NS3700
+ heat transfer by ventilation	49	45	42
+ heat transfer by transmission	87	53	32
- internal heat gains	26.8	27	26.6
- solar heat gains	12.5	10	9.9
= Net Energy demand for space heating	96.7	61	37.5
+ heat loss/heat gain due to all heat generators	18	-8	-1
+ heat loss due to storage	0	0	0
+ heat loss due to distribution	0	0	0
- space heating contribution of the ventilation heat	0	29	30
- recoverable heat loss of the DHW system	5	2	2
= Delivered Energy use for all heat generators	109.7	22	4.5

Table 16 Results for data obtained from Enova [34] rapport and calculated using Tabula Calculation Method for three different scenarios: a single family house built in 19801-1990 in its original state, renovated up to TEK 10 standard and up to NS3700 standard.

As for the energy demand for ventilation, the base equation is from NS 3031:

$$E_{fan,i} = \frac{\dot{V}_{on} SFP_{on} t_{i,on} + \dot{V}_{red} SFP_{red} t_{i,red}}{3600} \; [kWh] \tag{1.4}$$

$E_{fan,i}$ – Energy demand for fans
$t_{i,on}$ - total number of hours during operating time during month i, in h;
$t_{i,red}$ - total number of hours outside the operating time during month i, in h;
$\dot{V}_{on}$ – airflow during the operating time, in m3/h
$\dot{V}_{red}$ – airflow outside the operating time, in m3/h
SFP_{on} – specific fan power in relation to airflow during the operating time, in kW(m3/s);
SFP_{red} - specific fan power in relation to airflow outside the operating time, in kW(m3/s);
Yearly energy demand for fans is calculated by summing monthly energy demand.

The SFP factor for the passive house is 1.6 and for the TEK 10 house is 2.0 kW/(m³/s). The net energy demand for the space heating for the passive house is assumed to be the highest net to energy demand for the 181m² single-family house situated in Oslo climate with an average temperature of 6.3 °C calculated with a method provided by NS 3031 standard.

Highest netto energy demand for heating (kWh/m²*year)			
Calculation method	Average yearly temperature	Reference area (m²)	Netto energy demand [kWh/m²*year]
$15 + 5.4 * \frac{(250 - Aff)}{100}$	6.3 °C	181 m²	19 [kWh/m²*year]

The delivered energy differs depending on the efficiencies of the heat generators.
The efficiencies of each heat generator were primary taken from Tabula Calculation Methodology [41]. The Tabula project collected data for heat generators, storages and distribution of space heating and DHW systems for countries taking part in the project. Values for efficiency in Tabula are compared with efficiencies for different energy supply systems given in the NS3031 standard.

Heat generation of heating systems.	Energy efficiency rating according to Tabula method (poor, medium, high)	Efficiency For Tabula Method	System efficiency (NS3031, Table B.9 B.10)
Direct electric heat generator	medium	0.98	0.98
Wood oven	medium	0.52	0.64
Solar vacuum collector	high	0	8.12
Air-to-air heat pump, heat source exhaust air	high	3.22	2.16
Electronic hot water heater for DHW system	Medium/high	0.75/0.97	0.98

Table 17 Efficiencies of heat generators taken from Tabula Calculation Methodology and NS3031 standard.

According to the NS3031 standard for the solar vacuum tubes collector, the heat losses are occurring throughout production, distribution and regulation. For that reason, the system efficiency is assumed to use values provided by the NS 3031 standard. For the DHW system, the values from Tabula Project are assumed for the house in its original state. It is assumed that the electric boiler for warm water from 1980s period has lower efficiency than boilers available today on the market.

4.5. Energy for electricity generation

Primary energy – energy that has not been subjected to any conversion or transformation process. For the building, it is the energy used to produce the energy delivered to the building. It is calculated from the delivered and exported amounts of energy carriers, using conversion factors [37].

Total primary energy factor – for a given energy carrier, non-renewable and renewable primary energy divided by the delivered energy, where the primary energy is that required to supply one unit of delivered energy, taking account of the energy required for extraction, processing storage, transport, generation, transformation, transmission, distribution and any other operations necessary for delivery to the building in which the delivered energy will be used [37].

4.5.1. Scenario 1a. Characterization of residual Norwegian electricity mix.

According to Statistics Norway (SSB) Norwegian mix manly consists of hydropower. Norway is the 6th largest hydropower producer in the world [42].

Electricity generation from different energy sources presented by shares					
	Hydro power production	Thermal power production	Wind power production	Imports	Primary energy factor[3]
1996	99.5%	0.5%	0.0%	13%	9%
1997	99.6%	0.4%	0.0%	8%	9%
1998	99.6%	0.4%	0.0%	7%	9%
1999	99.5%	0.4%	0.0%	6%	8%
2000	99.6%	0.3%	0.0%	1%	8%
2001	99.5%	0.5%	0.0%	9%	9%
2002	99.5%	0.4%	0.1%	4%	8%
2003	98.9%	0.9%	0.2%	13%	9%
2004	98.9%	0.8%	0.2%	14%	10%
2005	99.0%	0.6%	0.4%	3%	9%
2006	98.6%	0.9%	0.5%	8%	9%
2007	98.2%	1.1%	0.7%	4%	9%
2008	98.5%	0.9%	0.6%	2%	8%
2009	95.7%	3.6%	0.7%	4%	8%
2010	94.8%	4.5%	0.7%	12%	9%
2011	95.2%	3.8%	1.0%	9%	8%
2012	96.7%	2.3%	1.0%	3%	8%
average	98%	1%	0.4%	7%	9%

Table 18 Generation, imports and losses from production of electricity in Norway [43]

In Norway the most common energy source to produce energy delivered to the building is hydropower energy. It accounts for around 95-99% of domestic energy mix, depending on the year. Electricity is the most used source of energy in Norway with the greatest share of the energy used for space heating, followed by appliances and miscellaneous equipment [3].

[3] According to SSB: Consumption in the power stations, Pump storage consumption, loss and statistical difference. From this, it is assumed that T&D (Transformation and distribution losses) are included in Loss and statistical difference.

4.5.3. The primary energy factor

Factors and coefficients

Table E.1 — Primary energy factors and CO_2 production coefficients

	Primary energy factors f_P		CO_2 production coefficient K
	Non-renewable	Total	kg/MWh
Fuel oil	1,35	1,35	330
Gas	1,36	1,36	277
Anthracite	1,19	1,19	394
Lignite	1,40	1,40	433
Coke	1,53	1,53	467
Wood shavings	0,06	1,06	4
Log	0,09	1,09	14
Beech log	0,07	1,07	13
Fir log	0,10	1,10	20
Electricity from hydraulic power plant	0,50	1,50	7
Electricity from nuclear power plant	2,80	2,80	16
Electricity from coal power plant	4,05	4,05	1340
Electricity Mix UCPTE	3,14	3,31	617

Table 19 Primary energy factors and CO2 production coefficients.

According to the Energy Performance of Buildings Directive (Directive 20002/91/EC, EPBD) it is up to each country to determine their primary energy factors. They should also decide if production of renewable energy sources would have a primary energy factor equal to 0 or 1 and to what group nuclear energy should be assigned to (renewable or nonrenewable sources) and how one should calculate losses. According to NVE, electricity production based on hydro is assigned to renewable energy source and the primary conversion factor should be equal to 1.0. This decision is made based on the system boundaries which includes only the conversion losses. Nevertheless, for the purposes of the analysis all of the losses including generation (upstream losses), conversion losses and distribution losses should be taken to account. This assumption is in accordance with the definition of primary energy factor given in EN 15603.

Total primary energy factor – for a given energy carrier, non-renewable and renewable primary energy divided by the delivered energy, where the primary energy is that required to supply one unit of delivered energy, taking account of the energy required for extraction, processing storage, transport, generation, transformation, transmission, distribution and any other operations necessary for delivery to the building in which the delivered energy will be used.

The T&D losses for electricity in Norway are based on data obtained from Norwegian Statistics (SSB) from the last 16 years and the average value is used in the analysis, which is 9% (see table 18). To conclude, the primary energy factor used for the analysis is equal to 1.09. This factor is lower than the guidelines given in EN 15603, where the proposed factor is equal to 1.5, which according to NVE is not relevant for use in the Norwegian case.

In the scenarios, different shares of domestic production of electricity and imports are considered. The factor 1.09 cannot be used equally for all of the cases, and because of significant differences in energy sources and their shares in electricity mix production it should be adjusted for both the European electricity mix and the Nordel mix. For the European electricity mix the primary energy factor is assumed to be 3.0 based on the report from ECOFYS. In this publication, the primary energy factor for different European countries is discussed along with presenting several scenarios of energy shares development towards 2050. From this the primary energy factor towards 2050 might vary between 1.8 and 3.0 depending from scenario. The conservative perspective was chosen and the factor equal to 3.0 was chosen for whole period from 2010 to 2050. On the same basis the primary energy factor for NORDEL is assumed to be 2.0 throughout the whole period.

4.5.2. Energy consumption and specific CO2 emissions – introduction to scenarios

It is uncertain how the Norwegian electricity mix will develop in the future. There are many factors that should be taken to account like the development of renewable energies, increased capacity of hydro plants and investing in new, small hydropower plants, and increased electricity demand along with improved energy efficiencies. According to Nordic Energy Technology Perspectives (NETP), in the 4 degrees scenario (future in which strategic action limits global average temperature increase to 4°C), the energy consumption for building sector will increase from 965 PJ in 2010 to 1031 PJ in 2050 which is 7% increase, which mainly would come from electricity, biofuels and waste (in the same time the use of fossil fuels would decrease). On the other hand, in the two degrees scenario the decrease of energy consumption is assumed to be 15% by the 2050 in comparison to 2010, with electricity and commercial heat as the main sources of energy [3]. Despite the prediction that renewable energies' use will grow fast in the future (despite 4 or 2 degree scenarios), according to Nordic Energy Research it will not alter future energy shares in Norway significantly [3].

In Norway most of the energy comes from renewable sources. With the limited capacity of hydro power plants and assuming that demand for electricity will grow in the future, six scenarios were taken to consideration. In the table below shares for the domestic and imported production depending on the scenario are given. For the imports, two different electricity mixes are assumed: Nordic and European mix. The difference between them originates in the different energy mix used for production of electricity, and associated with it different specific CO_2-eq emissions levels.

Scenario	Norwegian residual mix (without imports)	Nordic mix	EU mix
1a	93%	7%	N/A
1b	93%	N/A	7%
2a	88%	12%	N/A
2b	88%	N/A	12%
3	N/A	100%	N/A
4	N/A	N/A	100%

Table 20 Energy scenarios. Shares for electricity mix: residual vs import from Nordic or European mix.

The scenarios are assuming different import ratios of Nordic and European mix for the Norwegian residual electricity production. The first two scenarios are in line with average import ratios given by SSB. The scenarios 2a and 2b are assuming an increase in the import in future due to growing consumption of electricity. These scenarios assume that the capacity for energy production in Norway stays the same while the demand for electricity consumption grows over time. With higher import rate the CO_2-eq emissions levels might stay the same, depending on the development of future energy mixes in other European and Scandinavian markets. How they will develop is difficult to predict since many factors are playing a significant role. The possible storylines for development of the primary energy sources is presented below with distinction between EU, Nordic and Norwegian residual mix.

<u>EUmix</u>

Sintef research center developed five different scenarios that are showing how future European electricity mix might develop, depending on development of renewable energies and consumption of electricity.

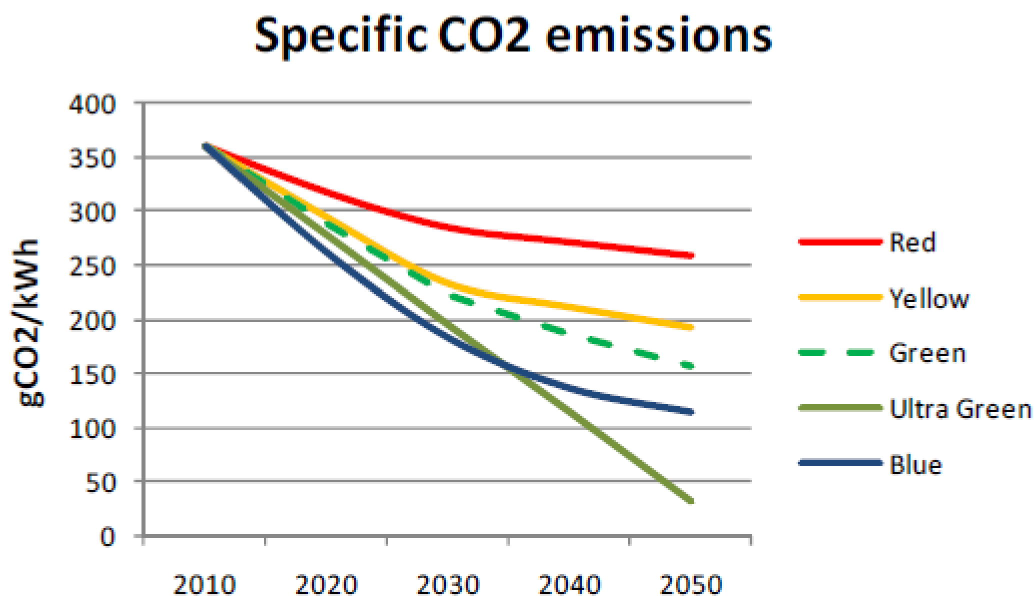


Figure 21 Scenarios for specific CO2 emissions development towards 2050 year. Source: [44]

From figure 21 one can see that there are big differences between the 'best-case' scenario (which is ultra green scenario) and 'buisiness-as-usual' scenario (which is the red line). For the analysis three different scenarios were chosen, two extreme scenarios (red and ultra green) and the green one. Each scenario was developed on the basis of the prediction of future electricity demand, shares of renewable energies, development of efficiency and technology of production of the electricity, and public attitude. The scenarios are also in relevance to zero emission buildings development in the future.

In the red scenario the total emissions stay almost the same throughout the time period. The improvement is due to the increase of renewable energy shares. In the green scenario the consumption of electricity is assumed to be lower and renewable production is coming from onshore wind and solar power. The best case scenario, is the ultra-green scenario that is a nearly CO_2 free electricity production scenario. In this case the consumption is reduced with 13.6% compared to 2010. Although the share of renewables is the highest among all of the five scenarios, it is because of the low demand (the volume of renewable is the lowest for this scenario). In the ultra-green scenario the transmission capacities are also assumed to significantly increase compared to 2010.

Nordic mix

Considering that the Ultra green scenario is nearly a zero emission scenario, the Nordic mix the 4 degrees scenario presented by Nordic Energy Research is chosen. In this scenario the emission reductions in 2050 are lowered by 20% in comparison to 2010 for electricity production from Nordic market. The specific emissions related to single renewable energy sources (hydro and wind power) are assumed to stay on the same level throughout the 2010-2050 period. For the wind power the specific CO_2 emissions are assumed to be 19g CO_2e/kWh (table 21). The hydro and thermal energy CO_2eq/kWh emissions are on the basis of the Ecoinvent v2.212 data base.

gCO2/kWh	**2010**	**2030**	**2040**	**2050**
European mix scenarios:				
Red	361	284	271	258
Green	361	223	187	157
Ultra-Green	361	196	113	31
NORDIC MIX	210	190	175	168
Wind power	19	19	19	19
Hydro	34	34	34	34
Thermal energy	362	362	362	362

Table 21 Development of specific CO2 emissions for the different scenarios [gCO2/kWh]

4.6. Modelling for scenarios

In order to be able to manage all of the energy and renovation scenarios the separate model was developed, using an excel program. The model is designed in a way to show a variety of results. The first part of the model compiles data including:

- Five different scenarios for development of CO_2 emissions related to European electricity mix (using scenarios and values presented in the Sintef report [44] Values are given in $kgCO_2$/kWh
- Values for emissions related to the Nordic electricity mix, production of renewable energies: hydropower, wind, thermal heat and use of wood oven, solar collector system and finally emissions related to usage of refrigerant in the air-to- air heat pump. All of the values are given in $kgCO_2$/kWh

Further model takes to account scenarios for renovation including:

- The TEK 10 scenario

- The NS3700 scenario
- The baseline scenario, without any renovations

All of the values are given in kWh/m^2 year for the functional unit.

Depending on chosen scenario for shares of imports and exports of the electricity used for operation of the building, different values are fed to the model. In the end, two types of results concerning primary energy needed for operation of the house can be obtained with use of the model:

- Amount of kgCO_2/kWh resulting from usage of different primary energy sources and electricity mix scenario
- The total amount of kgCO_2/m^2 year related to the functional unit depending on the chosen energy and renovation scenario.

The emissions related to the operation of the house are separated from emissions related to the materials used for renovation. All of the results related to the impacts from extraction, production and use of materials needed for the renovations are incorporated in to the model and convert to the same units as the results for primary energy needed for the operation (kgCO_2/m2 per year). The final results are accounting for emission related to both renovation and operation of the house.

In order to be able to account for embodied primary energy in operation and renovation of the building, the model also was adjusted. In this case, the amount of kWh/m^2 per year for the operation of the house (including primary energy factor) and embodied energy related to renovations were put together. In this case, the model is working in the same way, with availability of choosing different energy and renovation scenarios. The difference is that this time the results from CED are taken as an input in to the model.

5. Materials: methodology & inventory

In this section the inventory of materials used for renovation is presented. First part concludes the energy systems used for renovation scenarios and the second part describes what kind of measures were used for insulating buildings envelope.

Most of the material inventory is based on EPD from different producers. Information provided in their documents was usually sufficient enough to be able to use it for presented in this thesis scenarios. Some of the data is as well based on adjusted information from Ecoinvent data base from previous studies on buildings [40, 46].

5.1.Heat pump

The most common measures for heating added during renovation are air-to-air heat pumps [1].

This type of heat pump extracts heat from the outside air and emits heat to the inside of the building through air blower. This kind of heat pump works as a point source heat. It provides 2-3 times as much heat as applied power, and the effect decreases with decreasing ambient temperature. Other kinds of heat pumps are use both different external sources and internal heat distribution systems:

-air to water heat pump – in this system air is extracted from outside and distributed in the water based system inside of a building (through radiators, underfloor heating or convectors)

- water to water heat pump. This system have higher efficiency (3-4 times as much heat as power is supplied). A water to water heat pump extracts heat from the surrounding bedrock, soils or water/sea and emits heat in a water based distribution system. This type of heat pump is less depended on outside temperature than other two types of heat pumps.

Heat pumps are mostly used for space heating, heating intake air in ventilation system or to preheat domestic water.

According to Enova, air to air heat pumps with electricity as an energy source constitute for 95% of all heat pumps that are installed in Norwegian houses [1]. For the TEK 10 scenario this type of the heat pump is chosen.

For Oslo area, the average yearly temperature is around 6.2 degrees. That means that if air-to-air heat pump is installed it can meet demand of 40% delivered heat for space heating, which lines with the recommendations given in TEK 10 standard for ratios for energy sources to cover the space heating demand [47]. In the climate zone in which Oslo is situated, air-to-air heat pumps are able to work efficiently throughout all year. The heat pumps are working well in environment where outside temperature varies between -15 and 30 degrees. Airwell, which is a producer of the air to air heat pump used in this scenario, claims to sustain the high performance efficiency (up to 5 COP) also at as low temperature as -20 degrees.

Monthly average temperatures

	Jan	Feb	Mars	April	Mai	June	July	Aug	Sept	Oct	Nov	Dec
Oslo	-3.7	-4.8	-0.5	4.8	11.7	16.5	17.5	16.9	11.5	6.4	0.5	-2.5

Table 22 Monthly average temperatures in Oslo [48]

The seasonal performance factor (SPF) is 2.16 for the high performance heat pump. It is calculated by dividing energy output (here in form of a heat) by energy input (amount of electricity that is needed to run the heat pump). The SPF factor can vary depending on the location of the building. The SPF is the average coefficient of performance (CoP) of a heat pump over the full heating season.

COP – Coefficient of Performance – tells about efficiency of a heat pump at set conditions. This relates to the Carnot efficiency coefficient and for the heat pump, it is:

$$\varepsilon_{carnot,heat-pump} = \frac{Q_k}{W} = \frac{T_k * \Delta S}{(T_k - T_0) * \Delta S} = \frac{T_k}{(T_k - T_0)} \tag{1.5}$$

The COP is falling down as the temperature difference between heat absorption and heat emission increases. That is why heat pumps are working more efficiently in the warmer climate conditions, than with extreme temperatures.

Different electricity mix could be assumed for heat pump, due to the marginal production of the electricity that is in line with electricity supply during the winter peak periods [49]. For the simplicity, it is assumed that electricity mix stays constant throughout the year but changes over years.

5.1.1 Inventory for Airwell heat pump.

Figure 22 The air-to-air heat pump by Airwell [50].

There are no EPD or sufficient LCA studies on heat pumps in current literature study, which would provide transparent LCIA for air-to-air heat pumps used in single family houses. The array of assumptions had to be made in order to build a material inventory. Ecoinvent specifies air to water heat pump with a power of 10 kW and this source is chosen as a baseline for inventory output. To complete the material list, the review on several LCA studies for heat pumps was made.

Main materials used for production of a heat pump according to different studies				
	EcoInvent (2010) 10 kW brine-water heat pump	Johnson P. [51] 10 kW air-to air heat pump	Viral P. Shah [52] With SEER=10	Rey F.J. [53] 25 kW air-to air heat pump
Tube insulation	10 kg	-	-	-
Refrigerant	(R134a) 3.09 kg	-	(R-22) 7 kg	(R-22)
Copper	22 kg	22 kg	17 kg	21.85
Steel, low-alloyed	20 kg	-	32 kg	-
Reinforcing steel	75 kg	95 kg	101 kg	80.84
aluminum	-	-	-	60.77
Elastomer	-	10 kg	-	-
Total weight	≈113 kg	≈130 kg	≈160 kg	≈ 230 kg (including indoor and outdoor unit)

Table 23 Analysis of different studies for material input for production of an air-to-air heat pump.

The model chosen for the analysis is FLO 30 from the company Airwell. The production place is assumed to be in Pons, France. The system for this kind of heat pumps is called split system, with two units: indoor for condenser, blower, and outdoor unit containing the evaporator and blower. Based on different LCA studies and Ecoinvent data the material list for Airwell FLO 30 model was created. It includes material demand for both internal and external unit and materials used for connection of those units. The material use for heat pumps presented in earlier studies, usually were based on bigger heat pumps units with much larger quantity of materials needed for production. The most similar heat pump to the Airwell is the one presented in Rey study, which is 25kW air-to-air heat pump. The inventory is presented in detail what helps to compare with a technical data of the Airwell heat pump. It is then estimated that around 60% of total material use for 25 kW heat pump is needed for building 10 kW air-to-air heat pump.

Main materials used for production of the Airwell heat pump	
Tube insulation	10 kg
Refrigerant	(R134a) 3.09 kg
Copper	8 kg
Steel, low-alloyed	12.8 kg
Reinforcing steel	48 kg
aluminum	22.08 kg
Polyethylene, LDPE	3.22 kg
Total weight	18.5 kg (indoor unit) 66 kg (outside unit)

Table 24 Main materials used for production of the Airwell heat pump

The lifetime of a heat pumps can vary between 15 and 25 years. For this scenario the 15 years lifetime was chosen with a total of two units needed during period 2020-2050. It is assumed that the change of the heat pump around 2040 will be with improved efficiency of a pump, hence more of the space heating demand will be covered by the air-to-air heat pump.

Airwell air-air heat pump technical specification	
Lifetime	15 years
No of units used for TEK 10 scenario	2
SPF	3.0
weight	84.5 kg
Dimension external unit	950x412x835 mm
Dimension internal unit	1200x236x340 mm
Scope	From cradle to use
Maintenance	Replacement of refrigerator
Transport	2000 km

Table 25 Airwell air-air heat pump properties.

Per each kwh used by heat pump there are occurring emissions due to usage of refrigerant (during operation of the heat pump). The emissions equal to 0.00148 kg Co2eq/kwh are calculated based on Ecoinvent data. Refrigerator used for this study is R-134a (1,1,1,2- Tetrafluorethan) which contributes to the overall emissions for climate change characterization factor. During operation of the heat pump emissions occur due to this substance and some leakage occurs as well. According to the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC) of the United Nations Environment Programme, it is estimated to be 6% of the leakage after [54]. This loss is accounted for in calculations and replacement of refrigerator is taken to account.

5.2. Ventilation system

Ventilation system is assumed for the second rehabilitation in both case scenarios. A very well insulated building envelope can cause reduced air change and more humidity in the indoor air. Therefore, it is important to use balanced ventilation system that is calibrated and used in a way that avoids those problems and overpressure. The need for good ventilation to keep exchange of the ‘old’, used air and supply with a fresh incoming air is essential for a very tight building.

There are two types of ventilation systems: natural and mechanical. Natural ventilation needs a good design and none of the operating systems are needed for it, the mechanical ventilation is non depended on the weather condition. Work with natural ventilation needs constructing a building in a way that allows air to naturally flow through openings in the building’s envelope designed for those purposes. If the air is coming in through the unwanted building’s envelope openings, then we refer to thermal bridges. For the natural ventilation to be efficient, several external variables have to be accounted. Natural ventilation utilizes wind pressure and the thermal buoyancy to replace the air in the building. Dependency on the external environment is a disadvantage. During days with low winds and with a high outdoor temperature this kind of ventilation works poorly. In addition to it, the air supplied to the building cannot be preheated and filtered. That can cause indoor air quality problems due to pollution and draft. In addition, the heat from the exhaust air cannot be recovered.

In older buildings, like the exemplary building in the original state, natural ventilation was the most common way of exchange an old with a fresh air. It was usually achieved by unintended ventilation, in which air flows through leaks in walls, around door and windows. In the more airtight buildings, like the exemplary building after deep renovation, the fresh air has to be provided in other ways.

The ventilation type chosen for the scenarios is the energy-efficient ventilation system with a high heat recovery. Nowadays the highest efficiency is achieved by the rotary heat exchangers. With this kind of heat exchanger, the risk of frosting is decreased and the efficiency of heat recovery is higher (up to 85%) [48]. The disadvantage of this system, might be due to conservation of the heat exchanger. The filters when dirty are almost impossible to clean. In addition, the separation of supplied and exhausted air in this kind of design is not recommended. The ductwork also takes up a lot of space and the leaks and odor problems are common in rotary heat exchanger.

The both, TEK 10 standard and NS3700 standard for the passive house, are setting the minium requirements for the energy-efficiency of the ventilation systems. For TEK 10 standard, 70% of efficiency of heat recovery is a baseline and 80% for passive house standard NS 3700. The materials that are used for constructing the ventilation system are included in the measures. Exemplary house does not have ventilation system to begin with so depending on the scenario it is installed during second renovation with different efficiencies. The efficiency of a heat recovery depends on tightness of the building envelope and that is why in different scenario, one will obtain different results (TEK 10 scenario house is less tight than passive house scenario).

VR 400 DCV/BL	TEK 10 standard	NS 3700 standard
SFP kW/(m3/s)	2.0 (daytime) 1.0 (nighttime)	1.6
η	70%	80%
Lifetime	30 years	30 years
No of units	1	1
weight	56.4 kg	56.4 kg
Dimensions	800mmx795mmx406mm	800mmx795mmx406mm
Scope	Cradle-use	Cradle-use
maintenance	3-4 times per year with exchange of the filter once per year	3-4 times per year with exchange of the filter once per year
Transport	500 km	500 km

Table 26 VR 400 DCV/BL –properties of rotary heat exchanger.

Figure 23 VR 400 DCV/BL – rotary heat exchanger (to the left) and exemplary aluminum rotor (to the right).

The system used for the scenarios is based on Sørnes ventilation system [40]. The data for the inventory contains high uncertainty level due to little information available about quantity of materials. Based on other technical data from other producers [55, 56], that contain information about dimension, weight, type of material use for rotary heat exchanger, the quantity of used materials, transportation and lifetime from Sørnes inventory, was adjusted for a given exemplary house. The main components of the rotary heat exchanger are steel and aluminum.

Main metals used for production of the ventilation unit	VR 400 DCV
Steel, low alloyed	43 kg
Aluminum	5 kg
Steel product manufacturing	43 kg
Total weight of a unit	56.4 kg

Table 27 Main metals used for production of the ventilation unit.

The main part of the ventilation unit is a rotor. The most common material used for building a rotor is aluminum. Steel is used to build a hardware for rotor. The inventory for filters, cables and printed circuit board is taken from Ecoinvent (after Sørnes, 2011). The system consists from rotary heat exchange unit, steel pipes for distribution of air and electric fans. The whole system is assumed for 25 years of lifetime.

Ventilation system		
System part	Database	comments
Air filter	Ecoinvent	Assumed for multi family house
Air distribution housing, steel	Ecoinvent	Components made of zinc ocated steel and PUR foam insulation for the same type of multi family house as in Air filter
Ventilation unit	Sørnes, 2011, Ecoinvent	Partly assumed materials from information given by producer and partly taken from Ecoinvent data base (filters, cables, printed circuit board)

Table 28 Ventilation system – description of the system and used of database for the system.

5.3. Solar system

For the second, deep renovation of the original building to the passive house standard, solar heating system was chosen to cover a part of energy demand for the heating of the tap water.

Need for the DHW stays constant throughout the year. It results from a demand for the hot water – amounts of water used for shower, cleaning etc. which stays fairly the same.

The application of the solar collectors is based on the Stord case-study building described in the Sørnes thesis [40]. Due to physical similarities of both, Stord and Exemplary buildings, it is possible to use energy system solutions applied in the Stord house example. Both buildings have similar total usable area (181m2 vs 187 m2) and the structure of the buildings envelope (number of floors, window area).

Location of Stord house is closed to Bergen, which receives on average less of the solar radiation than it would if situated in Oslo.

Values for monthly irradiation	Solar radiation - horizontal [W/m2] Oslo	Solar radiation - horizontal [W/m2] Bergen
Jan	13	14
Feb	43	33
Mar	90	81
Apr	153	122
Mai	198	206
Jun	249	194
Jul	219	180
Aug	175	144
Sep	107	83
Oct	45	47
Nov	19	18
Dec	8	8
Average	110	94.1

Table 29 Values for monthly solar irradiation – horizontal for Oslo and Bergen [W/m2] [39], [34].

The amount of solar energy that could be harvested would be bigger (by around 16%) in Oslo than in Bergen which is further north. In order to maximize possibility of solar energy that can be utilized, solar collectors are usually mounted using tilted construction or on an angled roof. The collector tilt angle shall vary by not more than +/- 25 degrees from the angle of the local latitude, and the azimuthal angle may vary by not more than +/-45% from due true south [57]. In the Stord house example solar collectors are mounted on the 30 degrees angled roof, whereas the exemplary house assumes a flat roof. As a result, the amount of solar radiation on tilted solar collectors is similar to the horizontal solar radiation in Oslo.

Values for monthly irradiation	Solar radiation Horizontal Oslo [W/m2]	Solar radiation tilted Stord [W/m2]
Jan	13	39
Feb	43	55
Mar	90	113
Apr	153	140
Mai	198	219
Jun	249	195
Jul	219	183
Aug	175	159
Sep	107	102
Oct	45	77
Nov	19	44
Dec	8	24
Average	110	112.4

Table 30 Values for monthly irradiation Oslo (NS3031) and values for monthly irradiation Stord.

If the solar collector would be mounted on the flat roof in Oslo it would then receive a little bit less of solar radiation that the system placed on 30 degrees angled roof situated in Stord. It is then underestimation of how much energy can be produced from solar collectors situated in Oslo, in case of tilted construction. For the simplification, the same amount of the solar irradiation was assumed for the exemplary house with a flat roof as for the Stord house. The scenario where more solar energy can be harvested (tilted roof in Oslo climate zone) is presented then in the discussion chapter.

To conclude, the same amount of 3311 kWh/year of heat retrieved from solar energy is produced in both cases: Stord house and exemplary house renovated to the passive house standard.

The cross comparison between monthly irradiation for the flat roof in Oslo and tilted in Bergen are approximately the same (table 30). Therefore, the same irradiation is assumed and capacity to produce heat from the solar system. Off course assuming that roof would be tilted in Oslo climate, we would obtain more useful energy for the house and that would be discussed in the chapter where sensitivity analysis was presented.

In standard NS3700 estimated amount of delivered electrical and fossil energy should be less than the total net energy subtract 50% of net energy for hot water.

$$\mathrm{Edel,el} + \mathrm{Edel,oil} + \mathrm{Edel,gas} < \mathrm{Et} - 0.5 * \mathrm{QW,nd} \qquad (1.6)$$

Et – Total net energy need (kWh/yr)

$\mathrm{Edel,el}$ – Energy from annual delivered electricity

$\mathrm{Edel,oil}$ –Energy from annual delivered fossil oil (kWh/yr)

$\mathrm{Edel,gas}$ – Energy from annual delivered fossil gas (kWh/yr)

$\mathrm{QW,nd}$ – Annual net energy need for heating of tap water (kWh/yr).

So for NS3700 scenario 3311 kWh fed to the DHW system from solar collector is fulfilling the requirements.

5.4.1. Inventory

The inventory for the solar thermal system was made by Sørnes [40] on the basis on Ecoinvent report [58] and adjusted using SimaPro program for the given passive house scenario.
The material input consists from the vacuum tube collectors, copper pipes, pumps and vessel (after Sørnes). Vacuum tube collector mainly consists from chromium steel, insulation, copper and glass.

Vacuumtube collectors Mazdon 30, Thermomax	
Lifetime	Adjusted for 30 years
Dimensions [m]	2.2x2.021 per unit
Number of units	3
Total weight	78 kg
Area of the roof covert by the solar system	13.4 m2
Scope	Cradle to use
Maintenance	Every 10th year pumps and the antifreeze-inhibitor is renewed
Transport	included
Heating to the system (netto)	3311 kWh/yr (excluding 6% loss)

Table 31 Properties of chosen solar collector system – Vacuumtube collectors Mazdon 30.

The loss of energy from the solar collector system is attributed to the surplus of energy that is not utilized during warmer months due to lower demand for heating.

The heat distribution system is adjusted in the calculation for 30 years of use with overall lifetime of 50 years. The heat distribution system consists from 600 l hot water tank, hydronic pipe system and radiators.

The heat distribution system	600 l hot water tank and distribution pipes	Radiators and hydronic floor heating
Lifetime	30 years	30 years
No of units	1	2
Volume	600l	5.4 l
scope	Cradle to Use	Cradle to Use
maintenance	not needed	Not needed
Transport	included	included

Table 32 The heat distribution system for the solar collector system. [48].

The closed loop interconnection for the Thermomax solar collectors is showed below, on the figure 25:

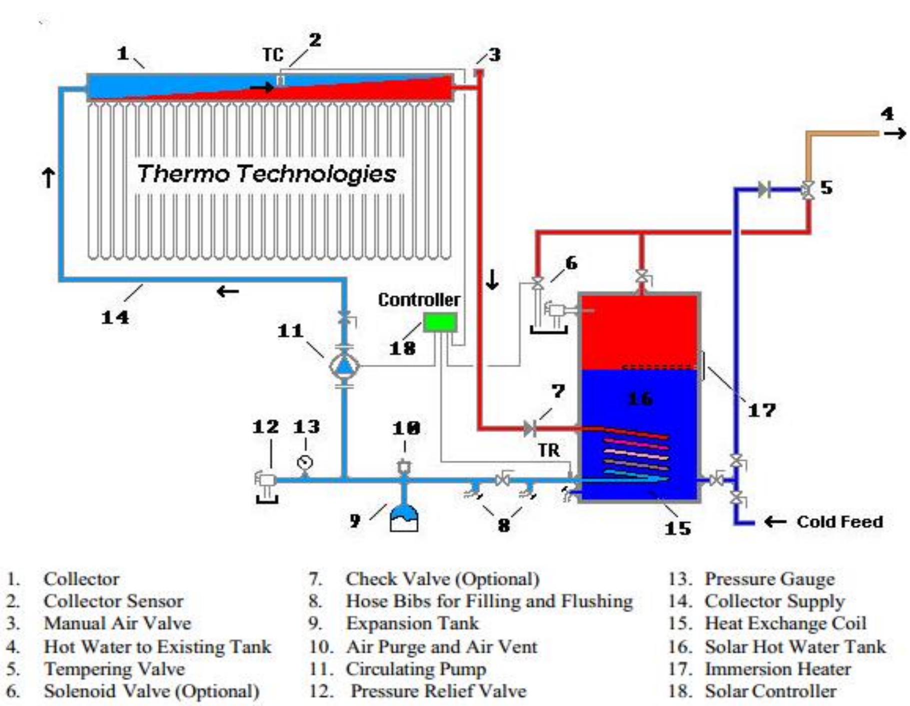


Figure 24 The Mazdon 30 system operation and plumbing details. [59]

The solar radiation is absorbed by the collector and converted into heat. It is a photo-thermal conversion. The heat is then transferred from the collector to the heat exchanger in the tank. Since the collector is mounted on the outside, the glycol is used to prevent freezing of the loop. The controller is set up to switch between heat from solar collectors or electricity to warm up the water in the tank. When there is not enough heat produced by solar collector, the demand is covered by an electric heater.

5.5. Insulation

Considering the retrofit insulation, one should begin with look at the properties of the original building envelope like U- value, air tightness and thermal bridges before starting with renovation. The transmittance loss in building envelope can be reduced by adding thermal insulation to walls, roof and floor. There is a clean correlation between thickness of the insulation and lowering the U-value (thicker insulation, better U-value one can obtain.).

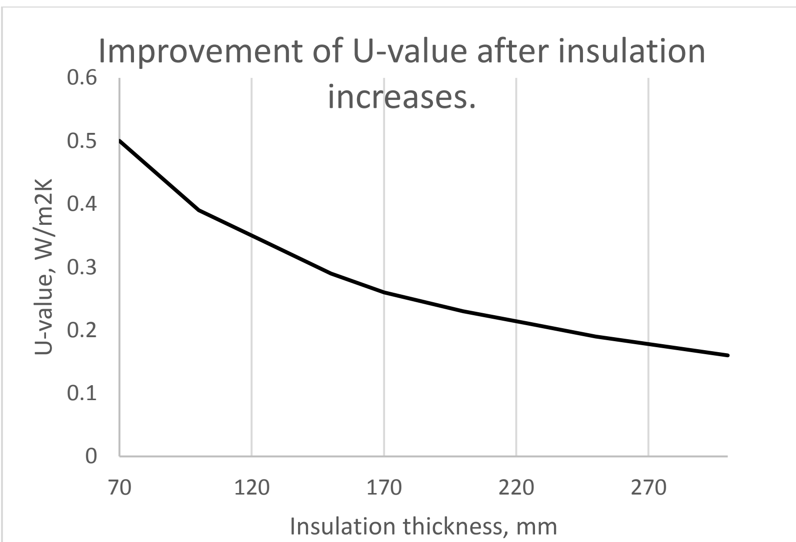


Figure 25 Improvement of U-value after insulation increases. Starting point is external wall insulated with 70 mm Flexi A plate with the thermal conductivity of 37 mW/mK, wind barrier, wooden studs and cladding.

When applying insulation, the right technique and additional products should be carefully chosen for assuring the functionality of the structure. The right application of a vapor barrier prevents air and humidity leaks from the inside. On the outside the wind barrier should be applied. The purpose of this type of barrier is to prevent the cold outdoor air from penetrating, and cooling of the insulation.

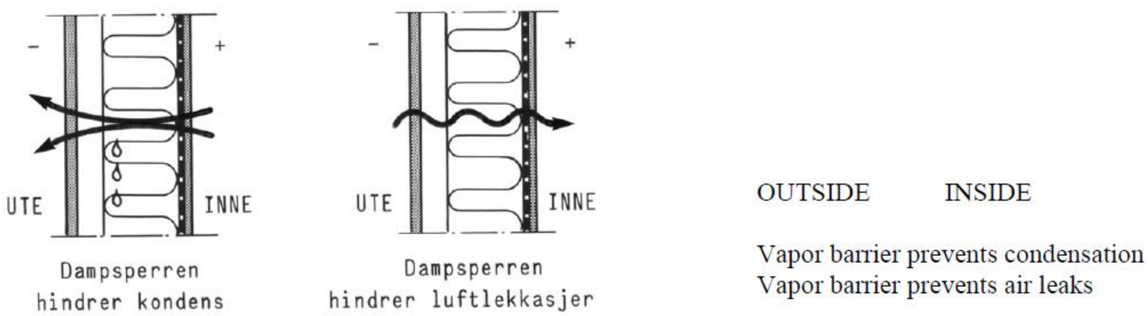


Figure 26 Vapor barrier on the warm side of the thermal insulation [48].

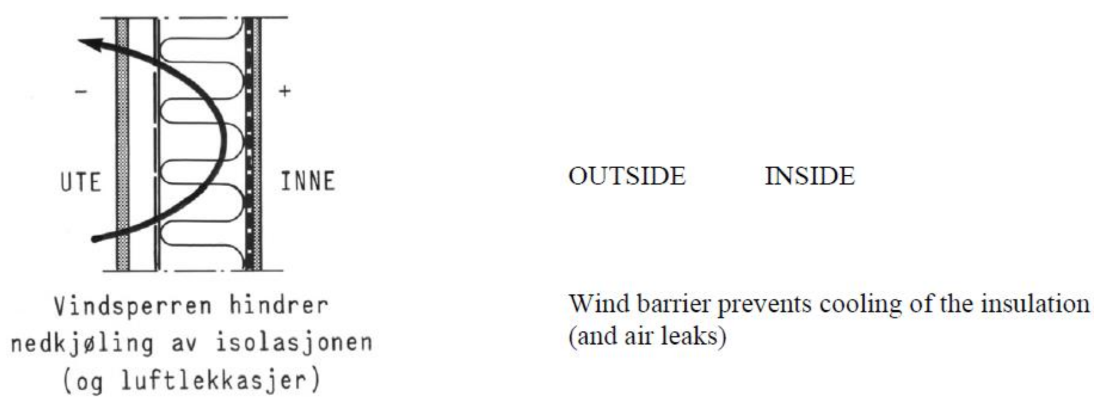


Figure 27 Wind barrier on the outside of the thermal insulation [48].

Exterior cladding should be aerated (have air gap between wind barrier and cladding). This way of construction helps to prevent rain from pushing water into the structure.

Retrofitting should be implemented in a careful way to avoid damages and thermal bridges. Mistakes can occur due to lack of knowledge of people involved with retrofit. The wrong choice of materials like insufflation of urea-formaldehyde foam for wood framework walls can be one of the examples of how wrong choice of materials can cause a large humidity surplus in the structure and lead to damages in building envelope. For that reason, it is fundamental, while renovating a house, to asses thoroughly physical features of the original structure before applying new measures.

In the analysis two different scenarios are chosen: first in which the original building is ongoing a deep renovation up to TEK 10 standard, and second where the same building is ongoing renovation up to passive house standard.

The baseline for parameters that the building has to have in order to fulfil the TEK 10 or NS3700 requirements, are given in the table below:

	TEK 10	NS3700
U value (W/m2K)	Minimum demand	Minimum demand
External wall	0.22	0.1-0.12
Roof	0.18	0.08-0.09
Floor	0.18	0.08
Windows, doors	1.60	0.08

Table 33 Minimum demand for U-values in accordance with TEK 10 and NS3700 standard.

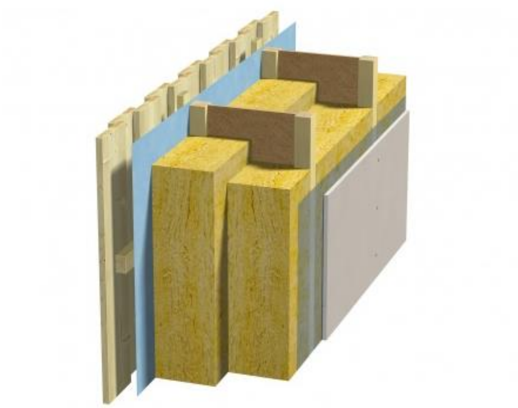
The amount and type of materials used for renovation in different scenarios is presented in table 34:

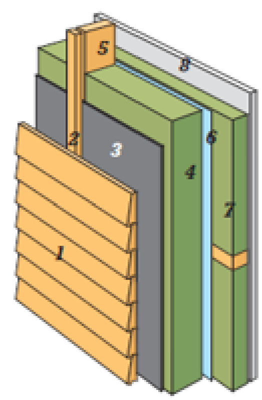
Building product	Name of the product	Density [kg/m3]	Thermal conductivity [W/mK]	Thickness TEK 10 [m]	NS3700 [m]
Rockwool					
External wall	Flexi A-plate	34.8 kg/m3	37 mW/mK	0.2	0.4
Roof	Flexi A-plate	34.8 kg/m3	37 mW/mK	0.15	0.5
Floor	Støpeplate Plus	104 kg/m3	37 mW/mK	-	0.25
	Flexi A-plate	34.8 kg/m3	37 mW/mK	-	0.048
Glava					
External wall	Proff 35	16 kg/m3	35 mW/mK	0.2	0.4
Roof	Extrem 33	22 kg/m3	35 mW/mK	0.15	0.5
Floor	Plate 40	39 kg/m3	38 mW/mK	-	0.25
	Proff 35	16 kg/m3	35 mW/mK	-	0.048

Table 34 Properties of different insulation materials.

The properties of Rock wool and Glava insulation are similar; therefor the allocation of the given insulation could be used for comparison between different scenarios. Further, in the discussion chapter, the comparison is made between insulation for TEK 10 with usage of Rockwool, Glava or Thermafleece and related with it environmental impacts.

5.5.1.External wall





NS3700 External wall TEK 10 External wall

Figure 28 The wall designs for the TEK 10 house and NS3700 (passive) house.

Both scenarios are assuming that the old insulation was removed and replaced with the new one. The demolition of the old insulation is assumed to be out of the system boundaries. Each scenario assumes using the design for walls on the basis of technical information provided by Glava, Rockwool and Byggforsk [61].

Construction element	Materials	
	TEK 10	NS 3700 (passive house)
Exterior cladding	Planed structural timber	Planed structural timber
Studs and joists	Sawn dried timber	Sawn dried timber
Wind barrier	polypropylene	polypropylene
Insulation	Glass wool/stone wool	Glass/stone wool
I beam	Sawn timber/shavings	
Vapor barrier	polyethylene	polyethylene
Interior cladding	Gypsum	gypsum

Table 35 Materials used for retrofitting external wall to the TEK10 or NS3700 standard.

5.5.2. Roof

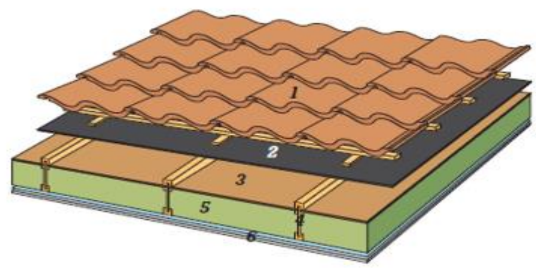


Figure 29 The roof design for retrofitting for both TEK10 and NS3700 scenarios.

The guide for insulating the roof differs for different buildings construction. In this scenario the area of the roof is assumed to be the same as the area of the floor. The technique for retrofitting the roof is assumed to be the same as for the tilted roof since it is the most common type of roofs in single family houses. In the analysis, it is assumed that the old insulation is removed and replaced with a new one. Studs are added with recommended by Byggforsk distance [62]. Vapor and wind barriers as well as new tiles, are also added or replaced during renovation. The inventory for materials and amount is given in the table 36.

Depending from the structure of the roof, there are several ways of retrofitting with insulation. Many single family houses have slanted wooden roofs with a half story on top that usually was not insulated (most popular before 1960, when the prefabricated houses become more common [48]). One ways to conduct the retrofit of that kind of roofs is to blow insulation into the empty spaces of

roof structures, but it should be done with insurance that the vapor insulation is applied in the same time. The problems of condensation damages and melting snow on the roof are challenges that should be thought while planning for insulating this part of buildings envelope.
The insulation in the presented cases is added on top of the old roof sheathing.

Roof structure design for TEK 10 and Passive house scenarios	
Material/product	TEK10/ NS3700
Vapor barrier	polyethylene
Insulation	Glass/stone wool
I-beams	Sawn timber/shavings
Underlay with wind barrier	Wood chips/oxidized bitumen
Support and counter battens	Sawn dried timber
tiles	Cement/ sand

Table 36 Roof structure design for TEK10 and Passive house.

Type of products and properties used for roof structure design for TEK 10 and NS3700 scenario					
Building product	Name of the product	Density	Thermal conductivity [W/mK]	Thickness TEK 10 [m]	Thickness NS3700 [m]
Stone insulation	Rockwool Flexi A plate	34.8 kg/m3	37 mW/mK	0.3	0.55
Glass insulation	Glava Extrem 33	22 kg/m3	35 mW/mK	0.3	0.55
Vapor barrier	Icopal Dampsperre	185 g/m2		0.02	0.02
I beam	Byggma I beam			47x47mm flang and height=0.2	47x47 mm flang and height=0.5
Underlay with wind barrier	Hunton Sarket		0.37-0.52 m2K/W	0.018	0.018
Support and counter battens	Sawn dried timber	Estimated 470 kg/m3		36x11 mm and 36x19 mm	36x11 mm and 36x19 mm

Table 37Type of products and their properties used for roof structure design for TEK 10 and NS3700 scenarios.

Use of new material solution was taken to consideration in the roof design. For example, there was no need for additional wind barrier layer, because of solution with underlay plates designed by

Hunton, that is combing underlay with wind barrier. With this type of construction of the roof a gap between the sub-roof and the wind barrier is not needed [63, 64].

5.5.3. Floor

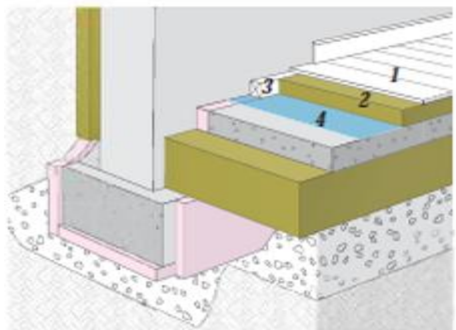


Figure 30 The floor design for retrofitting for both TEK10 and NS3700 scenarios.

Concrete floor is chosen for the type of the floor construction. The figure 30 shows the design of retrofitted floor. While insulating it is important to remember about moisture that can occur due to condensation between heated area and colder ground. For that reason vapor barrier also should be used. Also to avoid casting of the water the wind barrier can be used. The design of the floor includes two kinds of isolation: one with a very high material density – for Rockwool it is Støpeplate and for Glava it is Plate 40 type. The recommended thickness is 250 mm for Rockwool product and 100 mm for Glava product in order to achieve U value equal to 0.08. On top of insulation the 70 mm thick concrete floor is laid down and Icopal moisture membrane. Then the vapor barrier goes before the other layer of lighter insulation. The floor is finished with wooden panel floor.

Building product	Name of the product	Density	Thermal conductivity [W/mK]	NS3700 [m]
Stone insulation	-Rockwool Støpeplate (250mm)	104 kg/m3	37 mW/mK	
	-Flexi A plate (48 mm)	34.8 kg/m3	37 mW/mK	
Glass insulation	-Glava 40 plate (100mm)		38 mW/mK	
	-Proff 35 (48 mm)		35 mW/mK	
Vapor barrier	Icopal Dampsperre	185 g/m2		0.02
Concrete floor	Norbetong B25M60	2131 kg/m3		0.07
Panel floor	Treindustri interior woold panel (crude wood)	470 kg/m3	39 kg/m3 16 kg/m3	0.014

Table 38 Properties of different insulation materials.

5.6. Windows& doors

5.6.1.Windows

Nowadays windows are filled with noble gas (argon or krypton) in between the panes (before it was only a dry air). This measure reduces convection and conduction in the cavity between.

Radiation exchange is then reduced between glass surfaces. This reduces the transfer of considerable energy and more than halves the U-value of the windows. Coatings can also play a role in a significant reduction of the solar radiation through window glass. New improved distance list reduces the thermal bridge at the edge and improves overall U-value for windows.

Changing of the windows is one of the most common measure to apply while refurbishing house. In Norway Sweden and Finland wood windows are taking lead with 70% of the market share of windows.

For the TEK 10 scenario H-window type AT 200E produced by MagnorVinduet is chosen. Two pane window with frame is expected to have a lifetime of 60 years. The transport form the factory in Eiskog to Olso is assumed 100 km. The main materials used for production of window are: glass, steel, aluminum, pine, composite like ABS/PVC. Approximately 70% of the window opening is glass. The weight of the window is 54.9 kg for 1.23x1.48 m window.

Figure 31 Exemplenary windows produced by manufacturer used in the study. Left: window with the U-value=1.2;, right: window with U-value= 0.8

Nowadays the U value as low as 0.8 for windows can be achieved with three pane windows. For the scenario NorDan three pane window with aluminum cladding is chosen with Inward opening tilt and turn. Nordan windows are produced in Moi, which is 450 km from Oslo.

For both types of windows, the energy usage during installation is considered negligible. The maintenance is considered. The timber frame needs to be painted every 7 years and interior maintenance is considered every 15 years.

	TEK 10 standard Magnor window	NS 3700 standard NorDan window
U-value	1.2 (W/m2K)	0.8 (W/m2K)
type	Two pane with alu frame	Three pane with alu frame
Lifetime	60 years	60 years
Area covered	27.15 m2	27.15 m2
weight	54.9 kg/ 1.23x1.48 m	65.67 kg/ 1.23x1.48m
Dimensions	1.23x1.48m per window	1.23x1.48m per window
Scope	Cradle-use	Cradle-use
maintenance	Water, detergents and paint included	Water, detergents and paint included
Transport	100 km	450 km

Table 39 Properties of windows used for TEK10 and NS3700 scenarios.

5.6.2. Doors

According to report from DG Environment for the European Commission [65] figures for external door demand in Europe are difficult to obtain. Door market is directly linked with windows market, since those two products are very often purchased in the same time. The main materials used for both windows and doors are: plastic (low cost, high energy efficiency) fiberglass, aluminum and timber.

As for windows, wood is a dominant material for production of doors in the Northern part of Europe.

Sweedor – Jeld Wen company is chosen for door supplier. P 100 clever line model has the right properties for the passive house standard. To be able to get better insulation, no glass parts are assumed for those doors. Glass parts are lowering overall U value and force thicker frame to be applied. Since amount of material use is in concern, plain doors are assumed to be the best choice. Since there are no may LCA studies that would investigate impacts from different kind of doors production, the inventory is built based on Ecoinvent inventory and Dahlstrøm inventory [46]. The thickness was adjusted to be 105 mm in order to fulfill passive house standard and distance for transportation was also changed.

The door lock is included in the analysis. The main components for lock is steel and the lifetime is considered to be the same as for doors.

	NS 3700 standard doors
U-value	0.8 (W/m2K)
Type	Sandwich construction
Lifetime	30 years
weight	50 kg per unit
Dimensions	0.9x 2.1x 0.105 m
Unit	2
Scope	Cradle-Use
Transport	422 km

Table 40 Properties of doors used for renovations.

6. Results

The structure of this chapter is split into four sections. In the first section, life cycle inventory analysis of materials used for renovation is presented. The second part shows the cumulative energy demand and climate change impacts from the production, transport and maintenance of the materials (from cradle to use phase). In the third section, operation of the house, the overview of accumulated impacts from the measures and operation of the exemplary house for *TEK10* and *NS3700* scenarios is presented. The results are presented in a relation to both: energy and emissions saving potential resulting from applied measures. The last section performs the implication of renovating along the *TEK10* or *NS3700* scenarios on the Norwegian single-family house stock built between the years 1980 and 1990. The energy saving potential is based on exemplary house presented in the earlier sections.

For the better overview, several simplifications were made while presenting the results:

→ All of the results for the operation of the exemplary house are presented for one electricity share scenario: 1a. This assumes that 93% of electricity demanded for the operation of the house comes from domestic Norwegian production, and 7% is imported (Nordic mix). This assumption is based on the statistics (SSB) and it represents the average electricity mix over the last years (the detail overview is given in chapter 4.5.3.

→ The terms TEK10 and NS3700 are representing two different scenarios described in detail in chapter 4. Each scenario assumes three renovation cycles during the same time but using a different amount and type of materials.

→ In the last section (dynamic model results), only one cycle of renovation is taken into account. That happens in 2020 after a 40 year of building's existence, with, a deep renovation to the TEK10 or passive house standard. In this part the whole accumulated single-family house stock (built between 1980 and 1990) is taken to account.

6.1 Materials used for measures

The results below of the life cycle inventory analysis performed are split into sections where each type of measure is presented. Each table shows the results for the cumulated embodied energy demand and GHG in materials needed for all of the renovations during the period 2010-2050, split between TEK10 and NS3700 scenarios. The system boundaries are from cradle to use.

6.1.1. Life cycle inventory analysis

Windows

The life cycle inventory of materials used for production of both passive windows (with a U-value=0.8) and lower standard windows (with U-value=1.2), and the estimation of shares of materials was made based on previous life cycle assessments done for the window industry. The biggest shares of embodied energy is coming from production of aluminum, glazed glass and timber. The energy embodied in raw materials used for the analysis is based on environmental product declaration from both companies NorDan and Magnor. The EPD contain total impacts for different characterization factors. The further contribution analysis is based on EPD’s and LCA studies . The later one are based on case study in factory placed in Moi in Norway, where the passive window used in the analysis is also produced [66]. [66]. For the purpose of this research, the density of pine timber used is 500 kg/m^3 (in accordance with both the EPD and Weir studies) with the embodied energy is 2.6 GJ/m^3 [67]. The energy required to produce one kg of aluminum is assumed to be the same as in Weir study, which is 13 MJ/kg [66, 67].

Production of aluminum demands high energy quantities, whereas energy for cutting and assembling the aluminum components for window construction is negligible. The crushing of raw bauxite, electrolysis of alumina and the casting constitutes the biggest shares of energy use during production of aluminum. The estimated energy use for aluminum production varies. For this analysis, 178 MJ of embodied energy is assumed for production of one kg of aluminum needed for window production [66, 68].

In the figure 32 the label “other” constitutes for additional materials used (packaging film, steel, zeolite, argon, krypton and other) and energy needed for manufacture of the windows

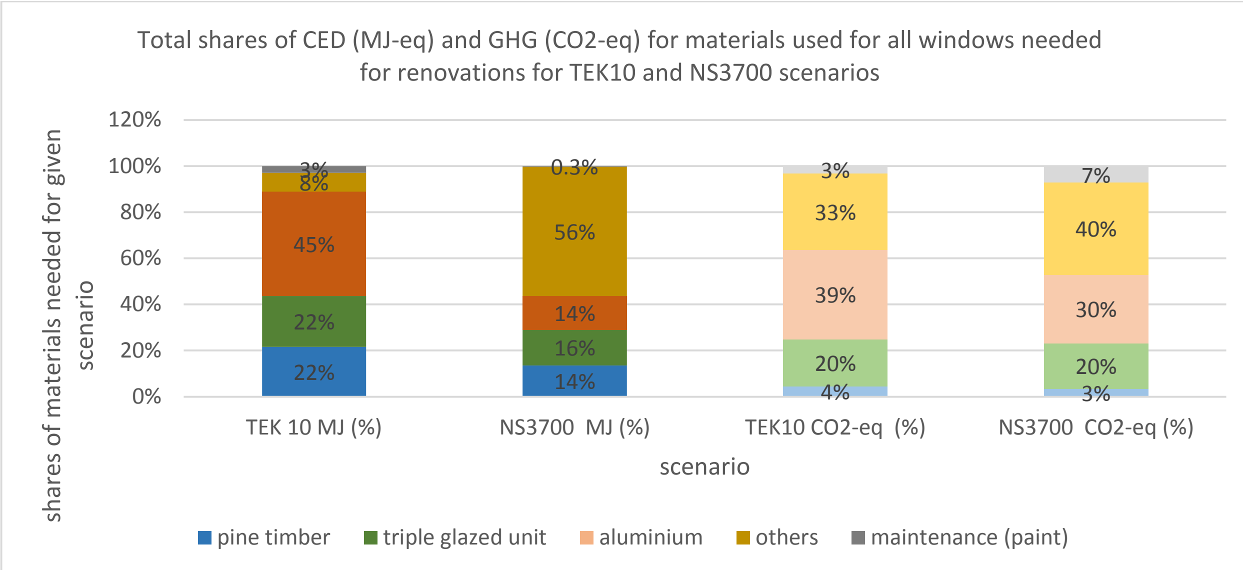


Figure 32 Total shares of CED (MJ-eq) and GHG (CO2-eq) for materials used for all windows needed for renovation of an exemplary house(functional unit) during 2010-2050 time and differentiated by scenarios.

Materials for total 27 m² of window area	Total embodied energy (MJ) per one exemplary house		Total Climate Change emissions (CO2-eq) per one exemplary house	
	TEK10 scenario	NS 3700 scenario	TEK 10 scenario	NS 3700 scenario
Pine	5.19E+03	7.37E+03	6.98E+01	7.11E+01
Glazed unit	5.29E+03	8.41E+03	3.22E+02	4.03E+02
Aluminum	1.09E+04	7.84E+03	6.07E+02	6.07E+02
Other	1.95E+03	3.04E+04	5.20E+02	8.26E+02
Transport	3.15E+01	1.38E+03	1.39E+02	8.01E+01
Maintenance	7.09E+02	1.56E+02	5.15E+01	1.38E+02
Total	2.41E+04	5.55E+04	1.71E+03	2.12E+03

Table 41 Total embodied energy and Climate Change characterizations results for materials used for production of all of the U=0.8 and U=1.2 windows needed for renovation of an exemplary house during 2010-2050 time and differentiated by scenarios.

The individual impact contributions of different materials used is presented in the table 41 Production of aluminum is the most energy intense process in production of a window. In the analysis it is assumed that 27% of aluminum is recycled, which reduces the overall CO_2-eq emissions. For the passive window, less aluminum and more timber is assumed to be used for the window frame. This results in lower scores for that passive window as compared to the TEK10 window used in the analysis.

External wall

Construction element	Materials for total 131 m² of wall area		Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	TEK 10	NS 3700	TEK 10	NS 3700	TEK 10	NS 3700
Exterior cladding	Planed structural timber		8.87E+03	8.87E+03	3.03E+02	3.03E+02
Studs and joists	Sawn dried timber		3.09E+02	5.61E+03	3.27E+00	5.93E+01
Wind barrier	polypropylene		3.15E+03	3.15E+03	1.33E0+2	1.33E+02
Insulation	Glass wool/stone wool		7.11E+03	1.25E+04	2.77E+02	1.09E+03
I beam	Sawn timber/shavings		4.57E+03	----	9.28E+01	-----
Vapor barrier	polyethylene		8.29E+02	8.29E+02	2.41E+01	2.41E+01
Interior cladding	Gypsum		3.43E+03	3.43E+03	1.44E+02	1.44E+02

Table 42 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for renovation of an external wall of an exemplary house during 2010-2050 time and differentiated by scenarios.

Roof

Construction element	Materials for total 120 m² of roof area		Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	TEK 10	NS 3700	TEK 10	NS 3700	TEK 10	NS 3700
Vapor barrier	polyethylene		2.16E+00	2.16E+00	2.20E+01	2.20E+01
Insulation	Glass/stone wool		1.37E+04	1.58E+04	5.36E+02	1.37E+03
I-beams	Sawn timber/shavings		6.05E+03	7.37E+03	1.30E+02	1.58E+02
Underlay with wind barrier	Wood chips/oxidized bitumen		4.93E+03	4.93E+03	2.13E+02	2.13E+02
Support and counter battens	Sawn dried timber		2.14E+02	2.14E+02	2.27E+00	2.27E+00
tiles	Cement/ sand		1.76E+04	1.76E+04	1.22E+03	1.22E+03

Table 43 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for renovation of a roof of an exemplary house during 2010-2050 time and differentiated by scenarios.

Floor

Construction element	Materials for total 120 m² of floor area		Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	TEK 10	NS 3700	TEK 10	NS 3700	TEK 10	NS 3700
Stone insulation	Stone wool Støpeplate (250mm)		2.18E+04	2.18E+04	1.87E+03	1.87E+03
	Stone wool (48 mm)		1.38E+03	1.38E+03	1.19E+02	1.19E+02
Vapor barrier	polyethylene		2.93E+03	2.93E+03	2.20E+01	2.20E+01
Concrete floor	Concrete B25M60		5.77E+03	5.77E+03	8.80E+02	8.80E+02
Panel floor	Crude wood		1.83E+03	1.83E+03	2.63E+01	2.63E+01

Table 44 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for renovation of a floor of an exemplary house during 2010-2050 time and differentiated by scenarios.

Doors

Construction element	Materials for total 3.78 m² of doors area		Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	TEK 10	NS 3700	TEK 10	NS 3700	TEK 10	NS 3700
doors	Aluminium		2.92E+03	2.92E+03	1.49E+02	1.49E+02
	Polystyrene		1.03E+03	1.03E+03	1.11E+02	1.11E+02
	Other (inc. Transport)		2.15E+03	2.15E+03	9.57E+01	9.57E+01

Table 45 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for renovation of a door of an exemplary house during 2010-2050 time and differentiated by scenarios.

Ventilation

Construction element	Materials for one system	Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	TEK 10 NS 3700	TEK 10	NS 3700	TEK 10	NS 3700
Ventilation system	Ventilation unit	7.38E+03	7.38E+03	4.25E+02	4.25E+02
	Air filters	1.94E+03	1.94E+03	7.61E+01	7.61E+01
	Air distribution system	5.73E+02	5.73E+02	3.25E+01	3.25E+01
	Other (incl. Transport)	3.15E+02	3.15E+02	1.91E+01	1.91E+01

Table 46 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for ventilation installed in an exemplary house during 2010-2050 time and differentiated by scenarios.

Heat pump

Construction element	Materials for two units	Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	TEK 10	TEK 10	NS3700	TEK 10	NS3700
Air-to-air heat pump system	Other (incl. Transport)	8.78E+03	N/A	2.37E+03	N/A
	Aluminum	6.03E+03	N/A	3.78E+02	N/A
	Steel	2.97E+03	N/A	1.85E+02	N/A
	Refrigerant R134a	1.01E+03	N/A	6.40E+02	N/A
	Tube insulation	2.53E+03	N/A	8.96E+01	N/A

Table 47 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for heat pump installed in an exemplary house during 2010-2050 time and differentiated by scenarios.

Solar collector system

Construction element	Materials for one system	Total embodied energy (MJ) per one exemplary house		Total Climate Change characterization (CO2-eq) per one exemplary house	
	NS 3700	NS 3700	TEK10	NS 3700	TEK10
Solar collector system	Radiators and pipes	2.64E+03	N/A	1.53E+02	N/A
	Hot water tank	7.48E+03	N/A	4.14E+02	N/A
	Propylene glycol	4.36E+03	N/A	1.72E+02	N/A
	Evacuated tubes (collector system)	2.29E+04	N/A	1.30E+03	N/A
	Other (incl. Transport)	5.39E+03	N/A	3.96E+02	N/A

Table 48 Total embodied energy and Climate Change characterizations results for materials used for production of all the materials needed for solar collector system iinstalled in an exemplary house during 2010-2050 time and differentiated by scenarios.

6.1.2. CED of measures used for renovations.

The total (CED) for materials is presented on figures 33 and 34. Each bar is presenting the total energy demand for the 181 m^2 exemplary house over the whole period from 2010 to 2050, using each scenario (TEK10 or NS 3700), from cradle to gate (with use phase) stages. The years of usage differ for some measures; therefore, a quick overview is given in the table 49. The total CED emissions for TEK10 scenario is 1.58E+05 MJ-eq and 2.10E+05MJ-eq for the NS3700 scenario (including all three renovation cycles). The biggest contributor to the CED impacts is from the retrofitting of roof to the passive standard (4.59E+04 MJ-eq) and applying the solar collector system (4.28E+04 MJ-eq). To be able to analyze which materials are contributing the most to these results, a more detailed contribution analysis of materials that are used for production of each measure is presented in the figure 35.

Measure	Years of usage used in analysis	Start and end year for the analysis of a given measure
Solar collector system	30 years	2020-2050
Ventilation system	30 years	2020-2050
External wall retrofit	30 years	2020-2050
Roof retrofit	30 years	2020-2050
Floor retrofit	30 years	2020-2050
Windows	40 years	2010-2050
Doors	40 years	2020-2050

Table 49 Depending on the year of applying the measure – number years of service used for the analysis.

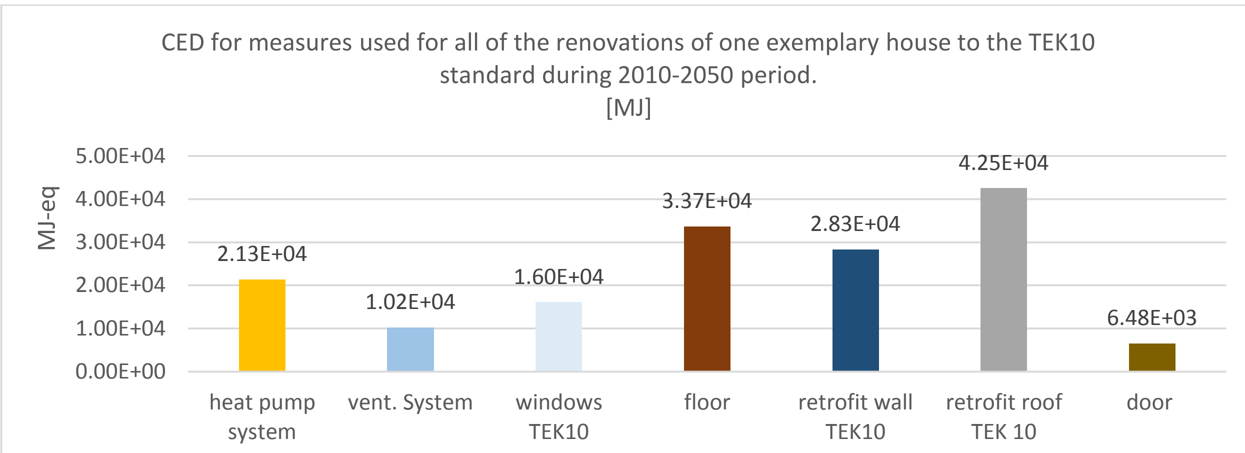


Figure 33 CED for measures used for renovation of the exemplary house to the TEK10 standard.

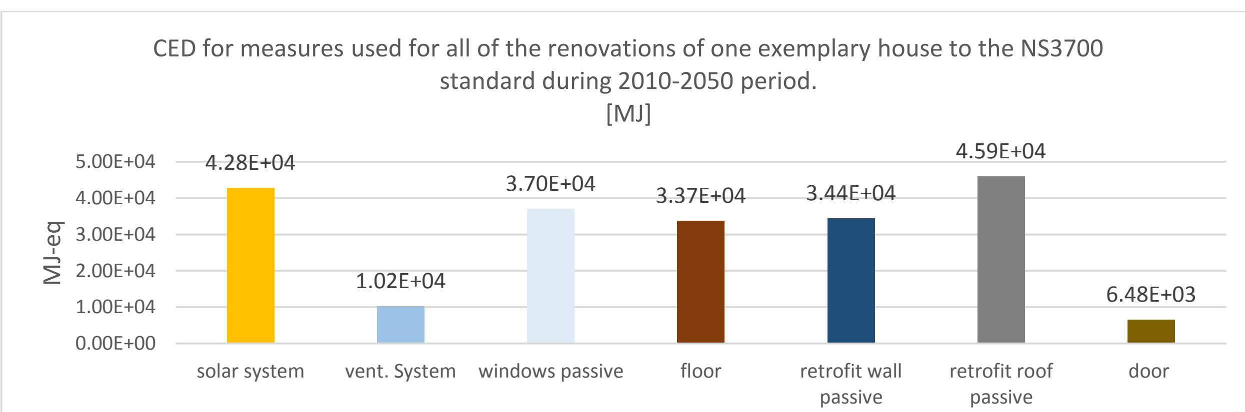


Figure 34 CED for measures used for renovation of the exemplary house to the NS3700 standard.

Among all of the materials, the CED for roof NS3700, solar collector system and passive windows scored the highest. The renovation of the wall both to the TEK 10 and NS3700 scored almost the same (6% difference), although the quantity of the insulation added to the wall is different for each scenario (200mm for TEk10 vs 400 mm for NS 3700). This result is due to the different type of insulation used in both scenarios. For the TEK 10 scenario, glass wool is used as an insulator that has a higher energy demand for production, whereas for NS3700 stone wool is used. The sensitivity analysis for insulation materials is presented in chapter 7, where differentiation between different insulation and their densities is analysed.

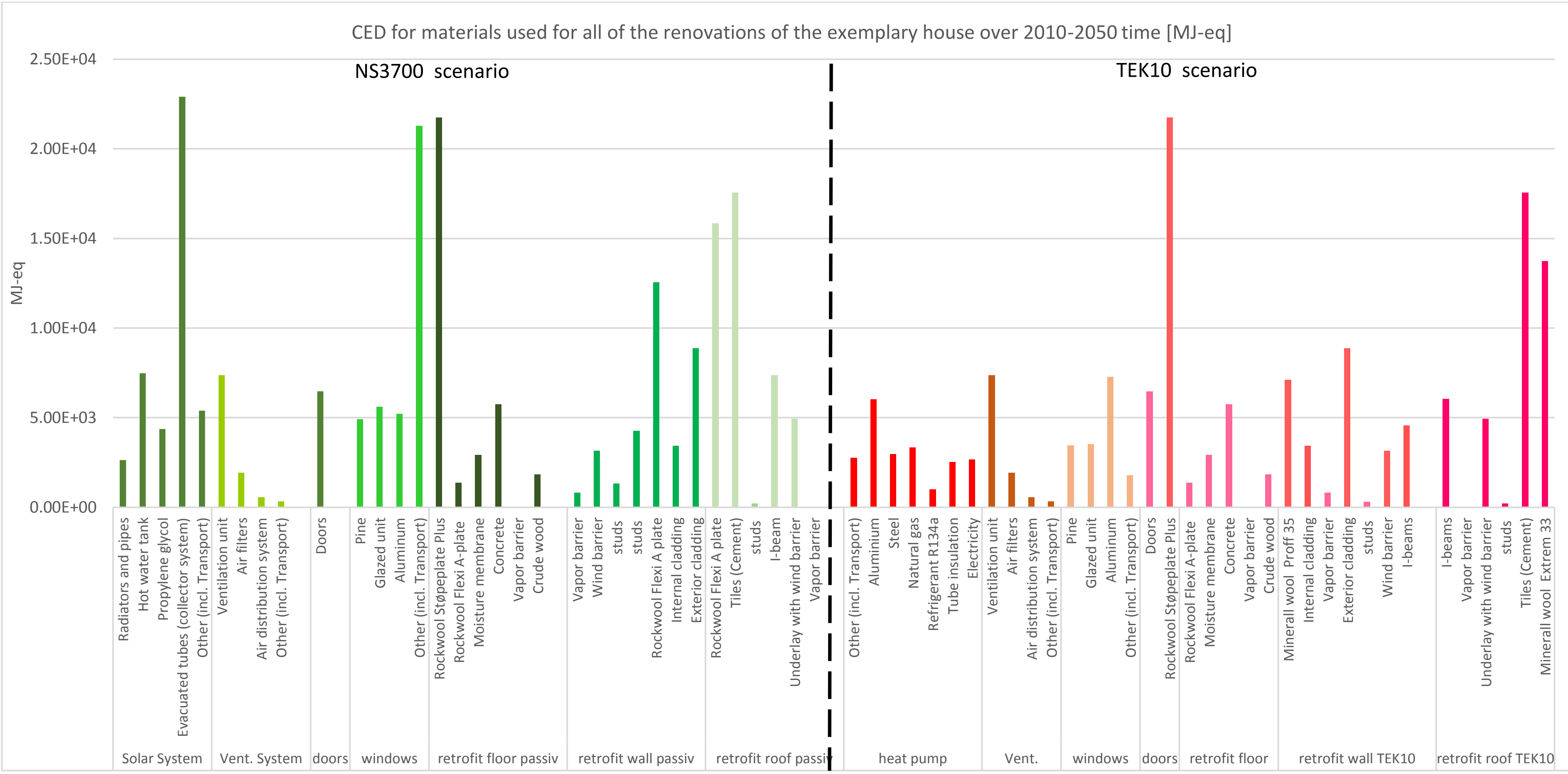


Figure 35 Detailed CED for measures used for renovation of the exemplary house to the TEK 10 and NS 3700 standard, taking to account years of usage depending on scenario.

The materials that are contributing the most to the construction of different measures used for renovation of building are:

1. Evacuated tubes used for the solar collectors system → 22.9 GJ-eq
2. Rockwool – stone wool used for insulating the floor in the NS 3700 scenario → 21.8 GJ-eq
3. Tiles used for external cladding for the roof in both TEK10 and NS 3700 scenarios → 17.6 GJ-eq

The evacuated tubes for solar collector system also have a high cumulative energy demand. For this material, the biggest contributors to the total energy demand are the production of the glass tubes that are made from borosilicate (38% of total impacts from production of evacuated tubes) and chromium steel (21%).

During production of the stone insulation, the energy intense processes are the melting of the raw material in a furnace (with the high temperature about 1500°C, which is an oven with coke as the main resource), and during curing (polymerization) and forming that takes place at a temperature of about 230 °C. The main materials used for production of stone wool are stones (basalt, diabase and dolomite accounting for 67% of total materials), as well as the secondary resources, which is mostly slag (19% of total) and cement (6 % of the total material input).

During production of cement for tiles, the most energy intense processes are due to mixing, extrusion and pre-cure coating and drying of the raw materials. The biggest impact for CED comes from natural gas used as non-renewable primary energy source.

Embodied energy used for production of the passive windows also has a high score. The energy use for production of aluminum (estimated 15%), triple glazed units (16%) and pine timber (14%) are contributing significantly to the production of the window. The rest of CED is embodied in the electricity needed for operation of the production site (lighting and factory services), maintenance (paint) and transport.

The contribution analysis of renewable and non-renewable energy sources used for production of materials is presented in the figure 36. The values are presented for the 181m^2 exemplary house. Each section is showing the contributors of CED for different parts of the building or the HVAC system (for example the bar titled “Wall TEK10” is showing the energy contributions used for production, transport, installation and use of materials needed for retrofitting the wall to the TEK10 standard for the 181m^2 house over 30 years).

Contribution analysis for renewable and non-renewable energy shares shows that for all of the measures, the non-renewable energy sources contribute more than renewable sources. The percentages are shown on the bars in the table (red color). For the window used for the TEK10 scenario, the share of renewable vs. non-renewable is fairly equal. Fossil oil is the biggest contributor mostly for all of the measures (35% of total CED).

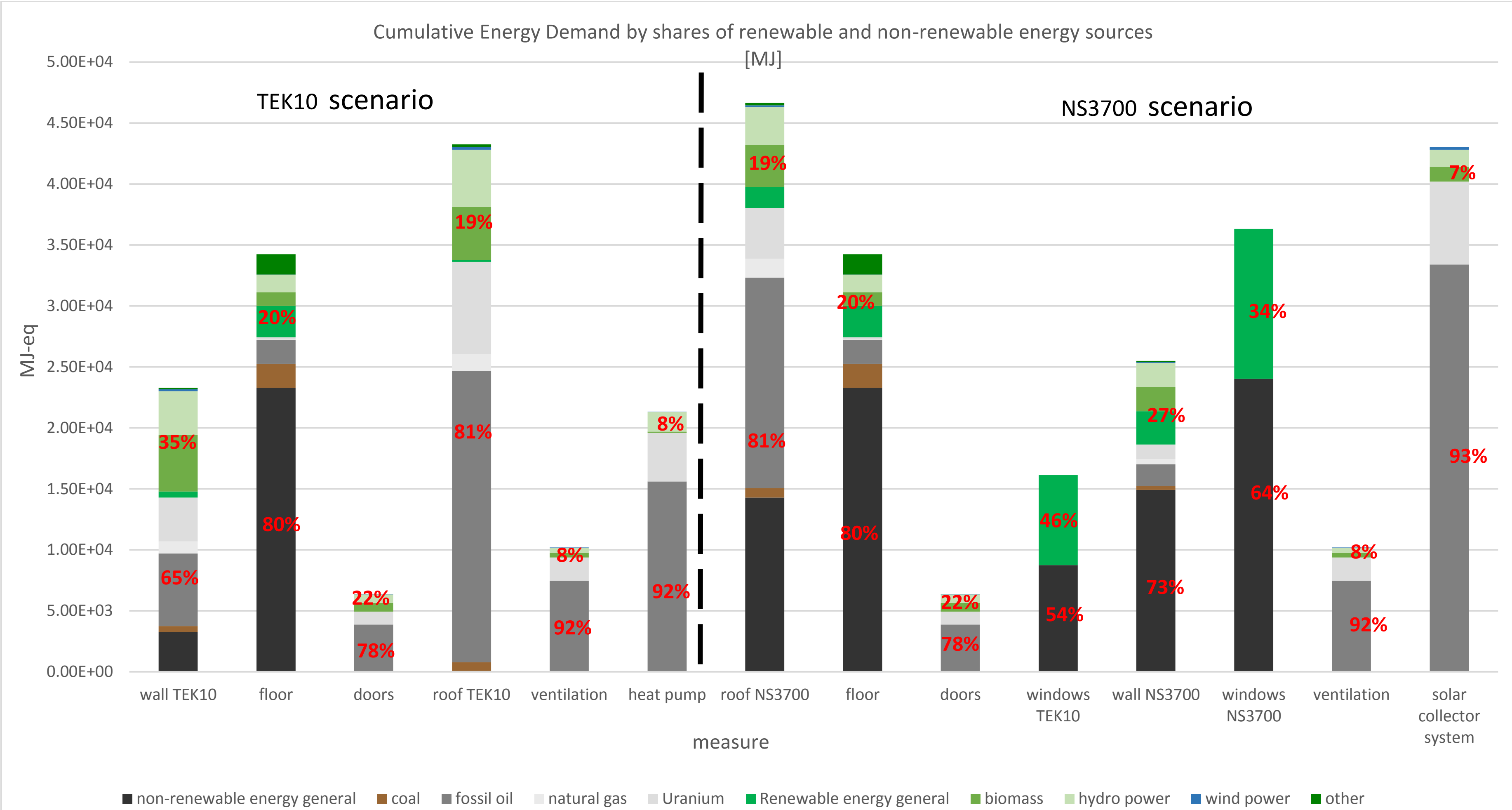


Figure 36 CED by shares of renewable and non-renewable energy sources[4] used for renovation of the original exemplary building to the TEK10 or the NS3700 standard.

[4] The method of presenting the split between renewable and non-renewable energies is explained in the method chapter 4.1.2

6.1.3 Climate change characterization for measures applied during renovations.

For the climate change characterization, the biggest impact comes from retrofitting of the roof and floor to the U-value=0.08 ($W/m^2/K$). The emission from production of the solar collector system also has a high contribution when compared to the rest of measures (2.45E+03 kg CO_2-eq). Overall, the renovation package for NS3700 scenario contributes more to the CC impact than for TEK10 scenario. The total difference between those two scenarios is 2.38E+03 (11%). This difference is relatively small when compared to the GHG reduction potential for both scenarios.

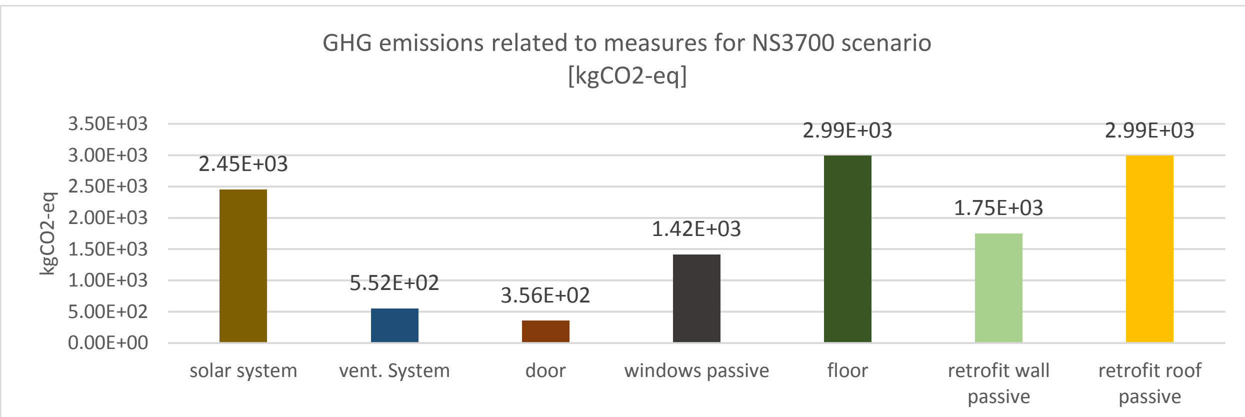


Figure 37 GHG for measures used for renovation of the exemplary house in the NS3700 scenario.

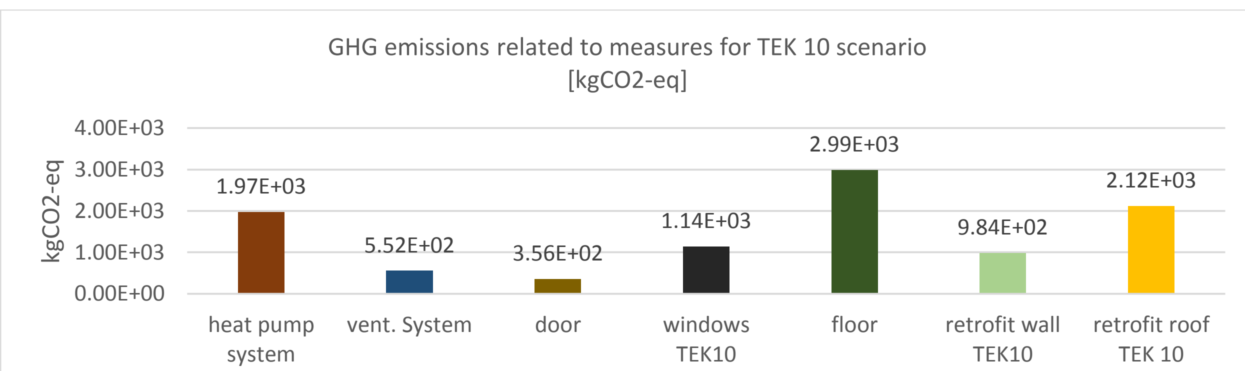


Figure 38 GHG for measures used for renovation of the exemplary house in the TEK10 scenario..

Looking into more detailed contribution analysis (figure 39), the biggest contributor to the climate change is a high-density stone wool used for insulating the floor (1.87E+03 kgCO2-eq), the evacuated tube collectors (1.30E+03 kgCO2-eq) and tiles (1.22E+03 kgCO2-eq). While results for energy embodied in materials are showing that production of windows is a significant contributor, for GHG emissions the results are lower in overall ranking due to big share of primary renewable energy sources used for production. The smallest contribution for overall GHG emissions related to applied measures is from production of doors with U-value=0.08 and materials used for installing the ventilation system.

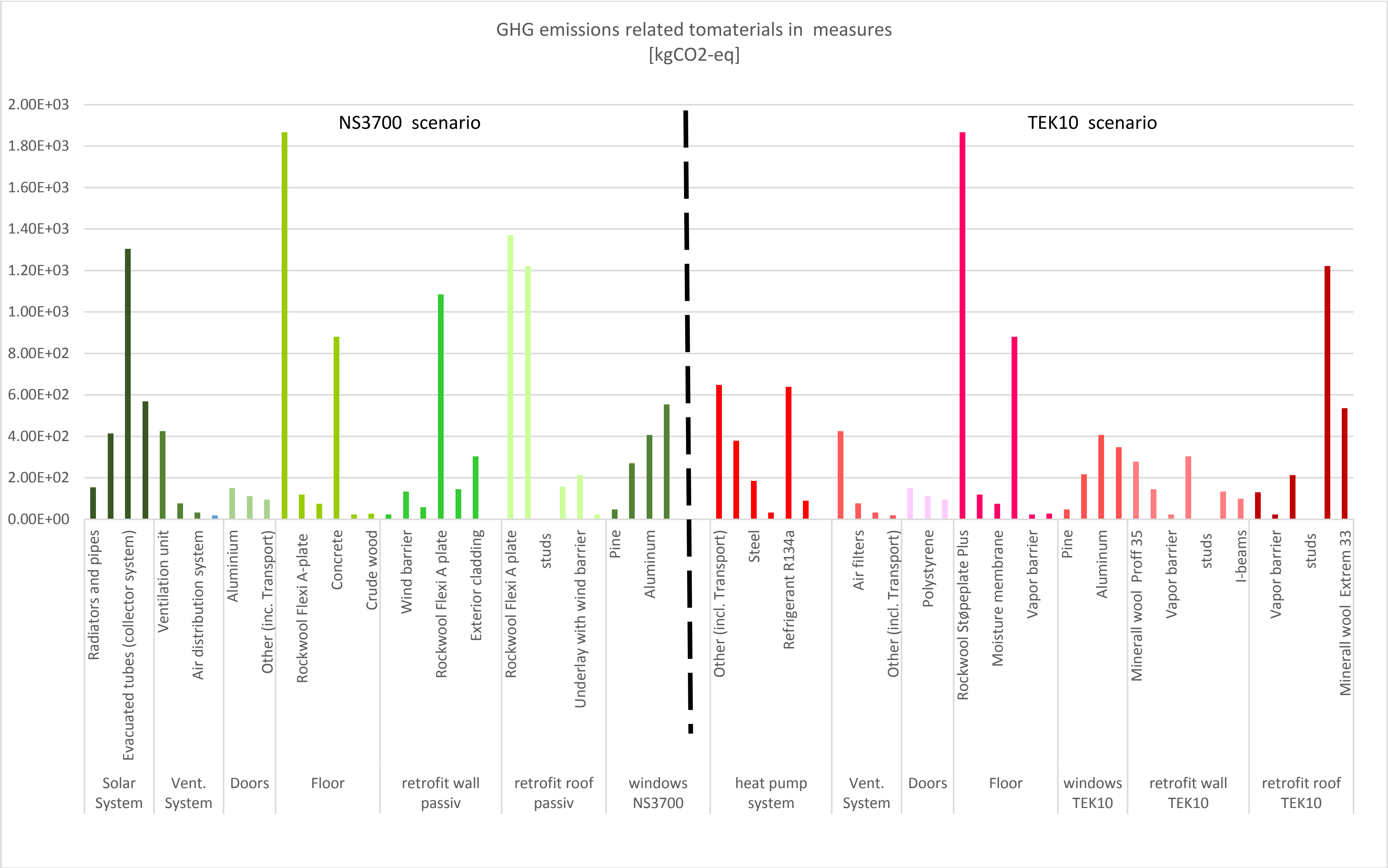


Figure 39 GHG emissions embodied in measures (scope: from cradle to use) used for renovation of the exemplary house.

6.2 Operation of the house

The results for the operation of the exemplary house are presented according to:

→ Default energy scenario with electricity mix from the 1a scenario: 93% Norwegian mix and 7% imports from Nordic mix.

→ Results are presented for the accumulated values for the exemplary house over time 2010-2050.

→ Results are presented with differentiation between TEK10 and NS3700 scenarios, where different measures where applied, hence different reduction of energy demand is achieved.

→ All of the emissions associated for materials are static and do not depend on the energy mix change over the years. It is assumed that materials were produced using existing technology and emissions related to the production process are given on the basis of current level. Therefore, in the model the results for emissions are evenly distributed over the period 2010-2050 ($kgCO_2/m^2/year$). For example GHG emissions for doors that are assumed to be changed during the second renovation (2020 year) in both TEK10 and NS3700 scenarios, were distributed evenly in the model by dividing the total emissions by $181m^2$ of the total area of the exemplary house per 30 years of assumed usage (2020-2050).

6.2.1. Net energy demand for exemplary house

The results obtained within semester project using Tabula Calculation Methodology (4.4.3) [38] do not reflect the results that Enova is presenting in their studies for TEK 10 and requirements for passive house standard given by standard NS 3031. The values obtained using Tabula Calculation Method seem not be representative for average values presented in other rapports and publications. That is why the additional analysis was made. In the table [NUMER Tablei] the net energy demand for space heating, DHW, electrical appliances, fan and pumps is given based on values given by Enova, Asplan Viak and according to NS 3031 standard calculations [1, 35, 39]

Net energy demand	Original building (1980-1990) [kWh/m²year]	Renovated from original to the TEK 10 standard (assuming 30% of energy reduction) [kWh/m²year]	Renovated from original to NS 3700 standard (values based on the calculation given by NS3031 standard) [kWh/m²year]
Space heating	80.7	56	19
Heat from ventilation, heat battery	-	3.2	2.4
DHW	30	30	29.8
Electrical appliance and lighting	28.9	28.9	28.9
Fans	0.7	5.76	4.56
Total	140.3	124	85

Table 50 Enova energy savings. Net energy demand

Direct energy need kWh/m2	original	TEK 10 (30% savings)	NS 3700 based on NS3031
HVAC	81.4	61.76	25.96
DHW	30	30	29.8
Electricity	28.9	28.9	28.9
Total	140.3	124	85

Table 51 Direct energy need for TEK10 and NS3700 scenario after second renovation in 2020.

The values for the original building are taken directly from Enova rapport where the average values are presented. The energy demand includes the energy demand of ventilation and heat recovery. According to the same source, with renovation from original state to TEK 10 standard up to 30% of net energy used for operation of the house can be saved with retrofitting of the house with technical measures like additional insulation added to external wall, roof and floor. Given 30% savings is a lower result than received with use of the Tabula Calculation Method. For better understanding what is a potential of adding additional insulation or changing windows, Asplan Viak made estimation of energy savings based on different types of buildings with the same average values provided by Enova.

Energy saving potential with applying different measures [kWh/m²y]	Upgrading to the TEK10 standard
Windows	16.6
External wall (36x148 studs, 200mm mineral wool)	6.1 (with U-value=0.21)
Roof (48x98 beams, 250 mineral wool)	4.5 (with U-value=0.16)
Floor (unheated basement 48x198 beams, 250mm mineral wool)	1.8 (with U-value=0.15)

Table 52 Energy saving potential with applying different types of measures for retrofitting house.

According to Asplan Viak the reduction potential just from installing window can be up to 16 kWh/m2. This measure alone gives significant reduction of overall energy demand. Considering that the external walls and roof are as well isolated, the potential could be higher than presented in the table above.

All energy savings are calculated individually, and without regard to dependence on other measures. This means that when several measures are done simultaneously, the total savings often do not correspond to the sum of savings for individual measures. Therefore, for the purposes of the analysis, 30% of energy reduction for the building renovated from original state to the TEK 10 standard is assumed. The energy used for ventilations and fans to run the ventilation is based on efficiencies of the given technical system [40]

The demand for fans for the ventilation was recalculated using NS3031 calculation method. SFP and airflow during and outside operation time are given on the basis of technical properties description of the ventilation system (see description of the ventilation system in the chapter 5.2) that are in line with TEK10 and passive house standard.

6.2.2. Results for operation of the exemplary house

After renovation to both TEK10 and NS3700 standard the emissions related to space heating and ventilation are reduced for both impact categories (figures 40 and 41). After retrofit the biggest energy demand is shifted from HVAC to DHW and electric appliances. This reduction comes from usage of alternative energy sources than direct electricity for space heating.

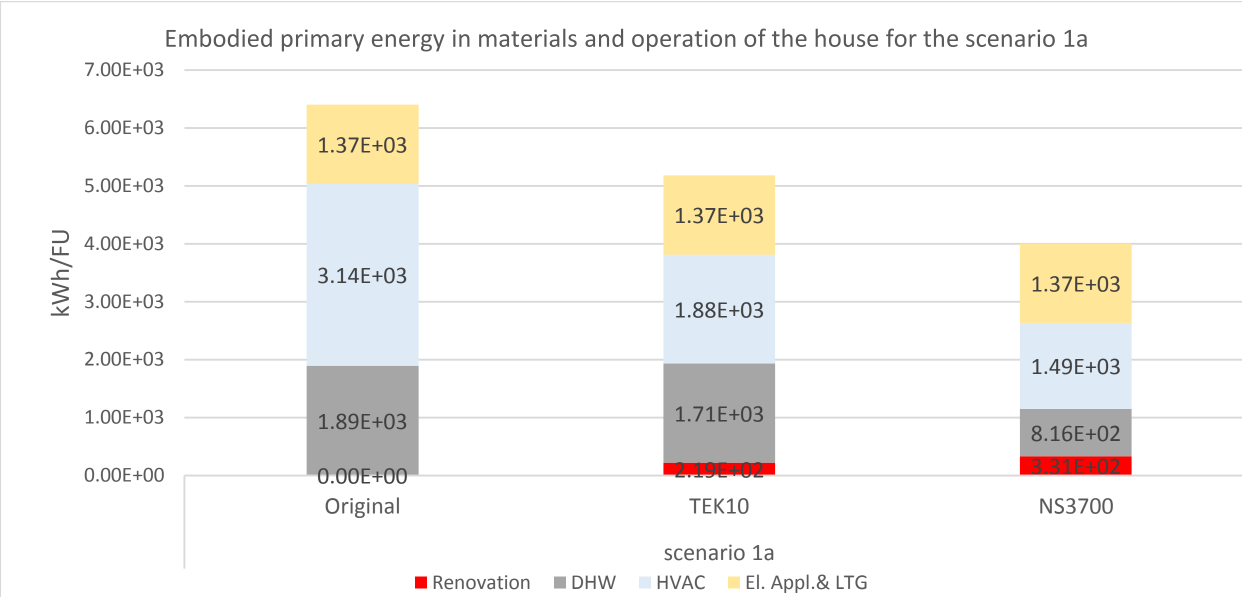


Figure 40 Embodied primary energy in materials and operation of the exemplary house without renovation and retrofitted with TEK10 and NS700 scenarios (kWh/ functional unit).

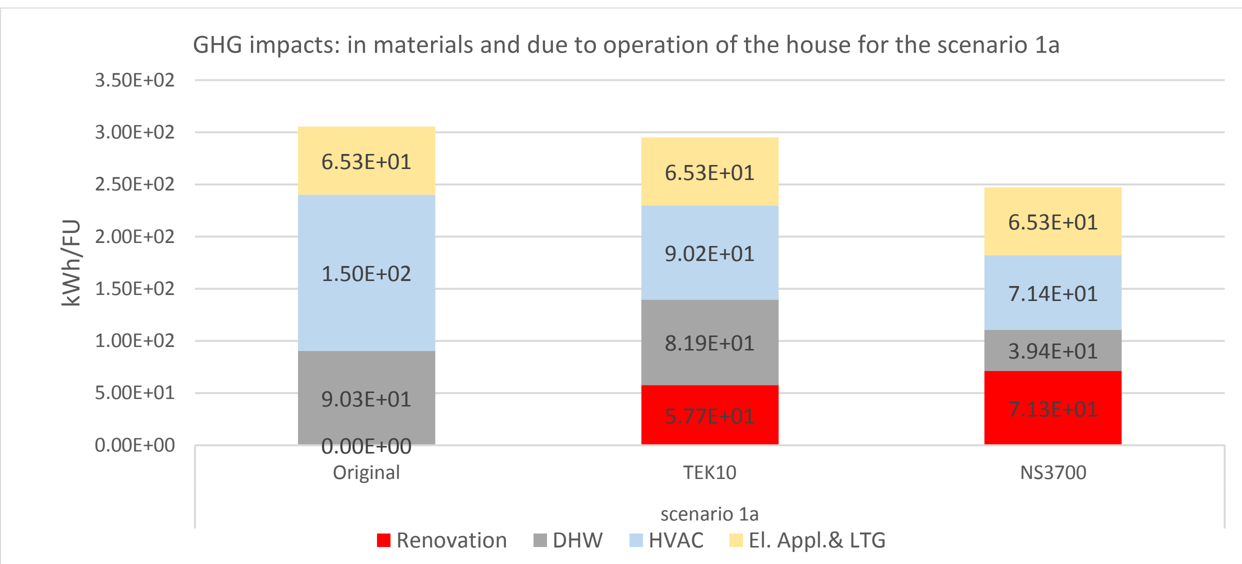


Figure 41 GHG emissions related to renovation and operation of the exemplary house without renovation and retrofitted with TEK10 and NS700 scenarios (kWh/ functional unit).

Shares of accumulated GHG and CED emissions over the period 2010-2050 for TEK10 and NS3700 scenarios using scenario 1a for electricity distribution are presented on figure 42. Materials significantly contribute to the accumulated GHG emissions for the passive house scenario. The percentage of GHG shares is the same as for the accumulated emissions for heating and ventilation (29%). Looking on the accumulated results for CED characterization, materials are contributing less than ten percent for passive house scenario (8%) and even less for the TEK10 scenario (5%). The high share of GHG emissions from materials might result from electricity mix used for the operation of the house. In Norway it consists mainly from renewable energy, hydropower. However, the electricity mix assumed for production of measures is mainly Nordic mix, which is dirtier than residual mix mainly used in Norway. For that reason the shares of emissions embodied in materials might be higher if Norwegian mix (energy scenario 1a) is used for the operation of the building (see discussion chapter).

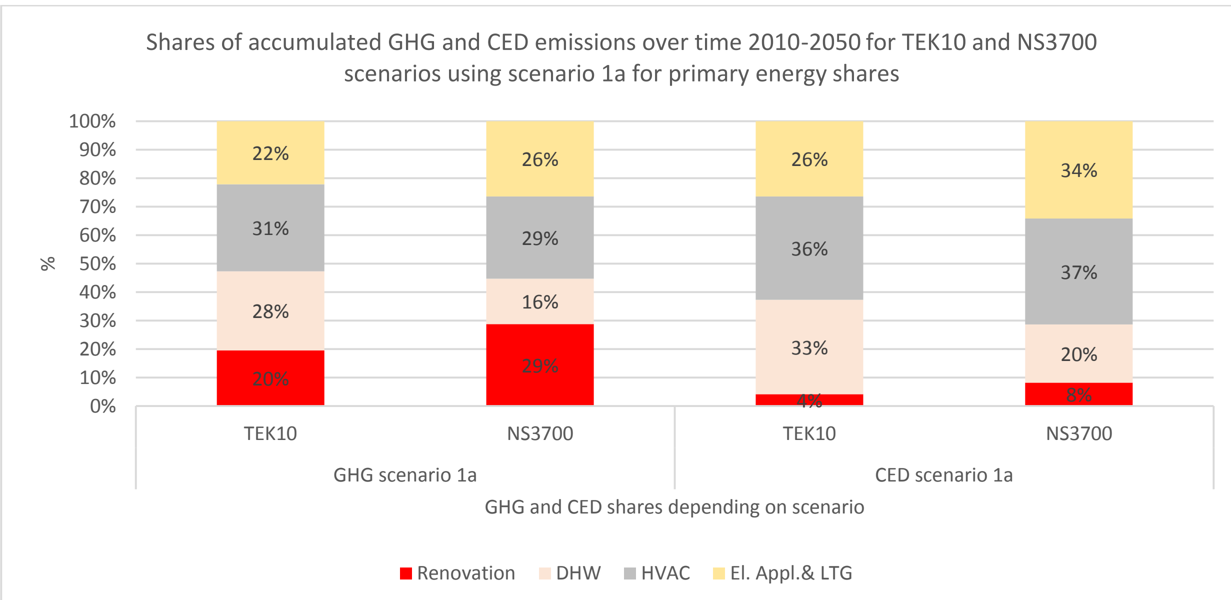


Figure 42 Shares of accumulated GHG and CED emissions related to the operation of the exemplary house and materials added during renovations, over time 2010-2050 using 1a scenario for electricity shares.

To be able to show the potential emission reductions from retrofitting the original building to the TEK10 or NS3700 standard, the reduction of the primary energy demand for the operation of the house has to be taken into account. The figure 43 shows the potential reduction of the emissions with the original building set as the reference point except the shares for the renovation, which are referenced to the TEK10 scenario since there is no renovations happening in the baseline scenario (original building). The total GHG emissions that refer to the operation and retrofitting of the building show little improvement for TEK10 scenario (3%), in comparison to the baseline scenario (where no renovation is conducted). The improvement is little due to the emissions embodied in materials used for renovation of the original building to the TEK10 standard. If one would not account for emissions embodied in those measures, the GHG reduction potential rises up to 22% with reference to the baseline scenario. As for the passive house scenario, the overall improvement while accounting for the emissions embodied in materials appears to be 19% for the GHG and 37% for the CED, with the reference to the baseline scenario. For better understanding of magnitude of influence that embodied emissions in materials used for renovation have, the lower part of the figure [RRZYPIS] shows the reduction in the total emissions for the building if one would not take to account emissions related to the measures. The GHG emission reduction potential is then much bigger for both TEK10 and NS3700 scenarios, whereas the change for CED characterization is less than 5%.

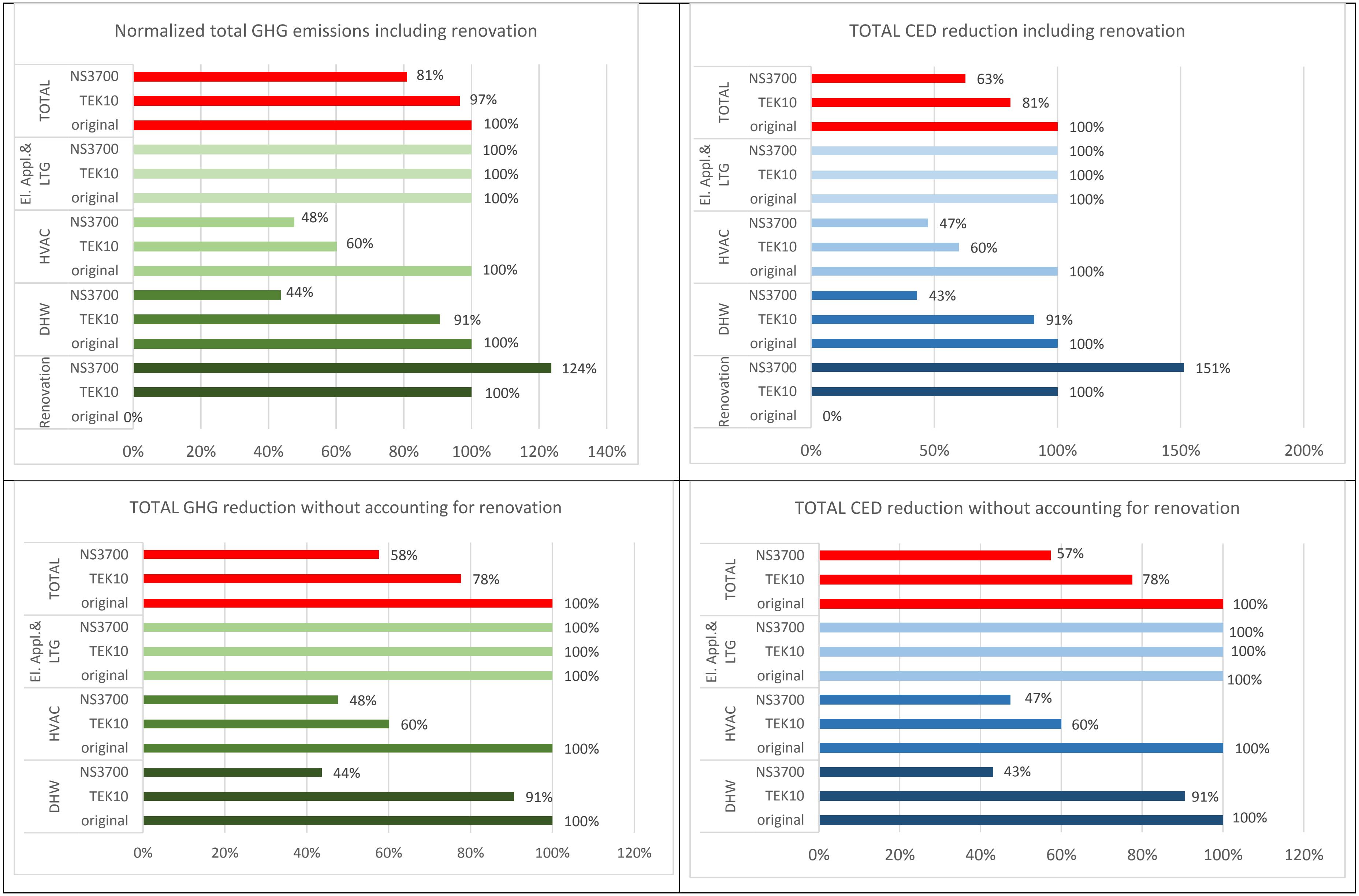


Figure 43 Comparison between total GHG and CED for accumulated emissions over time 2010-2050 for the exemplary house for TEK10 and NS3700 scenarios, for the 1a energy scenario (93% Norwegian mix and 7% Nordic mix).

6.3. Transport

In the both case scenarios (TEK10 and NS3700 scenarios) the transportation constitutes for 5% of total embodied emissions in materials. Most of materials are assumed to be transported by less than 100km distance, due to short distance to manufacture places (exemplary house is assumed to be in Oslo, in which area several production site are situated along with distribution and warehouse centres). In this phase the type of vehicle used for transport was mainly truck (lorry, >32t, EURO4).

6.4. Using dynamic model for segmented dwelling stock – energy saving potential.

The results for the accumulated stock of single-family houses built in the period 1980-1990 present the total energy reduction of the stock taking to account:

→ The results are assuming one cycle of renovation (40 year cycle). That means that the total accumulated results are shown for the case if the total stock is renovated only once (not three times like in the case of the one exemplary house). If the three cycles were taken into account, the reduction of overall emissions would be bigger due to an increased number of renovations. Due to the limitation of adjusting the dynamic model for the analysis needs', this simplification had to be made. The detailed description of the method can be found in chapter 4.3.

→ The results are representative of the primary energy demand. The whole chain of energy demand is covered for both materials and demand for the operation of the house.

→ The reference unit is in TWh/year. It is assumed that all stock consists of the buildings that have the same properties as the exemplary house used in the analysis.

→ The results are presented using the 1a electricity share scenario (93% of Norwegian domestic production and 7% of Nordic import).

The figure 44 represents results for energy use related to the operation of the house and embodied energy in materials for three different scenarios; baseline (no renovations), TEK10 scenario and NS3700 scenario. The renovations are made assuming a forty-year cycle. The demolition of the building stock has been included in this analysis. The comparison between TEK10 and NS3700 scenario shows that there is a larger energy saving potential using more materials and insulating to the lower U-value, rather than investing in a smaller amount of retrofitting measures. However, figure 44 shows that in case of all three scenarios, the energy demand is dropping. The energy demand in the baseline scenario (original building without renovations) as well is dropping. That is due to demolition of the old houses that will occur during period 2010-2050. Figure 54 shows the annual energy use for accumulated building stock.

	original		TEK10		NS3700	
	TWh	% change	TWh	% change	TWh	% change
2010	4.91E+00	100%	4.91E+00	0%	4.91E+00	0%
2020	4.91E+00	100%	4.59E+00	-7%	4.38E+00	-11%
2040	4.26E+00	100%	2.98E+00	-30%	2.44E+00	-43%
2050	3.76E+00	100%	2.42E+00	-36%	1.86E+00	-51%

Table 53 Energy use in the remaining stock in a given year with reference to baseline scenario (original).

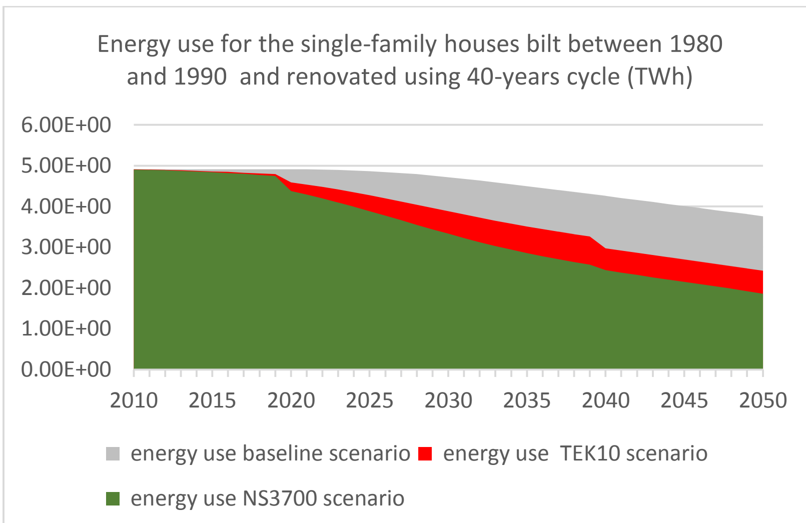


Figure 44 Energy use for accumulated single-family houses stock built between 1980-1990 renovated with 40 years cycle to the TEK 10 and NS3700 standard using scenario 1a for electricity.

In 2050 for the NS3700 scenario, there is energy use reduction of around 51% with reference to the baseline scenario where no renovation is assumed. With reference to the starting point which here is 2010 the biggest saving potential would results from deep renovation to the passive house standard. Annual energy saving potential (figure 54) shows that for NS3700 scenario it is possible to save around 3.05 TWh in 2050, whereas for TEK10 scenario it is 2.49 TWh.

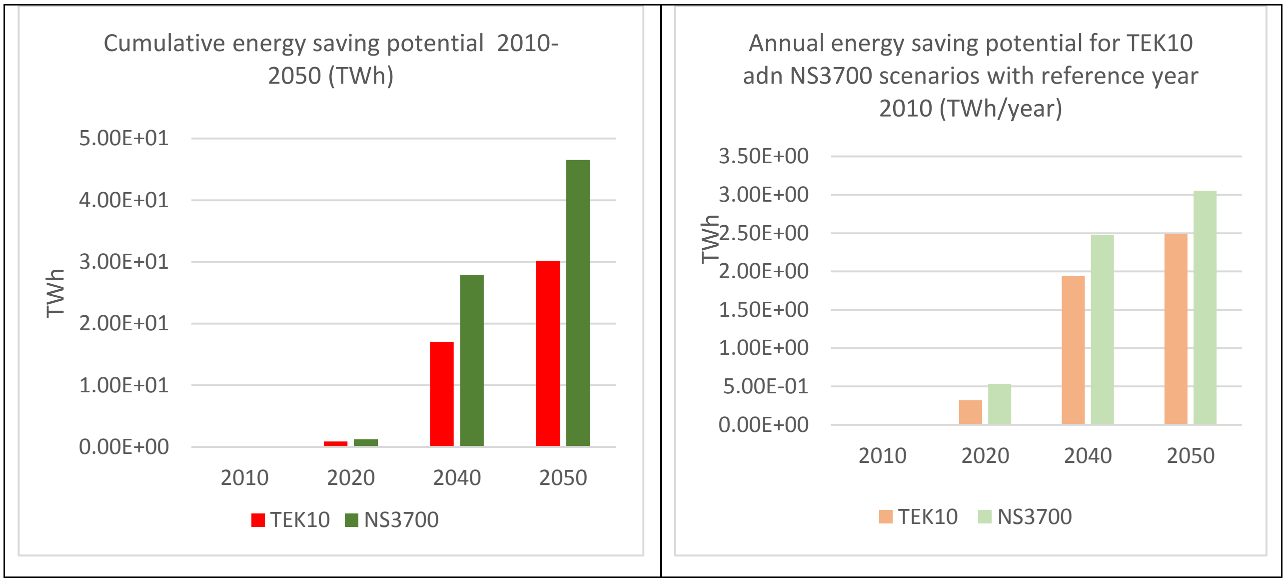


Table 54 Cumulative energy saving potential 2010-2050 and annual energy saving potential for TEK10 and NS3700 scenarios compared to the 2010 level of baseline scenario (no renovation) with energy scenario 1a.

6.5. GHG accumulated

There is a difference between the energy saving potential expressed in cumulative energy demand needed for the analysed stock and the CO_2 emissions related to this energy demand. From table 55, it can be seen that the annual reduction of emissions are almost none for the TEK10 scenario while compared to the baseline scenario. As it was shown before, for the one exemplary building, the reduction in emissions over 2010-2050 period is 3% for one single building, whereas for accumulated building stock the change is almost non-existent. For the passive house scenario the GHG reduction potential is much higher. Moreover, in 2050 the accumulated saving potential assumes to reach a change of 35% from the baseline scenario. This shows again that even though almost 30% of accumulated emissions related to one exemplary building are coming from materials, the overall GHG emissions reduction potential significantly outweighs the emissions related to increased material usage for passive house scenario.

	original		TEK10		NS3700	
	ktCO2/y	% change	ktCo2-eq	% change	ktCO2/y	% change
2010	2.23E+02	100%	2.23E+02	0%	2.23E+02	0%
2020	2.20E+02	100%	2.20E+02	0%	2.05E+02	-7%
2040	1.85E+02	100%	1.76E+02	-5%	1.30E+02	-30%
2050	1.61E+02	100%	1.52E+02	-6%	1.05E+02	-35%

Table 55 GHG emissions from the remaining stock in the given year with the reference to the baseline scenario (original)

The accumulated GHG reduction potential related to energy demand for Norwegian stock of single-family houses differs extremely between the TEK10 and NS3700 scenarios. In the NS3700 scenario the annual CO_2-eq saving potential is around 119 kilotonCO_2-eq at the end of 2050; however, for the TEK10 scenario the annual GHG savings are on average 50% lower than potential GHG saving for the passive house scenario. Emissions embodied in materials used for renovation to the TEK10 standard are contributing significantly to overall emissions for the stock due to too low energy demand reduction for the operation of the house. Cumulative GHG saving during period 2010-2050 with reference to 2010 level are very low for TEK10 scenario. By 2050 the cumulative saving potential is estimated to be 112 ktoneCO2-eq which is 8% of cumulative saving potential for NS3700 by the same year (figure 46).

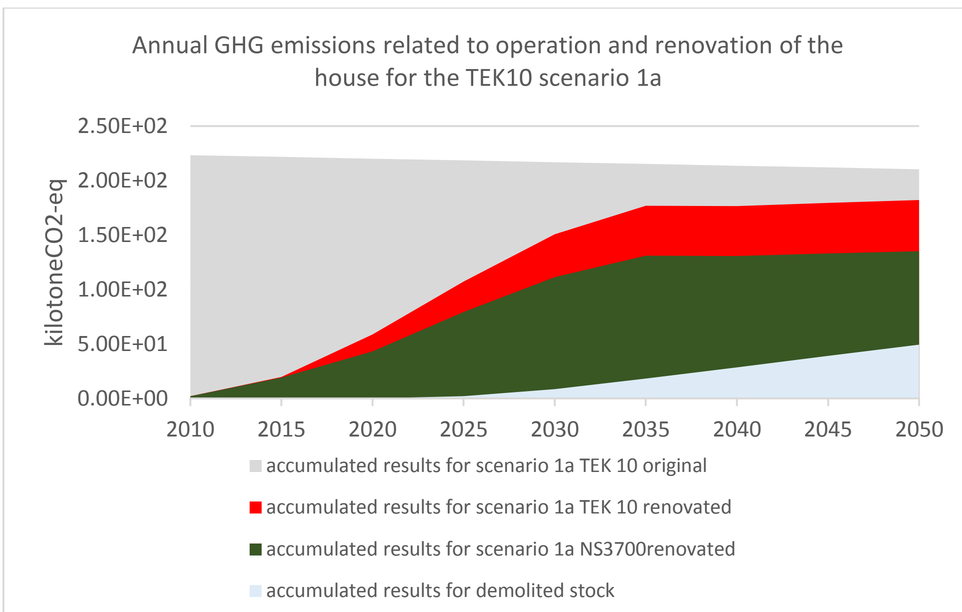


Figure 45 Annual GHG emissions from operation and renovation related to accumulated dwelling stock of single-family houses.

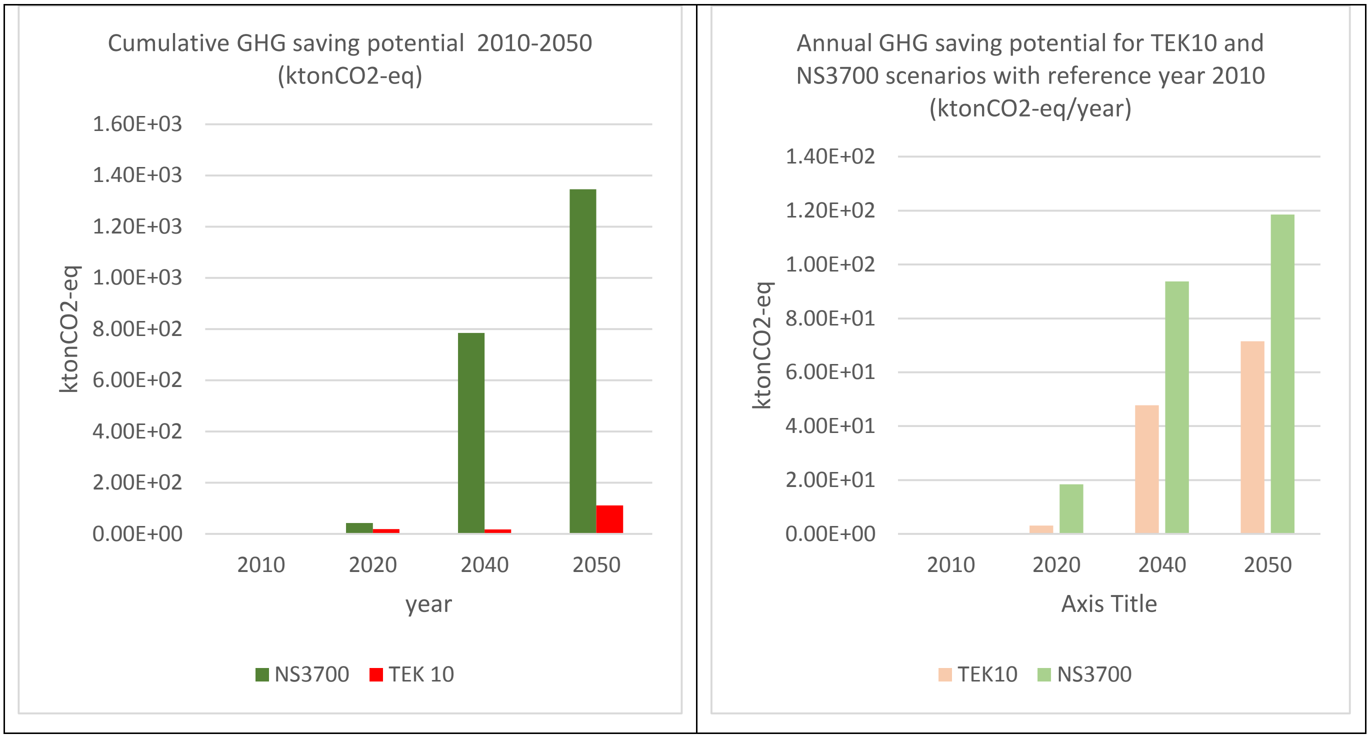


Figure 46 Cumulative GHG saving potential 2010-2050 and annual GHG saving potential for TEK10 and NS3700 scenarios compared to the 2010 level of baseline scenario (no renovation) with energy scenario 1a.

7. Discussion

7.1. Comparison with other studies

The comparison between founded results and other renovation is based on several assumptions and simplifications. Each retrofitted house differs; therefore, it is difficult to compare one renovation of the building to the other. The other LCA case studies that are done on renovation of the single-family houses, are investigating houses with different structure (wooden or brick houses), with different dimensions, and are assuming different amount of materials used for renovations. This makes more difficult to compare results obtained in this thesis with studies that have been already done. Below, in table 56, several other studies are presented with corresponding results for impacts due to renovation (detailed description of other LCA studies is presented in chapter 3.5). For the TEK10 and NS3700 scenarios the average values for CO2-eq and kWh are given, taking to account all of three renovations (electricity mix scenario used: 1a).

Study	Embodied energy (kWh/m2)	GHG (kgCO2-eq/m2)
NS3700 house scenario	322 kWh/m2 for FU during 40 years	69 kgCO2-eq/m2 for FU during 40 years
TEK10 scenario	243 kWh/m2 for FU during 40 years	55 kg CO2-eq/m2 for FU during 40 years
Two-storey apartment [24]	231kWh/m2 for 120m2 house for 50 years lifetime	
Passive house [22]	110 kWh/m2 for 50 years of lifetime	
Single detached house [20]	480 kWh/m2 for total renovation	110kgCO2-eq/m2 for total renovation

Table 56 Comparison of embodied energy and GHG emissions due to different renovation (based on literature review).

The embodied energy in materials needed for renovation in listed in table 56 vary between 110 kWh and almost 500 kWh/m2. This is due different locations of the case study buildings, different electricity mix used during production of materials and different quantity of used materials. Those characteristic make it difficult to compare those renovations between each other without high level of uncertainty.

7.2. Sensitivity analysis

7.2.1. Tilted roof for exemplary house.

In the analysis, a flat roof was assumed for the exemplary house. If a tilted roof would be considered the heat gains from the solar collector system would increase. Five cases were chosen for a sensitivity analysis of the solar collector system:

1) Baseline scenario – the exemplary building is not renovated
2) NS3700 scenario – flat roof with 13.4m2 of solar collector gross area mounted on top.
3) Tilted roof – assumed that 13.42 gross area of solar collector is mounted on the roof with 30 degree slope, facing 11 degrees West [40].
4) Tilted roof with one extra collector – 17.84m2 of the total solar collector area.
5) Tilted roof with two extra collectors – 22.3m2 of the total solar collector area.

The table 57 presents the results for the sensitivity analysis of the solar collector system. Almost no influence for GHG is observed from adding more area to the solar collector. The emissions from the production of the evacuated solar tubes are offset by the reduction of direct electricity needed to cover DHW demand and GHG emissions related to the production of electricity. If two extra collectors are mounted on the tilted roof, the GHG emissions savings are only 2% smaller compared with NS3700 scenario. In the same time, embodied primary energy needed for the operation of the building is reduced by 50% with the reference to the original exemplary building.

	Baseline scenario	NS3700 scenario	Tilted roof	Tilted roof + one extra collector	Tilted roof + two extra collectors
kWh fed to the system for DHW (kWh)	N/A	3511	3974	4508	5624
Share of DHW covered by energy from solar collector system	N/A	65%	74%	83%	100%
Average GHG emissions after rehabilitation 2020-2040 (kgCO2-eq/m2 year)	8.01 0%	5.93 -26%	5.93 -26%	6.01 -25%	6.09 -24%
Average embodied energy after rehabilitation 2020-2040 (kWh/m2 year)	177 0%	87.7 -50%	87.7 50%	88 -50%	88.4 -50%

Table 57 Sensitivity analysis for solar collector system – average GHG and embodied energy emissions during 2020-2040 period for one exemplary house.

7.2.2. Choice of different insulation materials.

The choice of materials matter. According to other LCA studies the use of low energy intensive materials or the ones that are locally available can reduce the impacts from renovation by half compared to the conventional house [15]. Using recycled materials can also significantly reduce the embodied energy [16].

To check how the findings from other studies are applicable for the analysis presented in this thesis, the sensitivity analysis was made for used insulation materials that constitute for a significant share of the total emissions and embodied energy in materials used for renovation.

Isolation materials chosen in the study have different densities per cubic meter depending on the purpose of usage. Table 58 presents properties of each insulation material used in the analysis.

Name of the product	Density [kg/m3]	Thermal conductivity [W/mK]	CED MJ/m3	GHG kgCO2-eq/m3
Rockwool				
Flexi A-plate	34.8 kg/m3	37 mW/mK	4.77E+02	4.13E+01
Støpeplate Plus	104 kg/m3	37 mW/mK	1.44E+03	1.24E+02
Glava				
Proff 35	16 kg/m3	35 mW/mK	5.41E+02	2.1E+01
Extrem 33	22 kg/m3	35 mW/mK	7.59E+02	2.96E+01
Plate 40	39 kg/m3	38 mW/mK	1.31E+03	5.1E+01

Table 58 CED and GHG per one m3 of different type of insulation.

Use of insulation in both scenarios constitutes for around 50% of total materials used for retrofitting buildings envelope (figure 47). Therefore, the choice of the insulation might alternate the results. The sensitivity analysis was conducted in order to see if use of different insulation materials does alternate the results for overall emissions related to the functional unit.

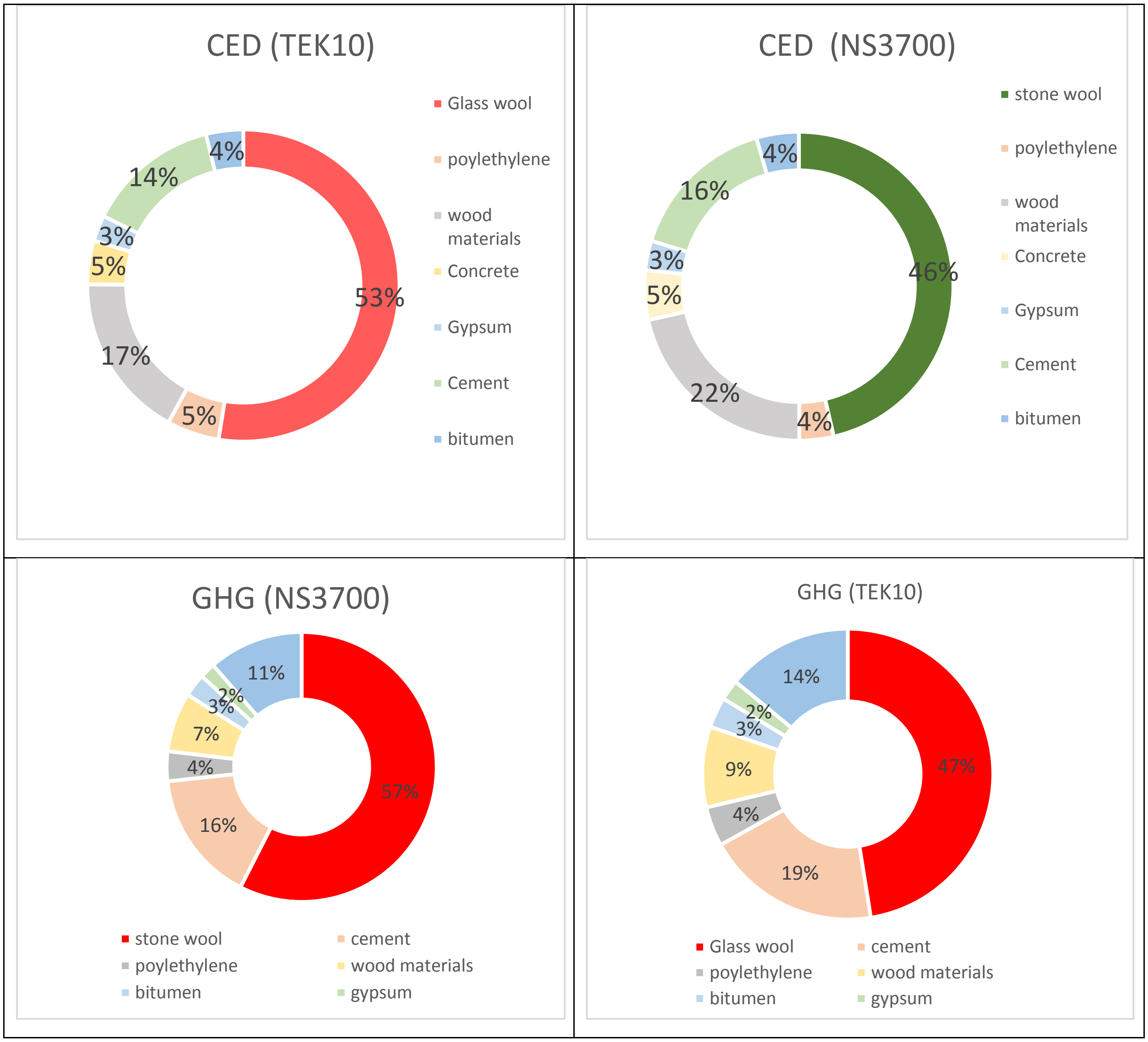


Figure 47 Shares of CED and GHG emissions of materials used for renovations of roof, wall and floor for TEK10 and NS3700 scenarios during 2010-2050 period.

The alternative insulation chosen for the sensitivity analysis is an material made from sheep wool produced by British company Thermafleece. The life cycle analysis and CED of the material was calculated using the SimaPro program. The life cycle inventory for Thermafleece was gathered on the basis of the LCA report on fibre insulations [69] and completed with background inventory data taken from the EcoInvent data base. The amount of material was in line with the requirement that it should fulfilled for the given renovation type (either to the passive house standard or TEK10). Figure 48 presents the emissions associated with extraction, production, transport and maintenance of one cubic meter of three different insulation materials.

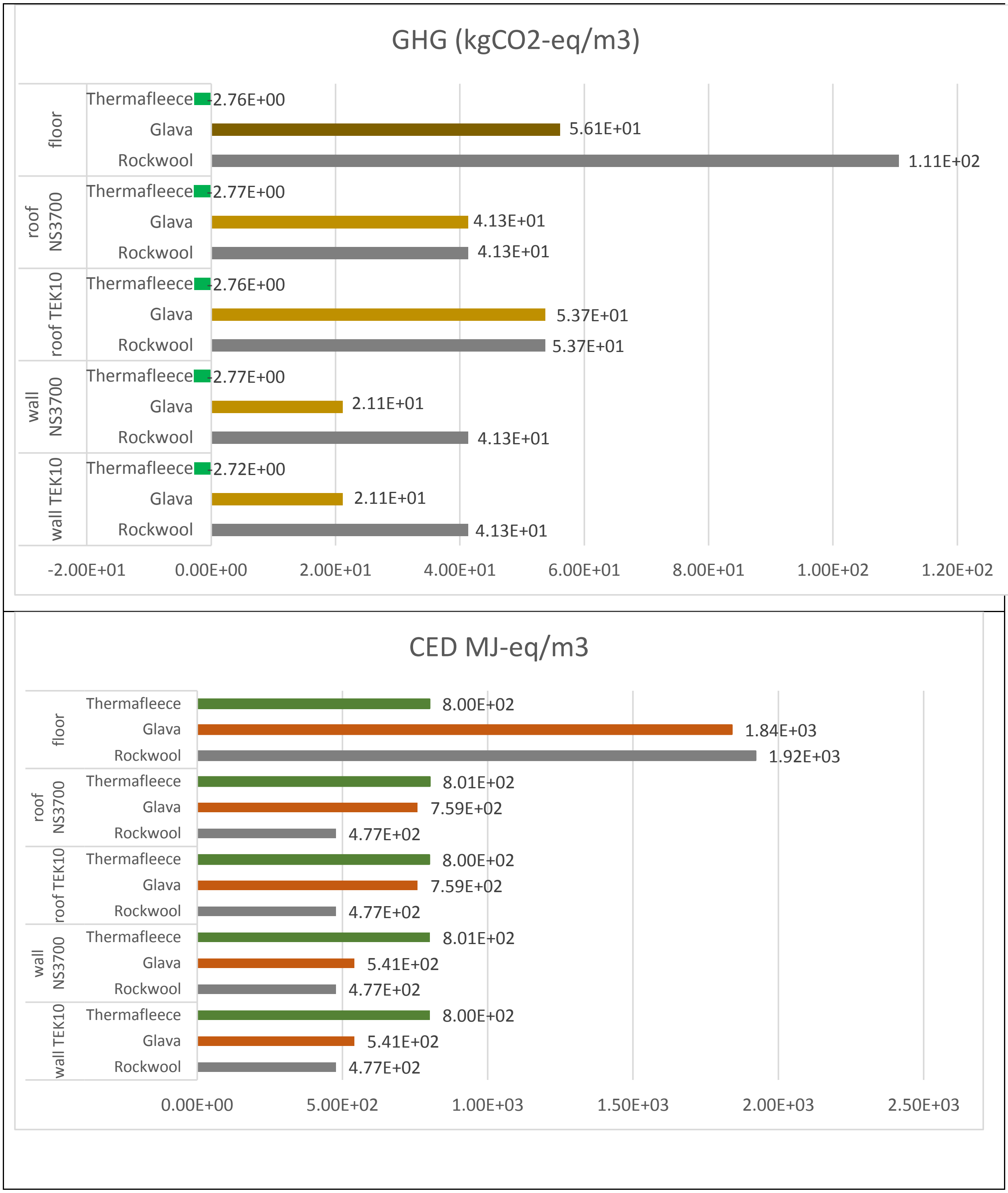


Figure 48 GHG and CED emissions related to usage of different insulation materials for retrofit.

For the CC indicator the Rockwool insulation scores the worst with the biggest impact for CO2-eq. For the Thermafleece insulation the results are negative, which means that production of this kind of insulation contributes positively to the reduction of GHG emissions. Thermafleece insulation uses sheep wool as a raw material, which is accounted for as being a waste. This assumes that no extra land is needed for meeting the demand for the raw materials, hence the product is assumed to be a side effect of another production purposes (meat, dairy). The LCA of sheep wool assumes negative values for GHG emissions, which means positive contribution to reduction of this impact. However, the CED for Thermafleece does not differ from production of Rockwool or Glava products.The technology to process the raw materials is as energy intense as for other insulation products. Overall if for the renovation of the exemplary house, Thermafleece product would be use, the biggest emissions saving potential would be for the CC indicator. The emissions related to the renovation would be reduced by around 10 % for passive house scenario and 6% for TEK 10 scenario. However, the embodied energy in materials and the operation of the house would stay the same.

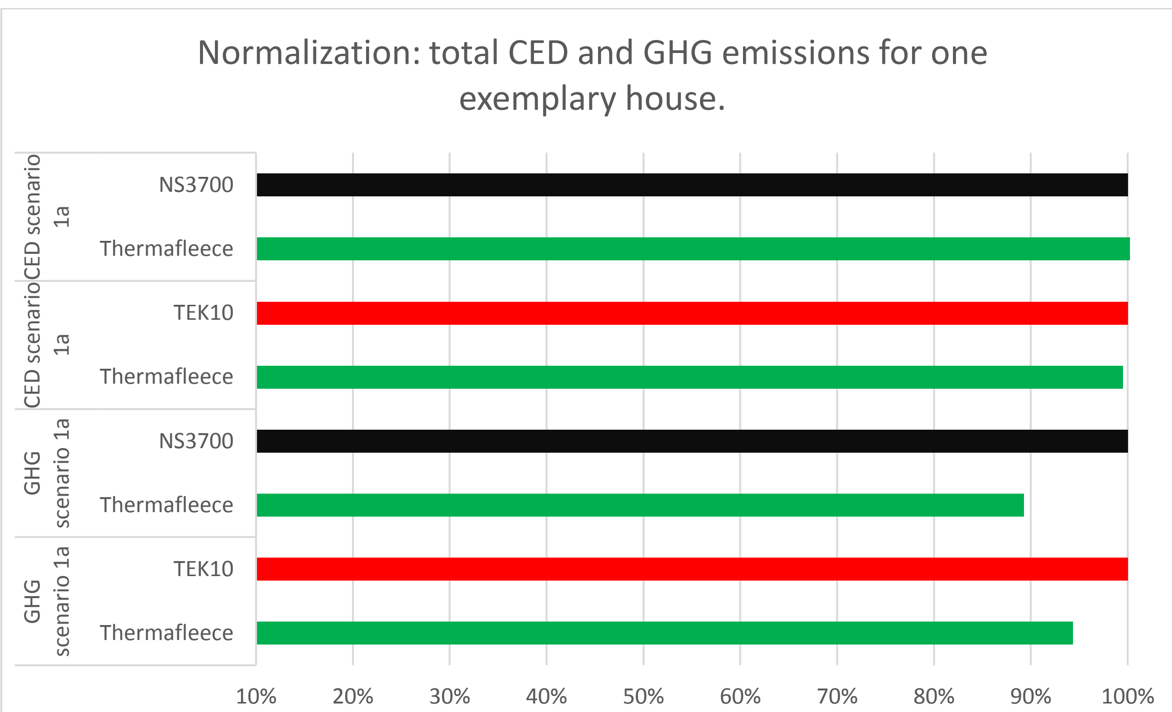


Figure 49 Total CED and GHG emissions for one functional unit using alternative insulation Thermafleece and with reference to the TEK10 or NS3700 scenario

7.2.3 Energy scenarios.

7.2.3.1. Sensitivity analysis for the functional unit

The shares for the electricity mix have a crucial effect on the overall results for the embodied emissions resulting from the operation and renovation of the house. Scenario 1a was the baseline for the discussed results in the previous chapter. The shares of CO2-eq embodied in materials were equal to 29% for the NS3700 scenario and 20% for the TEK10 scenario. Those shares are significantly different if other electricity mixes are used in the analysis. The table 59 presents the accumulated embodied emissions related to the operation and materials used for the exemplary building during 40 years of usage. The electricity mix shares used for comparison are as follow

1) Scenario 1a – 93% of Norwegian domestic production and 7% imports from Nordic mix
2) Scenario 1b – 93% of Norwegian domestic production and 7% from EUmix red
3) Scenario 2a – 88% of Norwegian domestic production and 12% from Nordic mix
4) Scenario 2b – 88% of Norwegian domestic mix and 12% from EUmix red
5) Nordic mix – extreme scenario – 100% Nordic mix
6) EU mix red – Extreme scenario – 100% EU mix using CO2-eq emissions related to red scenario presented in chapter 4.5.

The Norwegian domestic mix assumes 98% of production coming from hydro, 1% thermal energy and 1% wind power. All shares, primary energy factors and detailed description for CO2-eq/kWh emissions related to each electricity mix can be found in chapter 4.5.

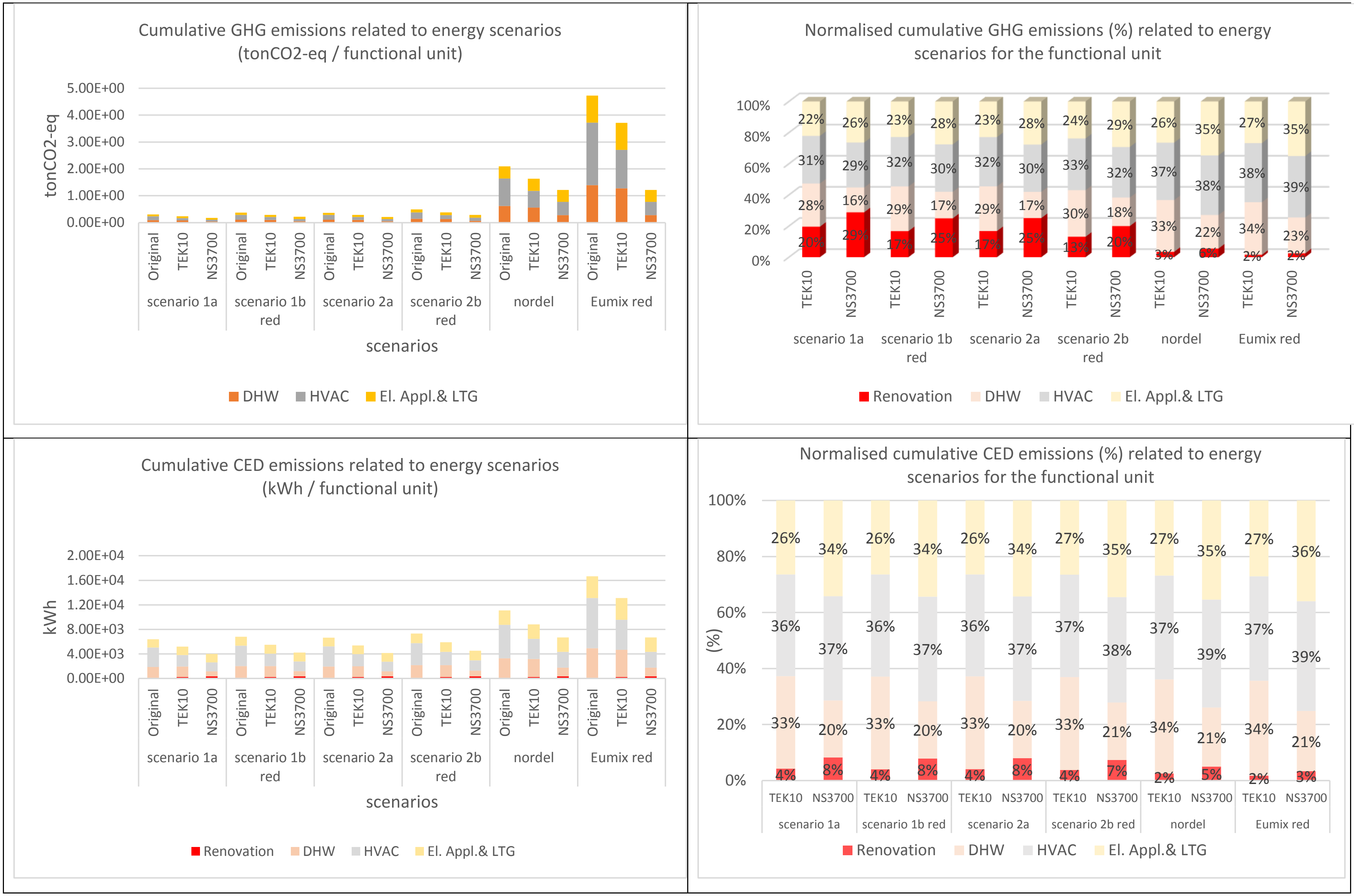


Table 59 Cumulative GHG and CED emissions related to energy scenarios for a functional unit (an exemplary building during 2010-2050 period of usage).

Depending on the imported electricity share used for the operation of the house, the share for embodied emissions in materials differ between over 20% and less than 5% for both the NS3700 and TEK10 scenarios. That shows that depending on the electricity mix used for the operation of the exemplary house (functional unit), the embodied emissions in materials applied for the renovation of the building will play more or less of a significant role in the life cycle of the building. If the entire European mix (100% of imports) would be used to cover demand for direct energy needed for the given building stock, the emissions related to materials used for renovation would be negligible. This might be the result of cleaner energy used for the production of measures, compared with energy production (if 100% EUmix assumed) for the operation of the building. The Nordic mix is less polluted than the European mix (210 vs 361 gCo2-eq/kWh) and the primary energy factor as well is lower for the Nordic mix (2.0 vs 3.0). If, on the contrary, the European mix would be assumed for the production of the measures, the total share could be different (most likely bigger for the renovation share). However, that could be an overstatement to assume that all materials can be produced in the same place and with the same ratio of, for example, renewable energy sources. Particular materials have different technologies for production and differ within intensity of energy use. However, the emissions from the production of materials could be reduced if they could be produced in countries where for example the share of renewable energy for electricity production is high. If all of the discussed materials would be produced in Norway, where hydropower is the main source of energy for the production of electricity, the emissions related to the materials production process would be lower than in the given analysis (where cleaner, Nordic mix is mainly used). From this, one could assume that the production of energy intense products should be placed in countries that use mainly renewable energy sources. However, in that case other factors should be considered that might offset overall benefits. Transportation of the materials is one of them. If the distance is too long between the production place and the building site, it might not be a profitable solution. The other uncertainty could be linked to the technology used for production of materials and possibility of replacement during production of the non-renewable with renewable primary energy sources.

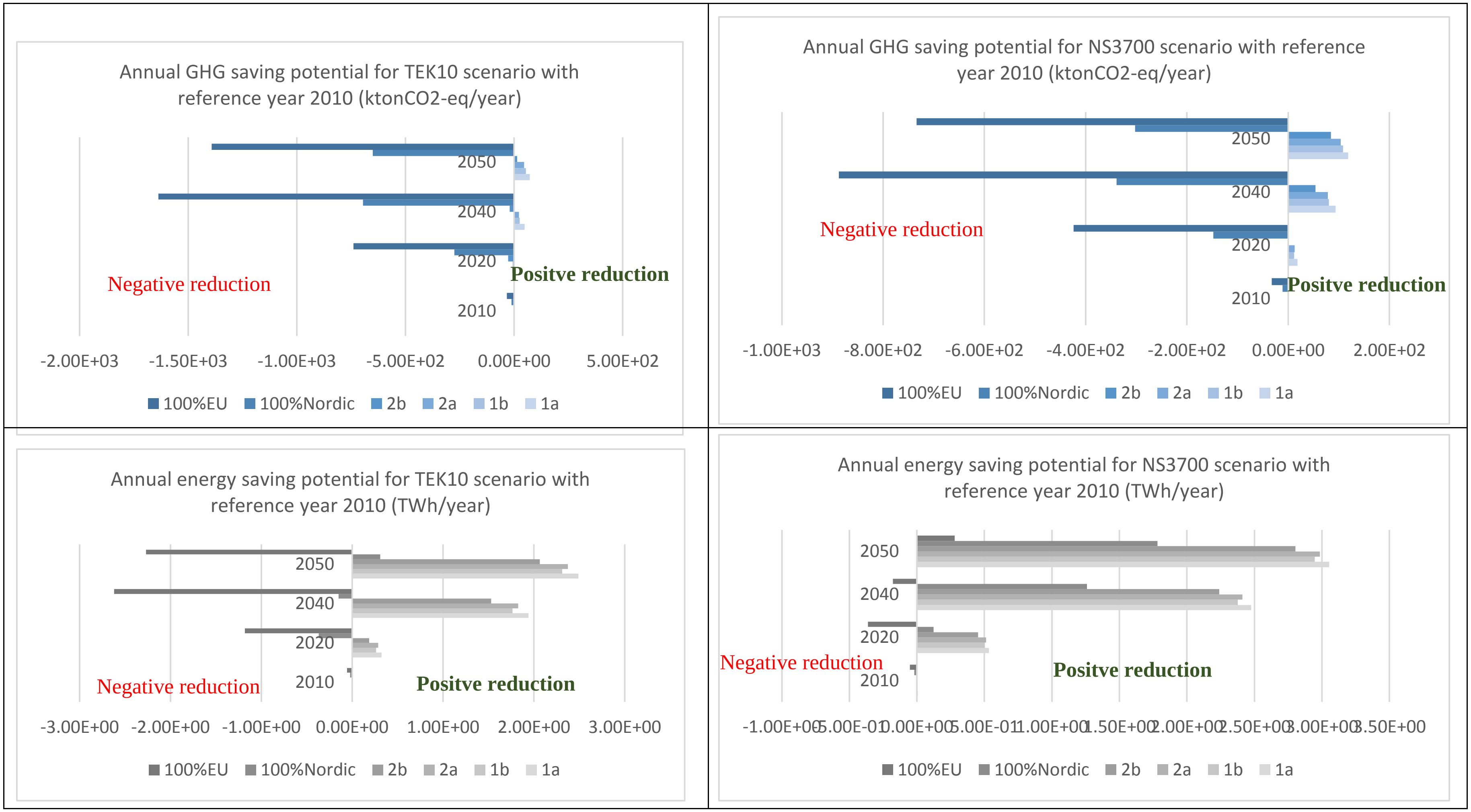
7.2.3.2. Sensitivity analysis for the segmented stock.

In the previous studies, the estimated annual energy saving potential for all of the Norwegian stock was assumed to reach 23 TWh in 2040 with reference to levels from 2007 [5]. In comparison with results obtained using dynamic modelling for the Norwegian stock, the energy saving potential in

2040 for the TEK10 scenario is equal to 1.94 TWh and for NS3700 scenario 2.48 TWh with reference year 2010 (4.9 TWh). The Norwegian stock of single-family houses accounted for 11% of the total energy use in 2010 (see section: 3.4.1). With this assumption, renovating single-family houses stock to the passive house scenario would result in 50% change and achieving the target for emissions reductions set by Norwegian authorities. Renovation to the TEK 10 standard would result in almost 22% difference between this standard and passive house. If electricity mix used in Norway nowadays would not change and the level of imported electricity would stay on the average of 7%, the energy saving potential for TEK10 scenario would not be that far from meeting the target (especially if other segments of Norwegian stock would be renovated with at least the same standard). However, it is predicted the demand for electricity will increase in the future, and so imported electricity will increase (due to limited capacity of hydropower plants and growing population which is linked with increased demand for electricity). With this in mind, renovating only to the current obligatory requirements (TEK10) in the upcoming years has a big potential for an energy lock-in effect for buildings that ought to be renovated, especially if the wrong measurements for retrofitting are chosen. Below is presented sensitivity analysis for different energy scenarios with reference to the entire single family building stock built between 1980 and 1990.

Figure 50 presents the annual energy and GHG emissions saving potential, using the dynamic model for segmented stock. The results are presented with reference to the baseline scenario (no renovations) for energy mix: 1a and compared to 2010 level. For the TEK10 scenario the GHG saving potential between 2010 and 2040 is mainly negative for all of the energy scenarios except the reference one: 1a. The later one has the cleanest energy mix among all of considered energy scenarios. Any increase in imported energy from Nordic or European mix results in decrease of the saving potential. Considering NS3700 scenario, the savings are positive for all of the energy scenarios except the extreme cases in which 100% of EU or Nordic mix is assumed to be imported. With the primary energy factor equal to 3.0 for the EU mix, the efficiency of production and losses during transmission and distribution would be almost three times bigger than for the reference scenario where mainly hydropower is used with primary energy factor equal to 1.09. Therefore, the biggest reduction potential can be observed with using the 1a energy scenario. For both NS3700 and TEK10 scenarios positive savings occur within the same energy scenarios but with different order of magnitude. For the TEK10 scenario assuming 100% of EU mix import, the annual savings after renovations are still negative by 2050. For the same energy scenario, there is a significant difference between annual energy savings within the TEK 10 and NS3700 scenarios. The reduced demand for energy in NS3700 scenario would be able to offset impacts related to use of EU mix.

Figure 50 Energy and related GHG emissions annual reduction potential depending on renovation scenario and energy scenario. For accumulated single-family house stock during 2010-2050 period.



The use of EU mix has the biggest negative impact on the results. The future development of the European electricity mix and the shares of renewable vs non-renewable primary energy sources is difficult to predict. Several studies are presenting the future possibilities of development of electricity mix use in Europe. One of them is used for the purposes of this analysis. The Sintef research center [44] developed different storylines for future energy mixes for the European electricity mix.

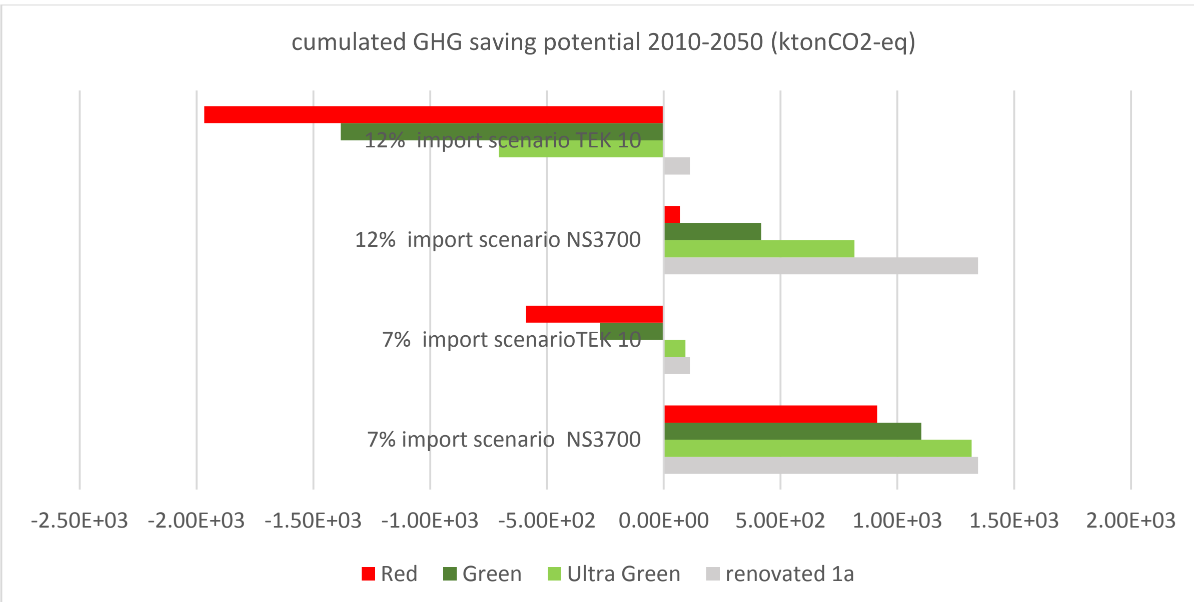


Figure 51 Cumulated GHG saving potential by 2050 compared to 1a energy scenario for renovated stock either to TEK10 or NS3700 standard.

Figure 51 presents cumulated GHG saving potential by 2050 for segmented stock compared with renovated stock to the TEK10 or NS3700 level using 1a energy scenario. The red, green and ultra-green scenarios correspond to future changes in the European electricity mix depending on the development of renewable energies and efficiencies related to production, distribution and transmission losses. For NS3700 scenario the accumulated GHG emissions saving potential would be positive for all three EUmix scenarios, for both cases when 7% and 12% of electricity is imported. The saving potential would still be positive even when the red scenario, which is the worst-case scenario for the EU mix, is taken into consideration. That shows the potential and role of renovating the existing building stock. The level of renovation as well plays a significant role. If the existing stock is renovated to the TEK10 standard the cumulated GHG emissions saving potential is only positive for the ultra-green EU mix scenario. If the shares of imported electricity will increase and the EU mix would be imported the potential for saving GHG emissions could be highly dependent on the level and quality of deep renovations. That is assuming that other variables such as behavior linked to energy use would not change.

To give a broader perspective, if the level of import would stay the same as it is today, which is on average 7%, only renovations to the passive house standard would have potential to meet GHG reduction targets set by IEA (50% up to 85% of global GHG reduction by 2050 in order to be able meet Two degree Celsius scenario). Even assuming the worst case scenario, which is import of EU mix in red scenario, the GHG saving potential would still be around 50% of level of the stock from 2010. For a more realistic case, where Norway imports more electricity than today (12% scenario) the results are worse for both: NS3700 and TEk10 scenario. Only 6% reduction of GHG emissions are predicted to be if imported electricity would be on the todays level of pollution for EUmix red scenario. If the source of import would be Nord pool electricity market (with 12% import), 46% reduction would occur if single-family houses would be renovated to the passive house standard.

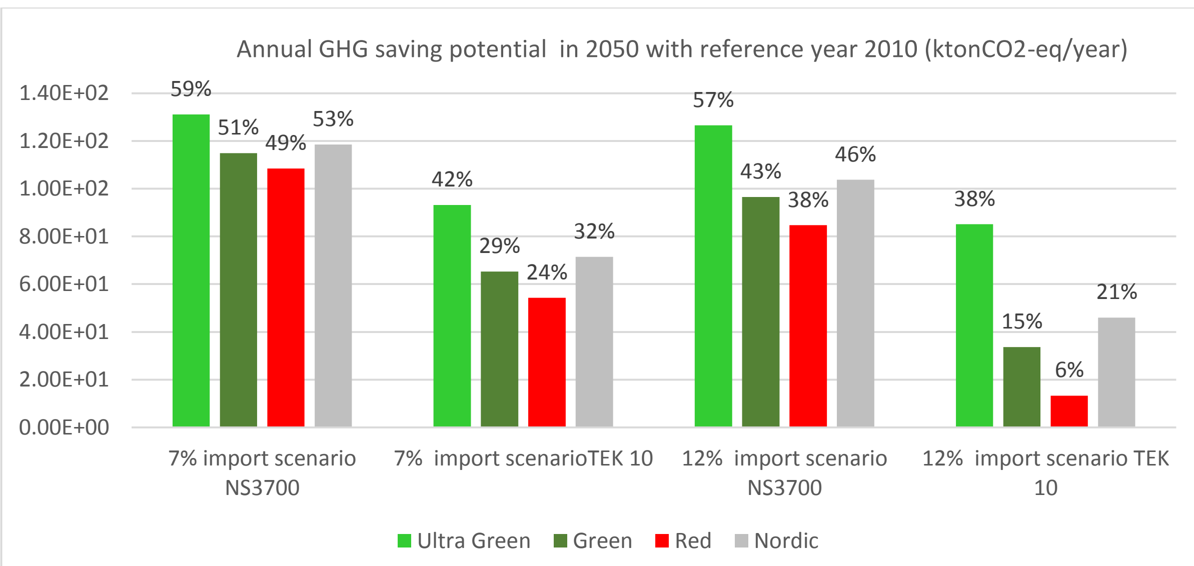


Figure 52 Annual saving potential in year 2050 compared to 2010 level (no renovation 1a energy scenario).

7.3. Reference building – a new build single family house

Figure 53 presents the GHG emissions saving potential if all of the buildings that are supposed to be renovated where newly built up to the passive house standard and alternative situation, where all buildings that supposed to be are retrofitted, are renovated to the NS3700 standard with the starting point in 2010. The results in figure 53 are representative of a 40 year cycle and dynamic model was used to estimate the turnover of the stock and number of renovated buildings. The emissions related to the new built houses: extraction, production, transport and maintenance for all of materials needed for construction of the houses, were assumed to be the same as it is presented in LCA made by Dahstrøm [46] In his thesis, a single-family house with 187m2 useful area was investigated. The emissions related to the operation of the building stays the same as it is in this study (assuming energy scenario 1a). From figure 53 it can be clearly seen that no GHG emissions saving potential could be assigned to the scenario where all of the houses (instead of being renovated) are newly built with a high standard. The amount of materials needed for the construction of a passive house exceeds the emission saving potential.

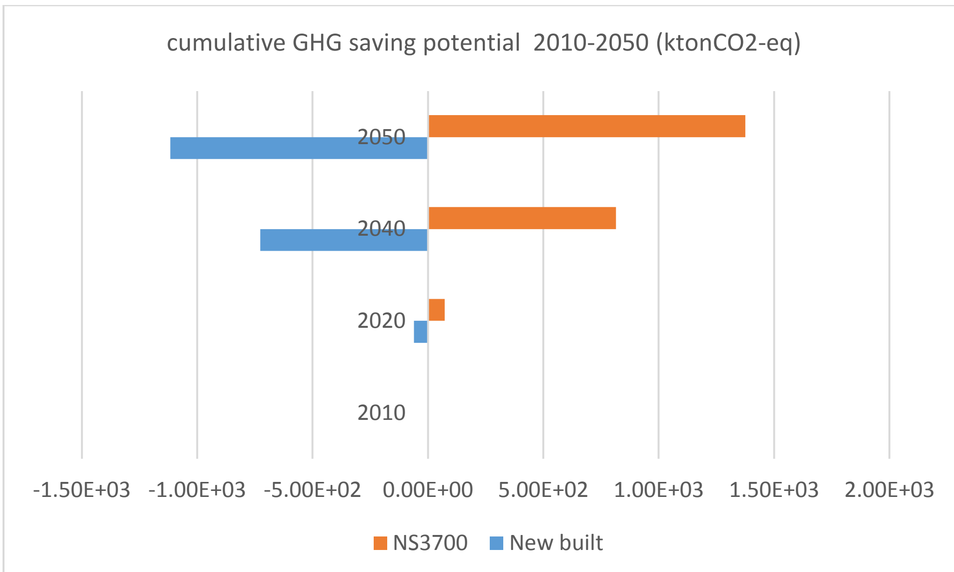


Figure 53 Cumulative GHG saving potential for two cases scenario (NS3700 newly built and NS3700 renovated) with reference to 2010 level for energy scenario 1a with no renovation.

Also literature shows that more energy can be saved by retrofitting existing buildings than constructing new ones with the same standard. Previous studies [23] showed that retrofitting an already existing building can save the same amount of energy that is needed for the construction and one year operation of the same building if it would be newly-built. According to Ravetz, the energy demand for the refurbishment of the building can be 10 time less intensive than new [72] construction buildings, due to the upstream impacts of production and the transport of materials Empty House Agency (UK) is also demonstrating that deep renovation can generate 15t of embodied Co2 while demolition and rebuild closer to 50t of embodied CO2 [73].

7.4. Uncertainties

7.4.1.Limits to retrofit in the case study

The increment in embodied energy caused by 2010 and 2020 renovations to the passive house standard is approximately equal to two year's operating energy in the baseline scenario of exemplary house without any retrofitting. As the results show – energy reduction with added measures to a building might not offset the emissions embodied in materials, when the reduction potential is too small (TEK10 scenario). For the case of the passive house scenario presented in this thesis, the upper limit of GHG emissions embodied in materials for the reduction of energy usage of the house to the passive house standard (19kWh/m2 for space heating) is twice as much materials used as in the case.

There is a limit to the reduction of the energy needed for the operation of the house. Installing energy intensive measures can exceed the gains from zero energy needed for the operation of the house through its lifecycle. It is shows in the extensive review made by Ramesh et al that not every self-sufficient building serves its purpose of lowering energy demand, if one accounts for embodied energy in measures that are used for obtaining the zero energy house [33]. In his study he concluded that '*carefully designed low energy buildings perform better than self-sufficient houses in life cycle context. Too many technical installations in order to make building self- sufficient are not desirable*'.

7.4.2. Lifetime

The renovation for TEK10 might be more beneficial if the building after renovation is promised longer life than to 2050. Longer lifetime, bigger energy and GHG emissions savings.

The original stock assume to have the same energy demand throughout whole period between 2010 and 2050. It might be uncertain how the dwellings would age without any renovations. Most probably, the energy demand would increase after years but it is uncertain how much. However, this should be noted and in further work adjustments should be made while accounting for energy saving potential.

7.4.3. Different choice of energy reduction potential for TEK10

It is uncertain how the implemented measures could decrease energy demand for space heating for given house. For the TEK 10 scenario, 30% decrease of energy demand for space heating was assigned to the second deep renovation, after which exemplary building suppose to achieve TEK10 standard. However, it is possible that the building would have higher energy savings, hence the usage of materials used for renovation would be enough to benefit in GHG emission terms. As results are showing the saving potential is very small for TEK10 scenario and that can be due to assigning to low energy saving potential after second renovation.

7.4.4. Behavioural issues. How realistic the implementation of scenarios is

According to McKinsey report the biggest energy saving potential among all of the sectors, that is not related to the technical abatements could result from behavioural change. The figure 54 is presenting the examples of how much energy could be saved in different sectors due to behavioural change. Those estimates have high degree of uncertainty however, in the optimistic scenario 1.5 Gton of CO2-eq could be saved globally in building sector just due to change of behaviour of energy users. The changes would have to come from reduction of heating/cooling in buildings, along with reduction of usage of appliances. It is difficult to change habits of how nowadays people are using their houses. Consciousness about issues related to households could be potentially changed with right effective incentives from policy makers.

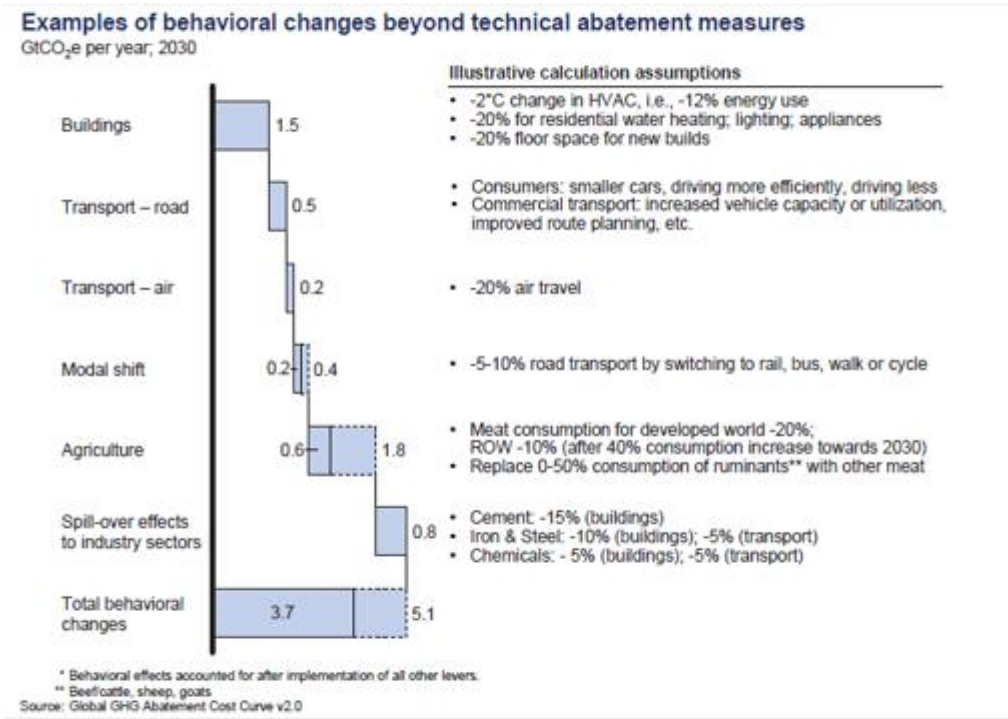


Figure 54 Examples of behavioral changes beyond technical abatement measures. Source: [11, 75]

The example of how it might be difficult to change behaviour associated with energy use in buildings and how sometimes implementation of energy efficient measure can have a negative impact, is an example of air-to-air heat pump. According to Enova, due to rebound effect related to use of heat pump, this is not the best choice for reduction of energy use in buildings [1].

7.4.5. System boundaries: demolition phase

Due to high uncertainty related to the fate of construction of materials after use phase, the demolition phase was not included in the scope of study. However, in the future studies, if possible, demolition should be accounted within scope of study. Related to it use of recyclable materials should also be considered. The potential of reuse of building materials for other renovations, if applied in that study, could alternate the GHG saving potential and overall results for emissions embodied in measures. This could cause a big source of uncertainty for overall calculations and used methods.

7.4.6. Uncertainties related to EPD use

A big share of uncertainty is associated with the use of environmental product declarations. During the collection of the necessary inventory data the key problems and sources of uncertainties associated with using EPD's were linked to the following issues:

- Electricity mix – most of EPDs specify the type of electricity mix that they are using (mostly it is Nordic mix for Norwegian EPD) but almost none specify the CO2 factor for the production nor what type of voltage is used (medium or high voltage).
- The life cycle phase labelled A4 (in accordance with guidelines from NS EN 15804 standard) "Transport [to the site]" in several EPDs did not have enough information in order to be able to use it for this analysis. The information that was given contained results for emissions related to the transportation of products to the site, but did not specify the distance, type of transportation or in some cases accounted for transportation together with another life cycle stage, which made it impossible to extract the values for individual use. In some cases, although the EPD had system boundaries that included transport, it only accounted for transportation during the production stage and omitted transport to the site.
- For the wood products, EPD's do not specify the density of use material. The moisture content of the given type of wood is the value to be reported. This led to the need for our own assumptions on the basis of the given average density for different types of wood in the analysis.
- Mentioned already in the methodology chapter, the reporting of CED results differ greatly in EPD documents. This led to the need of assuming how different primary energy sources should be labeled and accounted for in the analysis. The unified system for reporting impacts with a clear separation of the life cycle stages is needed for better use in EPD reporting.
- In EPD for the insulation materials different products from manufacturer were considered. In order to be able to calculate emissions related to those products the scaling factors were given. However the documents did not provide background on how the scaling was made and what kind of basis. In the documents, the conductivity was not specified for different types of insulation products. It was then assumed that by using scaling factors, the same conductivity as for the functional unit was achieved. However, more detailed information provided by the manufacturer on their website was giving different information about properties of the material.

Each EPD document has to comply with specific Product Category Rules (PCR) made for different product categories. The PCR guidelines provides with the information how to report LCA results and which information about raw materials, consumption, processes and emissions are the most significant for a given product category. Although these rules are specifying in detail how the manufactures should report their LCA results, several studies on EPD documents have found that there is still a lot of work to be done in order to assure the same level of transparency and formatting for EPD’s [76].

7.4.7. Use of segmented dynamic stock model

The dynamic model for dwelling stock was used in the analysis only for one renovation cycle – 40 year. That creates difference between results for one exemplary house where three renovation cycles are assumed and results for accumulated stock of single- family houses. Due to lack of possibility of differentiating between three different renovation cycles, only one had to be chosen. It was also not possible to account for only single-family detached houses that are assumed to be renovated. The calculations were made for whole cohort of detached houses (including farmhouses, terraced houses and semidetached houses) which drives to the overestimation of calculating energy saving potential for single-family houses. The amount of renovation applied to the stock does not changing the demolition rate in the dynamic model. This might be potential error because improvement of the building leads to prolonging its lifetime. Therefore, if more buildings are renovated the total number of demolished buildings should somehow decrease.

8. Conclusion

The aim of this study was to assess the environmental impacts of renovating an exemplary single-family house built between 1980 and 1990 to the current building requirement TEK10 or more ambitious, passive house (NS3700 scenario) level. The scope of the analysis was split in to two steps. First, one exemplary house was analysed using LCA methodology and impacts from renovation depending on the refurbishment scenario and different shares of primary energy mix were compared against each other. Subsequently, the analysis of the whole stock of single –family houses built between 1980 and 1990 was conducted. Dynamic modelling was used for assessment of the stock metabolism with use of 40 year cycle renovation rate on the given cohort of single-family houses. Finally, sensitivity analysis was made in order to present the impacts on the overall results from a potential increase in import of electricity into Norwegian market. Different electricity mixes and several potential scenarios for future renewable and non-renewable primary energy sources needed for production of electricity, were compared with the reference to the results for energy use needed for given building cohort.
The scope of this study included analysis for two characterizations: cumulative energy demand (CED) and climate change (CC). Using those indicators and methodology, both: materials used for renovation and energy needed for the operation of the house were investigated. Beyond the scope of this thesis was assessment of the demolition of the house and materials and impacts related to the construction of the exemplary house.

The results are in line with previous studies.
<u>To conclude results for retrofitting one exemplary house with use of the TEK10 or NS3700 scenario are</u>:
→ The total CED emissions per building for TEK10 scenario are 1.58E+05 MJ-eq and 2.10E+05MJ-eq for the NS3700 scenario (including all three-renovation cycles). The biggest contributor to the CED impacts is from the retrofitting of roof to the passive standard (4.59E+04 MJ-eq) and applying the solar collector system (4.28E+04 MJ-eq). Detailed contribution analysis of particular materials used for renovation revealed that use of Evacuated tubes for the solar collectors system (22.9 GJ-eq) and Rockwool – stone wool used for insulating the floor in the NS 3700 scenario (21.8 GJ-eq) contributed the most to the CED.

→ The contribution analysis considering renewable vs non-renewable primary energy sources showed that fossil oil was the biggest contributor mostly for all of the measures (35% of total CED).

→ For the climate change characterization, in both scenarios the biggest impact came from retrofitting of the roof and floor (48% of the total emissions related to measures for NS3700 scenario and 51% for TEK10 scenario). The emission from production of the solar collector system also scored high if compared to the rest of measures used for NS3700 scenario (2.45E+03 kg CO_2-eq which constitutes for 20%). Overall, the renovation package for NS3700 scenario contributes more to the CC impact than for TEK10 scenario. The total difference between those two scenarios is 2.38E+03 (11%). This difference is relatively small when compared to the GHG reduction potential for both scenarios.

After retrofitting the exemplary house, the biggest energy demand was shifted from HVAC to DHW and electric appliances. This reduction came from usage of alternative energy sources (solar collector system, air-to-air heat pump together with heat exchanger) than direct electricity for space heating.

<u>Results for the operation of the exemplary house over period 2010-2050</u>

→ Considering the 1a energy scenario (7% of electricity imported from Nordic mix and 93% produced domestically, mainly from hydropower), emissions related to materials significantly contributed to the accumulated GHG emissions for the passive house scenario. The percentage of GHG shares is the same as for the accumulated emissions for heating and ventilation (29%) over 40 years of operation of the house. Looking on the accumulated results for CED characterization, materials contributed less than ten percent for passive house scenario (8%) and even less for the TEK10 scenario (5%).

<u>In order to sum up the results for the cumulative single-family house stock:</u>

→ Results for energy saving potential showed that by 2050 for the NS3700 scenario, the energy use reduction occurred of around 51% with reference to the baseline scenario where no renovation is assumed. With reference to the starting point, which in the analysis was 2010, the biggest saving potential would results from deep renovation to the passive house standard. Annual energy saving potential shows that for NS3700 scenario it is possible to save around 3.05 TWh in 2050, whereas for TEK10 scenario the annual potential in 2050 is 2.49 TWh compared to 2010 level.

→ The accumulated GHG reduction potential related to energy demand differs extremely between the TEK10 and NS3700 scenarios. In the NS3700 scenario the annual CO_2-eq saving potential was around 119 kilotonCO$_2$-eq at the end of 2050; in the same time, the annual GHG savings for the TEK10 scenario were on average 50% lower. Emissions embodied in materials used for renovation to the TEK10 standard were contributing significantly to overall emissions for the stock due to too low energy demand reduction for the operation of the house. Cumulative GHG savings during period 2010-2050 with reference to 2010 level were very low for TEK10 scenario. By 2050 the cumulative saving potential was estimated to be 112 ktoneCO2-eq which was 8% of cumulative saving potential for NS3700 achieved by the same time.

Results for the sensitivity analysis

→ Almost no influence on GHG emissions was observed from adding more area to the solar collector.

→ The GHG emissions related to the renovation would be reduced by around 10 % for passive house scenario and 6% for TEK 10 scenario if the alternative insulation material would be applied (sheep wool instead of rock or mineral wool). However, the embodied energy in materials and in the operation of the house would stay the same.

→ Depending on the imported electricity share used for the operation of the house, the share for embodied emissions in materials differ between over 20% and less than 5% for both the NS3700 and TEK10 scenarios. That showed that depending on the electricity mix used for the operation of the exemplary house (functional unit), the embodied emissions in materials applied for the renovation of the building will play more or less of a significant role in the life cycle of the building.

→ In comparison with results obtained using dynamic modelling for the Norwegian stock, the energy saving potential in 2040 for the TEK10 scenario would be equal to 1.94 TWh and for NS3700 scenario 2.48 TWh with reference year 2010 (4.9 TWh). With this assumption, renovating single-family houses stock to the passive house scenario would result in 50% change compared to 2010 levels and it would achieve the target for emissions reductions set by Norwegian authorities. Renovation to the TEK 10 standard would result in almost 22% difference when compared to the passive house standard renovation. If electricity mix used in Norway nowadays would not change and the level of imported electricity would stay on the average of 7%, the energy saving potential for TEK10 scenario would not be that far from meeting the target (especially if other segments of Norwegian stock would be renovated with at least the same standard).

→ Any increase in imported energy from Nordic or European mix results in decrease of the GHG saving potential. Considering NS3700 scenario the savings are positive for all of the energy scenarios except the extreme cases in which 100% of EU or Nordic mix is assumed to be imported.
→ For NS3700 scenario the accumulated GHG emissions saving potential would be positive for all three EUmix scenarios, for both cases when 7% and 12% of electricity is imported. The saving potential would still be positive even when the red scenario, which is the worst-case scenario for the EU mix, is taken into consideration. That shows the potential and role of renovating the existing building stock. The level of renovation as well plays a significant role. If the existing stock is renovated to the TEK10 standard the cumulated GHG emissions saving potential is only positive for the ultra-green EU mix scenario. If the shares of imported electricity will increase and the EU mix would be imported the potential for saving GHG emissions could be highly dependent on the level and quality of deep renovations. That is assuming that other variables such as behavior linked to energy use would not change.

8.2. Recommendations

It is estimated that Norway could save 12 TWh by 2020, which corresponds to 80 billion NOK from improving the existing building stock [5]
However, despite this big potential, according to Tor Helge Dokka, nowadays it is seldom that house owners refurbish houses to the current house standards, and even more rare is a renovation to the passive house standard.
The most desired by policy makers and building specialists is to renovate up to a passive house standard [5] but without incentives from the government it is difficult to convince owners to refurbish houses with the higher standard than their wallet say so. Usually they stop on the lowest level refurbishment package, which is also the most affordable. To be able to achieve the nearly zero energy-building target several conditions have to be fulfilled. Long-term policy has to be set along with the removal of administrative barriers. The consensus on definitions and guidance should be achieved for better and quicker implementation of existing solutions. The best practice should be introduced to all major players along with the robust application of those practices. The challenges should be addressed. Equipped with all of those means, major actors should come to act and implement best practices and recommendations through an active dialogue between policy makers and private homeowners. Without reaching to the primary energy end-consumers and

keeping proactive conversation between them and building professionals there is high risk that not much will be done in direction of major, energy efficient renovations.

8.3. Further work

In the future studies if possible, system boundaries should be expended and include as well demolition phase in to the scope of studies. This way, the potential of reuse of construction materials could be correctly acknowledged. This study aimed to see the implication of using the most common measures for renovations that are applied today, however a new study could see the energy and GHG saving potential related to the building materials that are in the development stage (like nano-insulation, or windows with applied photovoltaics). The challenge of future work is also within including influence from non-technology related changes like social behavior associated with energy use.

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9. Appendix

Appendix is available upon request.